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Digital image processing and isostatic studies
of the regional gravity field of Great Britain
and adjacent marine regions

by

Richard W. Woollett

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Doctor of Philosophy

Grey College



October 1988

- 6 JUL 1989

Abstract

This thesis presents the results of an investigation into the regional gravity field of Great Britain and the adjacent regions. A prerequisite for this study was the development of a computer database designed to store, manipulate and display the information contained within nearly 400,000 gravity and topography point observations for the region.

Digital image processing techniques have been applied to the reduction and display of the Bouguer anomaly data. The observed Bouguer anomaly lineaments display a pattern of geological basement structures which correlates closely with those predicted by recent plate tectonic models of the Lower Palaeozoic Caledonian orogeny which assume the convergence of three distinct continental plates.

The nature of the isostatic compensation of the topography in the vicinity of the United Kingdom has been investigated using cross spectral analysis of the gravity and topography. The observed cross spectral relationships are compared with those for a theoretical isostatic model which assumes the lithosphere behaves like a thin elastic plate loaded by both surface topography and internal density contrasts overlying an inviscid fluid substratum. For a uniform elastic thickness of the continental lithosphere the best fit between the observed and theoretical relationships is obtained for values of the elastic thickness of the lithosphere of 22.5–24.5 km. A better fit is obtained if the continental lithosphere is assumed to comprise a population of distinct tectonic provinces of equal area with the values of the elastic thickness of the lithosphere for the provinces distributed uniformly between 6–8 km and 86–90 km.

Detailed investigations into the structure of the crust beneath the Tertiary igneous complexes of Mull and Skye, northwest Scotland, indicate a possible slight thickening of the crust which is considered to be an important consequence of the mechanism of the emplacement of the complexes.

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CHAPTER 1

Introduction

1.1 Outline of research

1.1.1 Introduction

The effective completion of the gravity survey of the UK (Smith et al., 1987) and the development of large databanks of gravity and topography data for the adjacent shelf seas and northwest Europe has facilitated an in depth examination of the regional gravity field of the UK and the adjacent marine regions. Gravity data provides an important constraint on the structure of the Earth's crust, especially the upper 10 km or so, allowing the subsurface form of geological features mapped at the surface to be more clearly defined and identifying previously unknown density contrasts at depth. This study examines the Bouguer anomaly gravity field in a regional context tracing the major tectonic fabrics across the UK region and interpreting their importance in the tectonic evolution of the region. The application of digital image processing techniques to the potential field data has been found to provide a useful form of displaying and reducing the large amount of data available within the databanks. The relationship between the measured gravity anomalies and the observed topography is also used to investigate the rheological nature of the continental lithosphere through the study of isostasy.

The only similar study to date is a report on the regional Bouguer anomalies of northern Britain by Hipkin and Hussain (1983) who were instrumental in the original compilation of the UK gravity and topography databank. However, the limited areal extent of the region of interest meant that the problems of the tectonic evolution of the UK as a whole could not be addressed and that the diagnostic long wavelength gravity anomaly information was absent from the study of isostasy.



1.1.2 The development of a gravity and topography database

The national gravity and topography databank compiled for the British Geological Survey (B. G. S.) by the University of Edinburgh Department of Geophysics (Hipkin and Hussain, 1983) contains approximately 270,000 point observations. Additional data sets obtained for the Republic of Eire, mainland Europe and the North Atlantic comprise over 100,000 further data point observations. The vast size of the total data set required the development of a computer database to store, manipulate and display the gravity and topography data. The design of such a database written in Fortran 77 is described in Chapter 2. The database provided a solid foundation for the subsequent analysis of the regional gravity field. The most important function of the database was the generation of gridded representations of the gravity anomaly field and topography for use in the digital image processing studies and the cross spectral analysis of the gravity anomalies and topography.

1.1.3 Digital image processing and gravity data

The application of digital image processing techniques to potential field data is a new innovation which has been found to produce an effective alternative to the more traditional contour map presentation. Digital images are able to display very large data sets and are, therefore, ideally suited to regional tectonic interpretations of potential field data. The digital images present a strong visual effect and their interpretation relies more upon visual perception and pattern recognition than the more quantitative analysis provided by contour maps.

In particular, digital images may be enhanced to highlight subtle trends in the imaged data allowing a detailed analysis of lineaments and lineament patterns. This enables the mapping of different tectonic provinces through the study of the trends and orientations of the macro geological structures represented in the gravity anomaly field.

In Chapter 3 digital image processing techniques are applied to the Bouguer anomaly data for the UK, the surrounding shelf seas and eastern Ireland. The Bouguer anomaly data for the Republic of Eire and Ulster is examined in Chapter 4.

An important concept throughout the interpretation of the digital images of the

Bouguer anomaly data is the reactivation of early tectonic structures by later periods of compression and tension. There is growing evidence for the formation of extensional basins over older reverse faults. Examples cited include the Minches basin, the Sea of the Hebrides trough and the Inner Hebrides trough (Smythe et al., 1982; Brewer and Smythe, 1986), the Worcester basin (Chadwick 1985; Beckinsale et al., 1986) and the North Celtic Sea graben (Birps and Ecors, 1986). The older reverse faults were generated by a number of different tectonic events. In northern and western Britain, the Irish Sea and Ireland the reactivation of NE–SW trending faults generated in the Caledonian orogeny predominates. However, in central England the reactivation of Malvernian and Charnian structures is also observed and in southern England and the Celtic Sea an important tectonic control was exerted by the Variscan front. The diverse orientation of these tectonic trends ensured that the reaction of the basement to later periods of compression and tension shows a marked complexity.

1.1.4 Gravity, isostasy and lithospheric flexure

The information provided by the gravity anomaly data about the density contrasts present within the lithosphere is also of importance to the understanding of isostasy, the process by which the elevation of the Earth's surface is supported by density contrasts at depth. The nature of the isostatic compensation of the topography of the UK is examined in detail in Chapter 5. The relationship between gravity anomalies and topography over the UK has been investigated using the cross spectral isostatic response function approach first proposed by Dorman and Lewis (1970).

This technique has been applied to oceanic regions with a degree of success (McKenzie and Bowin, 1976; Watts, 1978; Cochran, 1979; McNutt, 1979). The observed relationship between gravity and topography in the wave domain is compared with the relationship predicted by theoretical models of the proposed mechanisms of isostasy. The most successful models for oceanic regions to date model the response of the oceanic lithosphere to loading by loads of geological duration as the deflection of a thin elastic plate overlying an inviscid fluid substratum by surface loads. In a study of gravity and topography over the mid-ocean ridges, Cochran (1979) estimated the best fit elastic

thickness of the oceanic lithosphere to be in the range of 2–6 km for the East Pacific Rise and 7–13 km for the mid-Atlantic ridge. In a similar study, Watts (1978) estimated the elastic thickness of the oceanic lithosphere in the vicinity of the Hawaiian–Emperor Seamount chain to be in the range of 20–30 km. Watts (1978) concluded that the elastic thickness observed for the oceanic lithosphere for any particular load was a function of the age of the lithosphere at the time of the emplacement of the load. The depth of the 450° C isotherm at the time of the loading was considered to give a rough estimate of the observed best fit elastic thickness.

The increase in the elastic thickness of the lithosphere with increasing age suggests that the older continental lithosphere should display a greater elastic thickness than the oceanic lithosphere, providing that the age of the continental lithosphere has not been reset by a major thermal event, such as an orogeny. This assumption appears to be generally true for estimates of the elastic thickness of the continental lithosphere deduced from the modelling of the deformation produced by isolated loads (Walcott, 1970a; Cohen and Meyer, 1966; Karner and Watts, 1983). However, estimates of the elastic thickness of the continental lithosphere derived from cross spectral studies of gravity anomalies and topography have produced very low values for the elastic thickness. Banks et al. (1977) estimated that the flexural rigidity of the continental lithosphere in the vicinity of the USA corresponds to an elastic thickness within the range of 5–10 km. McNutt and Parker (1979) found that the best fit to the relationship between gravity and topography observed for the Australian continent requires an elastic thickness of less than 1 km. Cochran (1980) argued that the low estimate for Australia may be caused by the isostatic response function being weighted towards the mechanism of isostatic compensation occurring at the mountainous regions of the continent, which may have formed under conditions akin to local Airy isostasy. The problems inherent in applying the cross spectral analysis to continental regions were examined in detail by Forsyth (1985). Forsyth (1985) suggested that the coherence between the gravity anomalies and topography provides a more realistic estimate of the elastic thickness of the lithosphere than the isostatic response function. This is because the continental

lithosphere is loaded both by surface topography and by internal density contrasts, and the subsurface loading is poorly analysed by the traditional isostatic response function approach alone. Bechtel et al., (1987) applied the methods proposed by Forsyth (1985) to a study of the nature of the isostatic compensation of the topography in the vicinity of the East African rift, Kenya. The best fit in a least squares sense to the observed coherence predicted that the flexural rigidity of the continental lithosphere equated to an elastic thickness of 25 km.

Chapter 5 investigates these techniques and discusses their practical application. The results of an examination into the mechanisms of isostatic compensation operative within the UK region are presented. This study indicates that the overall relationship between gravity and topography for the region is complicated by isolated systems of local Pratt isostasy occurring within the upper crust associated with the major granitic complexes.

1.1.5 The deep structure of the crust beneath Mull and Skye, northwest Scotland

The theme of isostasy is partially continued in Chapter 6 which investigates the possibility of a slight thickening of the crust beneath the Tertiary igneous complexes of Mull and Skye, NW Scotland. The thickening of the crust is considered to be a direct consequence of the diapiric intrusion of magma into the lower crust and the subsequent emplacement of the central complexes by stoping (Bott and Tantrigoda, 1987). The resultant thickening of the crust provides an interesting form of regional isostatic compensation for both the excess mass of the complexes and the associated high topography.

1.2 Geological setting of the United Kingdom

The United Kingdom is located on the northwest margin of the European continental shelf. The region has experienced a complex history of tectonic activity and the geology of the United Kingdom is the subject of a vast accumulation of previous literature. Therefore, in this section only a very brief explanation of the geological setting

of the United Kingdom is given to form an initial basis for the later discussions.

Ziegler (1982) identified five main episodes of megatectonic activity within the Phanerozoic evolution of northwest Europe. These events may be summarized as follows:

- (1) the Caledonian and Hercynian suturing of the Pangaeon supercontinent;
- (2) the development of tectonic instability within Pangaea during the Permo-Trias;
- (3) the Jurassic-early Cretaceous break up of Pangaea and the opening of the Tethys and Atlantic oceans;
- (4) the onset of Alpine plate collision in the late Cretaceous and the rifting of the Arctic and North Atlantic;
- (5) the Cainozoic opening of the Norwegian-Greenland Sea, the continuation of the Alpine orogen and the final late orogenic collapse.

The Caledonian orogeny was the result of the Lower Palaeozoic closure of the Iapetus ocean. The Iapetus ocean was initially formed by an earlier period of continental rifting and separation during the late Precambrian (Watson, 1984). The closure of the Iapetus ocean is now considered to have involved two periods of convergence (Soper and Hutton, 1984; Soper et al., 1987; Pharaoh et al., 1987). The first stage of the orogen which formed the orthotectonides of the Grampian Highlands was caused by the east-west collision of Laurentia and Baltica in the Ordovician to late Silurian. A later period of deformation was generated by the accretion of Cadomia during the late Silurian-early Devonian (Soper et al., 1987). This produced the deformation of the slate belts of the paratectonides in northern England and central Ireland and may have initiated the late strike slip displacement of the orthotectonides. The proposed suture marking the site of the former Iapetus zone of convergence is considered to traverse along the Solway Firth in northern England, across the Irish Sea and through the Irish paratectonides (Phillips et al., 1976). The location of the continuation of the suture to the east beneath the North Sea is less certain.

The Caledonian orogeny was followed by a period of relatively quiescent tectonic activity in the UK region. During the Lower Carboniferous, a series of blocks and

troughs developed in northern England and central Ireland. The subsidence of the basins resulted from tension associated with Hercynian plate margin processes but the form of the blocks and basins was often influenced by structures generated in the Caledonian orogeny (Leeder 1982; Brown and Williams, 1985).

The second episode of the suturing of Pangaea occurred during the Hercynian or Variscan orogeny. The Hercynides of Europe, the Alleghenides of northeast America and the Mauritanides of northwest Africa mark the suture between the Laurasian and Gondwanaland supercontinents which joined to form Pangaea. The deformation was diachronous occurring between the early Carboniferous and early Permian. The deformation occurred in a series of pulses generated by the progressive accretion of the Avalon–Meguma and Austro–Alpine microcratons during the mid–Devonian, the Aquitaine–Iberian microcontinent during the late early Carboniferous and the final closure of the Proto–Tethys ocean in the late Carboniferous (Ziegler, 1982). The trace of the Variscan front is considered to traverse across southern England, along the coast of south Wales to Pembroke and across the north Celtic Sea into southern Ireland where it can be followed as far west as Dingle Bay. North of the front the deformation of the basement is often strongly influenced by pre–Variscan structures.

The Mesozoic–Cainozoic tectonic evolution of the UK and northwest Europe has been reviewed by Dewey (1982) and Ziegler (1982). During the late Permian, the Pangaea supercontinent started to become unstable. By the end of the Triassic an extensive system of continental rifts had developed. Many of the rift boundaries were influenced by earlier basement structures. The rift framework included the Cheshire, Cardigan Bay, St. George’s Channel, Bristol Channel, Western Approaches and Wessex basins, and the Celtic Sea, Viking and Central grabens.

In the early–mid Jurassic localized stretching caused crustal failure and the opening of the central Atlantic. Following the initial rupture changes in the location of the opening of the Atlantic ocean generated a complex history of compressional and tensional stress within northwest Europe. Further extension in the North Sea region occurred between the mid–Jurassic and mid–Cretaceous. In the late Cretaceous, the

opening of the Labrador Sea modified the relative motion between Africa and Europe (Dewey, 1982). The Alpine trough was subjected to compression and this was felt within the foreland of northwest Europe. In the central North Sea tension ceased and a period of thermal relaxation and subsidence of the lithosphere ensued (Wood and Barton, 1983; Sclater and Christie, 1980). In some regions basin inversion was initiated by wrench faulting (Glennie and Boegner, 1981).

In the early Tertiary, compression in the northwest foreland of the Alpine orogen again relaxed. NE–SW tension in the Hebridean region of the Thulean province preceded the extrusion of basaltic plateau lavas and the subsequent intrusion of the central igneous complexes. An extensive NW–SE orientated dyke swarm was also emplaced. Finally, a further episode of compression generated by the Alpine orogen produced basin inversion along roughly east–west orientated axes in the Wessex basin of southern England (Dewey, 1982; Stoneley, 1982).

CHAPTER 2

The development of a national gravity and topography database

2.1 Introduction

Over recent years the amount of information collected relating to the Earth sciences has increased dramatically. This has enabled the establishment of large databanks containing many thousands of individual records. A databank is a set of similarly structured data records which forms a significant store of information. Most databanks store only information relating to one aspect of the Earth sciences, such as geochemistry, hydrogeology or geophysics.

The usefulness of the databanks can be greatly improved by the development of computer databases to organise the storage, retrieval and processing of the data within a specific databank. The database should be designed to facilitate the rapid presentation and analysis of the data within the databank. More specialized databases may be used to define relationships between the data in several databanks. This enables an integrated analysis of all the available data corresponding to a particular problem.

Engles (1970) gave the following definition of a database: "A database management system allows multiple independent users to have concurrent access to a central repository of information". In this chapter the philosophy behind a computer database designed to store the national gravity databank (Hipkin and Hussain, 1983) and other data sets is described. The database is written in Fortran 77 and designed to operate under the Michigan Terminal System (Salisbury, 1984), which is the standard operating system at the University of Durham Computer Centre. The computer programmes most relevant to this discussion and the research in the later chapters are listed in Appendix B.

The advantages to be gained by developing a database are

- (1) the gravity and topographic data can be efficiently stored on magnetic disc space in a virtual access memory, which when interfaced with a data retrieval mechanism provides rapid data retrieval;
- (2) data updating programmes may be developed to maintain the accuracy of the data;
- (3) centralized storage of the data allows standards to be maintained;
- (4) data presentation and analysis programmes can be interfaced with the data retrieval programmes to enable rapid analysis of the data.

The facilities provided by the database have been utilised frequently throughout the course of my studies. The following features have been found to be particularly useful:

- (1) the ability to generate gridded representations of the observed Bouguer gravity and topography;
- (2) the ability to retrieve, and write to an external file, all the data associated with a particular region of interest;
- (3) the ease with which new datasets may be entered into the database;
- (4) the ability to remove incorrect data from the database.

The database has been specifically designed to store gravity and topographical point observations, but the techniques used could be modified and applied to any scalar field observed at random points on a surface.

2.2 Databases in the Earth Sciences

The development of the gravity and topography database reflects a growing interest in the use of databases in the Earth Sciences. Several other databases have been developed for gravity data. Hipkin and Hussain (1983) designed a Fortran 77 system at the Edinburgh Regional Computer Centre solely for use with the national gravity databank. The Durham system is an extension of a world gravimetric/topographic databank developed at the Lamont Doherty Geological Observatory (Karner, 1983). The gravity data centre, Ottawa, has utilized a commercial database, System 2000 (MRI Systems Corp., 1974), to store gravity and topographic data for Canada.

Databases have become increasingly important in other fields of geology. The British Geological Survey, B. G. S., is developing an extensive database covering many aspects of the geological sciences. The main interests are in deep subsurface geology, hydrogeology, industrial mineral assessment, mineral economics, geochemistry, petrology, geophysics and the geology of the UK continental shelf (Horder, 1981). Other databases include IGBADAT, a world database for igneous petrology now distributed by the World Data Centre A, Boulder Colorado (Le Bas et al., 1983). A global file of marine geophysical data at the National Geophysical Data Centre, USA, is managed by the Geodas database (Hittelman and Metzger, 1983).

2.3 Databank processing

The database developed at Durham contains gravity point observations covering much of NW Europe and the UK continental shelf. Land observations have been accumulated for the region 47°N – $62^{\circ}\text{N}/15^{\circ}\text{W}$ – 12°E . Marine observations partially cover the region 49°N – $64^{\circ}\text{N}/25^{\circ}\text{W}$ – 12°E . The complete data set comprises several databanks. The most important sources of information are the national gravimetric/topographic databank compiled by the Geophysics Dept. of the University of Edinburgh for the B. G. S. and a databank for mainland Europe provided by the Defense Mapping Agency, St. Louis, Missouri. Additional datasets include a databank for Eire kindly provided by the Dublin Institute for Advanced Studies and a marine dataset for the northeast Atlantic obtained from the Institute of Oceanographic Sciences.

The gravity record formats used by the contributors are not uniform but commonly follow some form of merge/merge format (Talwani et al., 1972). Merge/merge formats are formed when navigational measurements are merged with geophysical measurements such as bathymetry/topography and gravity. Additional data such as station identifier codes are often included. The various record formats are processed into a common format before entry into the database. This procedure is largely cosmetic involving changes of the data field units into decimal degrees, metres and mGal, and conversions of integer data fields into real numbers. More complex reduction problems are discussed

later.

Within the database the gravity records are stored in unformatted, or binary, files. The information contained within each record is as follows: latitude, longitude, grid easting, grid northing (Ordnance Survey of Great Britain, OSGB, or O. S. of Ireland, OSI), topography, observed gravity, free air gravity, Bouguer gravity, terrain correction, Bouguer density (kg m^{-3}), terrain correction code, ten byte processing flags, a four byte character variable used for a number of purposes, such as indicating local gravity base stations, a four byte code to identify the record contributor, and finally two four byte station identifier codes. Examples of listed data records are displayed in table 2.1. The terrain correction codes are explained in Appendix A. Two of the processing flags have been utilized. The first flag has been set to 1 to indicate that the grid references are only accurate to decametres. Flag two has also been set to 1 whenever Irish grid references are used.

All of the gravity readings are referred to the 1967 IGRF. The datum is the 1973 National Gravity Reference Net (Masson Smith et al., 1974), which is tied to the International Gravity Standardisation Network 1971, IGSN71 (Morelli et al., 1971).

The national databank contains approximately 270,000 point gravity observations. Most of the readings are from land or surface marine stations, but some seabottom surveys are included. The land observations cover most of the UK and Ireland east of the origin of the OSGB grid. Marine observations cover most of the North Sea and the UK continental shelf, except for the NW Approaches. The B. G. S. provided updated surveys of Ulster, Shetland, the Outer Hebrides, east Hants., west Sussex, South Yorks., Notts., and a marine dataset for the NW Approaches (56°N – 59°N / $9^{\circ}30'\text{W}$ – 5°W). Surveys by the Applied Geophysics and Marine Geophysics units of the B. G. S. form the basis of the databank, but much additional information has been supplied by university researchers and commercial concerns.

The accuracy of the gravity observations for land stations is controlled by a number of possible causes of error. These include errors in the precise position of the station, measurement reading errors, earth tides, base network errors and errors in the applied

Table 2.1. Formatted listing of part of the database data file GD00857

FILE:GD00857

FILE CREATED: DEC 4, 1986

FILE STATISTICS

DATA FIELD	NUMBER OF RECORDS IN FILE=104	AVERAGE VALUE	RMS DEVIATION	UNITS
LATITUDE		57.2348		DEGREES
LONGITUDE		8.5758		DEGREES
TOPOGRAPHY		-91.26	200.94	METRES
ABSOLUTE GRAVITY	98169	1.75		MGAL
FREE AIR ANOMALY		3.68	7.34	MGAL
BOUGUER ANOMALY		9.39	14.65	MGAL
TERRAIN CORRECTION		0.0	0.0	MGAL

LINE NUMBER*1000

6000000	57.5921	8.0559	9999940	9900000	-207.30	9817116	0	-7.44	6.81	0.0	2700.0Z	10000000000
6000001	57.5838	8.0338	9999988	9900000	-202.50	9817119	0	-3.74	10.18	0.0	2700.0Z	10000000000
7000000	57.6058	8.0221	9999920	9900000	-224.10	9817112	5	-12.04	3.36	0.0	2700.0Z	10000000000
7000001	57.6065	8.0508	9999910	9900000	-223.10	9817114	0	-10.64	4.70	0.0	2700.0Z	10000000000
8000000	57.7700	8.0300	9999950	9900000	-488.00	9817446	6	-8.56	42.73	0.0	2700.0W	10000000000
8000001	57.7350	8.0683	9999913	9900000	-443.00	9817180	0	-17.16	13.85	0.0	2700.0W	10000000000
8000002	57.7367	8.0317	9999930	9900000	-448.00	9817233	1	-12.20	19.16	0.0	2700.0W	10000000000
8000003	57.7316	8.0016	9999950	9900000	-439.80	9817331	1	-3.77	26.47	0.0	2700.0Z	10000000000
8000004	57.7321	8.0441	9999964	9900000	-439.40	9817330	3	-1.67	28.54	0.0	2700.0Z	10000000000
8000005	57.7326	8.0690	9999920	9900000	-439.00	9817300	6	-4.37	25.81	0.0	2700.0Z	10000000000
8000006	57.7750	8.0667	9999960	9900000	-494.00	9817444	4	-5.95	40.54	0.0	2700.0W	10000000000
9000000	57.8008	8.0141	9999930	9900000	-504.40	9817554	3	1.37	48.99	0.0	2700.0Z	10000000000
9000001	57.8115	8.0366	9999960	9900000	-510.30	9817552	2	10.81	45.99	0.0	2700.0Z	10000000000
9000002	57.8220	8.0591	9999930	9900000	-516.20	9817449	1	6.80	42.99	0.0	2700.0Z	10000000000
9000003	57.8833	8.0816	9999920	9900000	-520.70	9817444	8	1.70	37.55	0.0	2700.0Z	10000000000
9000004	57.8698	8.0231	9999900	9900000	-481.00	9817770	7	24.49	57.55	0.0	2700.0Z	10000000000
9000005	57.8781	8.0555	9999920	9900000	-480.00	9817777	9	30.99	63.99	0.0	2700.0Z	10000000000
1000000	57.9030	8.0713	9999910	9900000	-480.00	9817551	9	2.99	35.99	0.0	2700.0Z	10000000000

terrain corrections. Overall the error of the final Bouguer anomalies is likely to be of the order of 1 mGal (Personal communication, I. F. Smith, B. G. S.). The marine data is less reliable principally because of navigational errors. Hipkin and Hussian (1983) estimated errors in the range 0.8–2.0 mGal. Tulley and Donato (1985) suggested a RMS error of 1.34 mGal for the B. G. S. surveys of the northern North Sea. The density of station coverage is roughly 1 station per km² in England and Wales and 1 station for every 2.5 km² in Scotland (Smith et al., 1987). Marine data coverage is usually confined to ship tracks. For example, the data for the NW Approaches consists of ship tracks with the free air gravity and bathymetry sampled every 10'.

The preprocessing of the national databank and B. G. S. files before entry into the database is straightforward except for the treatment of the observed gravity. The initial data sets record the observed gravity using a two part code. The two part code is formed from a four digit integer code identifying the reference gravity base station and an integer data field recording the difference in gravity between the station and base. Land base stations are identified by a code of the form $-nn$, where $0 < nn \leq 96$. The integer nn corresponds to the position of the base station in Table 7 of “The National Gravity Reference Net 1973” (Masson Smith et al., 1974). The code -99 refers to the fundamental gravity base for Great Britain prior to 1973, located at Pendulum House, Cambridge.

This representation is precise, but it does not easily facilitate further analysis. Therefore, the two part code has been replaced by a real numbered value for the observed gravity determined by retracing the gravity reduction back from the recorded free air anomaly. The observed gravity recorded at land stations can be deduced from

$$G_{\text{obs.}} = \text{Free Air Anomaly} + G_{\text{lat.}} - 0.3806h \quad 2.1$$

where $G_{\text{lat.}}$ is the theoretical gravity on the spheroid at the latitude of the station and h is the height of the station above sea level in metres. Although the Eötvös correction has been applied during the reduction of the marine gravity measurements the applied correction is not stored in the databank records. Therefore, equation 2.1 has been used to determine the value of the absolute gravity on the geoid. Seabottom measurements

have similarly been processed to obtain the absolute gravity on the geoid. For seabottom stations the formula 2.1 needs to be modified to

$$G_{\text{obs.}} = \text{Free Air Anomaly} + G_{\text{lat.}} - 4\pi\rho Gh \quad 2.2$$

where G is the gravitational constant ($6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$), ρ is the density of sea water (1030 kg m^{-3}) and h is the bathymetry ($h < 0$). The constants used in the reference formula differ slightly between the databank and the B. G. S. files. The databank uses the formula of Mittermeyer (1969) which is defined as

$$G_{\text{lat.}} = 978031.85 + 5162.927 \sin^2 \theta + 22.948 \sin^4 \theta \quad 2.3$$

whereas the Applied Geophysics Unit of the B. G. S. uses the formula

$$G_{\text{lat.}} = 978031.8 + 5162.927 \sin^2 \theta + 23.08 \sin^4 \theta \quad 2.4$$

The difference between these formulae in the UK region is approximately 0.05 mGal. The error introduced by the use of the two formulae is, therefore, significantly less than the RMS errors of the data.

The gravity data for Norway, Denmark, West Germany, the Netherlands, Belgium, France and parts of Switzerland and Austria were provided by the Defense Mapping Agency. Approximately 95,000 records have been added to the database. The gravity readings are compatible with the UK data as the IGSN 71 and 1967 IGRF have been used for datum and reduction. The Bouguer density of 2670 kg m^{-3} has been converted to 2700 kg m^{-3} ; the density used in the UK. Only records with verified standard deviations for the free air and Bouguer gravity of less than 3 mGal have been included. No terrain corrections were available for this data set.

Gravity data for the Republic of Ireland was obtained from the Dublin Institute of Advanced Studies. A total of 21,069 records were provided for the whole of Eire. The data required reprocessing as the original reduction used the 1980 IGRF and a Bouguer density of 2670 kg m^{-3} . The 1980 IGRF is defined as

$$G_{1980} = 978032.7 (1 + 0.0053024 \sin^2 \theta - 0.0000058 \sin^2 2\theta) \quad 2.5$$

Around Eire the value of $G_{1967} - G_{1980}$ is approximately 0.93 mGal. The probable error in the Bouguer anomaly is ± 0.1 mGal. Terrain corrections have been applied where necessary. In some regions the low density overburden (2200 kg m^{-3}) may be in excess of 30 m deep. This causes an apparent error of up to -0.7 mGal. In these regions terrain corrections are considered inappropriate. The details of the Eire dataset were given in a personal communication from Mr. P. Readman of the Dublin Institute for Advanced Studies.

Data for the north Atlantic (49° N – 64° N / 25° W – 6° W and 58° N – 64° N / 6° W – 1° E) was obtained from the Geodas database (NGDC, Boulder, Colorado) with the assistance of the Institute of Oceanographic Sciences. Approximately 10,000 records were processed. The main data contributors were the Bureau Gravimetrique and the Lamont Doherty Geological Observatory. The Geodas records were formatted using the marine geophysical data exchange format, MGD77 (Hittelman et al., 1977). The Bureau Gravimetrique observations were reduced using the IGRF 1969 and the IGSN71 datum. The Lamont data was referenced to the earlier Potsdam system and was reduced using the 1930 gravity formula. The absolute gravity measurements for the Lamont dataset have been recovered using the 1930 formula (Lambert, 1945)

$$G_{1930} = 978049.0 (1 + 0.0052884 \sin^2 \theta - 0.0000059 \sin^2 2\theta) \quad 2.6$$

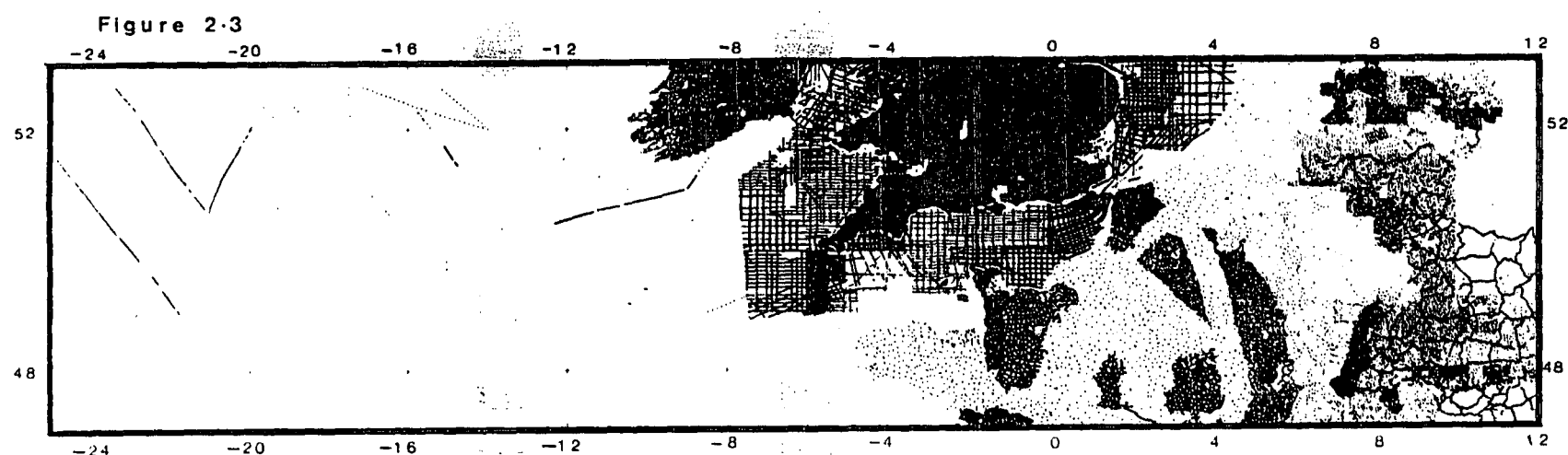
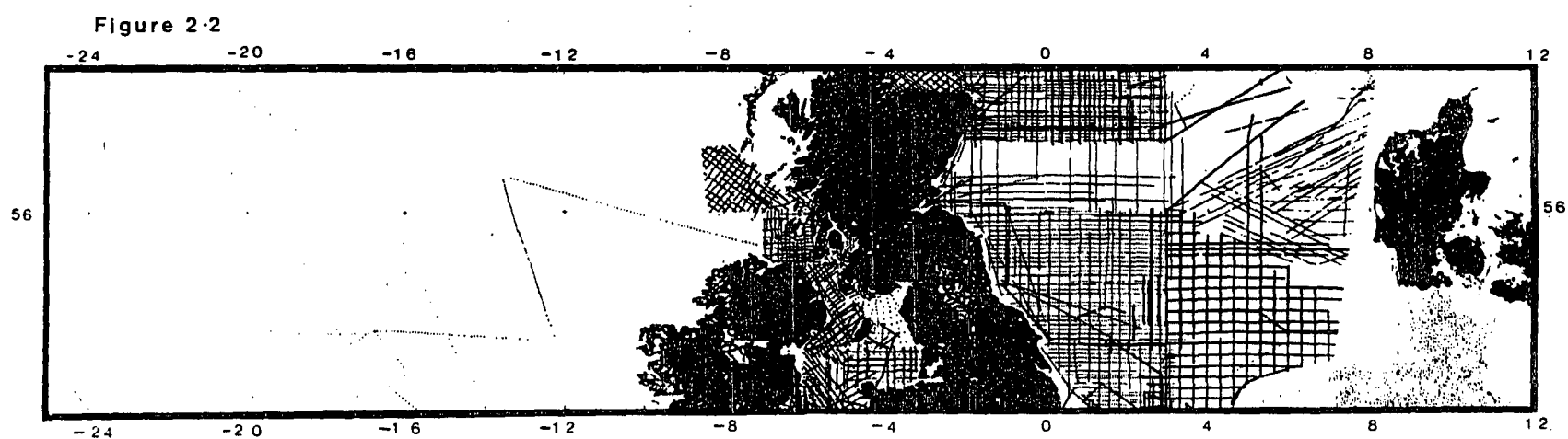
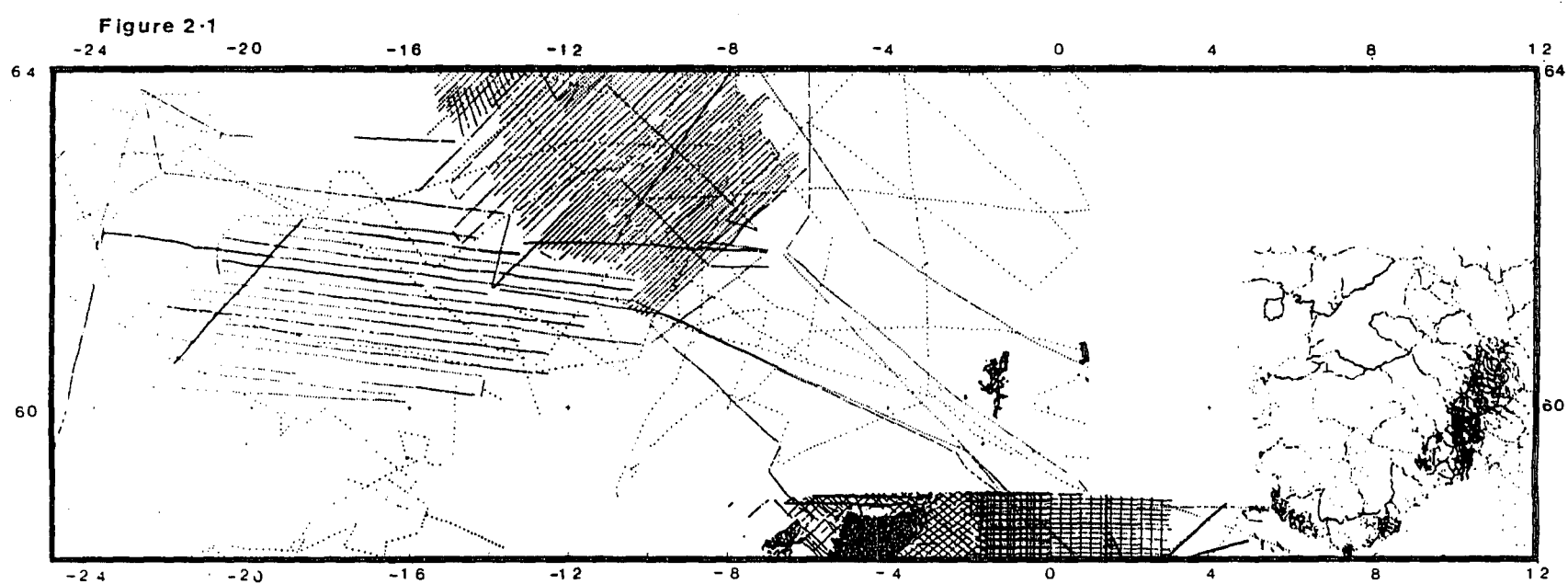
and then reduced with the 1969 formula. A Potsdam correction of 13.7 mGal has also been applied.

The distribution of all the data currently stored in the database is shown in the station point plots in figures 2.1, 2.2 and 2.3. The NW Approaches dataset is stored in a separate file to the main database and is accessed when required.

2.4 Database Development

The preprocessing allows a common record format to be used within the database for both land and marine data. The next stage of development is to design a central storage and retrieval system for the data records. Before designing the database software

Figures 2.1, 2.2 and 2.3. Distribution of gravity and topography point observations currently held in the gravity and topography database at the University of Durham.



it is important to decide the major operational requirements for the database (King, 1981). The database should be most efficient at those tasks that it is likely to be asked to perform most often. In the design of this database consideration was given to the following points:

- (1) the efficiency of the retrieval of data from a given, user specified, geographical region;
- (2) the amount ^{of} storage space required to store the database;
- (3) the amount of data simultaneously on-line during the processing of large data sets;
- (4) the design of data updating programmes to maintain the integrity of the data;
- (5) the development of user friendly data presentation and processing facilities.

Generally databases should not be structured for a single use alone (Anderson, 1978), but it was considered that the retrieval of the data for a specific region was by far the most important feature of the database. The database structure is, therefore, biased towards this requirement. Secondary importance was given to the amount of storage space required and the development of software to update the contents of the database.

2.5 Spatial data structures

The problem of storing an n-dimensional data set within the sequential memory of a digital computer, so that subsamples of the total data set may be retrieved on the basis of "geographical" locality, is fundamental to the design of geographical information systems (Guptill, 1978). This form of retrieval is known as range searching. A precise definition of range searching is: "given a set of records referring to points randomly distributed over a region we wish to retrieve all those records associated with points lying within a specified rectangle". The complexity of any algorithm designed to perform range searches may be determined from

- (1) the preprocessing time,
- (2) the search time,
- (3) and the storage space

required to execute the search (Shamos and Bentley, 1978). Additionally, the complex-

ity of updating the data may be considered. The term spatial data structure refers to the file structure and data access methods developed to perform efficient range searches.

The efficiency of different spatial data structures can be compared using the technique of asymptotic analysis. Asymptotic analysis measures the efficiency of an algorithm by determining the order of magnitude of the number of computer operations required (Shamos and Bentley, 1978). This removes the difficulties introduced by comparing algorithms operating on different computers with different speeds of computation. The number of operations required is expressed in the form of $O(f(N))$. This represents the set of all functions $g(N)$, such that there exist positive constants C and N_0 where

$$|g(N)| \leq Cf(N) \quad \text{for all } N \geq N_0 \quad 2.7$$

(Shamos and Bentley, 1978). This terminology is commonly abused so that the function $4N^2 - 6N$ may be expressed as $O(N^2)$. In the analysis of spatial data searches N defines the total number of records stored in the database. $O(f(N))$ usually expresses the average or expected number of operations, but it may also be used for the worst case estimation. The simplest form of range search is the Brute force technique. All N records of a data set are examined; each one being tested to see if it lies in the region of interest. This search requires $O(N)$ operations.

A more efficient search technique is the “inverted file” method. The records are indexed by sorting the data with respect to the x coordinate. Range searches begin with a binary search (Martin, 1986, p. 39–40) for $x_{\min}$ and $x_{\max}$. Then all the data between $x_{\min}$ and $x_{\max}$ is tested. This method requires a preprocessing time of $O(N \log(N))$ for the sort. The search time depends on the size of the area selected, but the worst case time for any search is $O(N)$. More sophisticated data structures include ECDF trees (Shamos and Bentley, 1978) and multidimensional search (K-d) trees (Bentley, 1975). These techniques are complex and are not discussed in detail, but their performance is described for comparison with the database structure. The K-d trees require a preprocessing time of $O(N \log(N))$ and $O(N)$ storage locations. The search time is not easy to approximate. ECDF trees use $O(N \log(N))$ storage locations. The preprocess-

ing requires $O(N \log(N))$ operations and the final search time equates to $O((\log(N))^2)$ operations.

2.6 Data structures for geophysical data

The data structures used in geophysical databases tend to be less complicated than those utilised in geographical databases. This is because geophysical records refer only to point locations, whereas geographical data sets may include vectors and polygons (e.g. roads, county boundaries). A common approach to geophysical data structures is to divide the total region of interest into a number of subsections. The data for each subregion is stored in a single file.

The database developed by Hipkin and Hussain (1983) uses a 3 layer hierarchial system of “partitioned” data files. All the data located within the 1000 km by 1000 km OSGB national grid is stored in four main files. Each file contains the data for one 500 km by 500 km block. Each block is subdivided into 25 subfiles covering 100 km by 100 km. Within the subfiles the data is arranged into 10 km by 10 km subregions. Each subregion is preceded by a header record identifying the subregion and recording the number of records within the subregion.

A similar system developed at the Lamont Doherty Geological Observatory stores all the data within a 1° by 1° region in a single datafile (Karner, 1983). Each file is identified by encoding the left bottom corner of the associated region into the filename. The files are called “bins”. The bins contain both marine and land data. Within each bin the individual records are stored arbitrarily. The advantage of a system based upon latitude and longitude is that the database is not constricted to any specific part of the globe.

Both systems preserve the locality of the data. By storing all of the data for a given region in a single file the data should reside close together in the memory of the computer.

A disadvantage of the Lamont system is that the data retrieval mechanism becomes inefficient if the region of interest partially straddles several bins. In response to a

request to retrieve, or process, the gravity data in a given region the system proceeds as follows:

- (1) All the bins that may contain the required data are identified;
- (2) Each bin is opened and every record in the bin is tested to determine if it lies within the area of interest.

The inefficiency arises because every record in each bin has to be tested even if only part of the bin's data is required. This inefficiency is especially important when the density of data coverage is high. To improve the efficiency of the retrieval a method of locating all of the gravity records for regions of areal extent less than 1° by 1° must be developed. A simple solution would be to reduce the area associated with each datafile. However, this would lead to the formation of a very large number of files, which would complicate the file nomenclature and reduce the locality of the data. An alternative is to define an internal structure for each 1° by 1° datafile. This may be achieved by subdividing the data into 100 subregions, each of $6'$ by $6'$ areal extent. This approach has been applied to the Durham database and the final data structure is explained below.

The gravity records for each 1° by 1° area are stored using a combination of a data file and an associated index file. Both files are direct access unformatted files. The file names are comprised of a code for the type of data ('G' for gravity), a code for the type of file ('D' for a data file, or 'I' for an index file), and a five digit code synthesized from the latitude and longitude of the bottom left corner of the region (i.e. code = lon. $\times$ 100 + lat.). The two files for the area 0° E -1° E/ 49° N- 50° N would be named GD00049 and GI00049.

Within the data file the records are grouped into subregions. Each subregion is identified by a 7 digit code. The code is produced by suffixing a 2 digit code onto the original 5 digit numerical code. The new code is synthesized from the coordinates of the left bottom corner of the subregion (e.g. 49.6° N, 0.5° E is represented by the code 0004956). The records for each subregion are assigned to a given line number region. The line number region is defined by $(n + 1) \times 10^5 \rightarrow ((n + 2) \times 10^5) - 1$, where n is

the 2 digit subregion code. Within this region the records are written out sequentially. The line numbers quoted refer to MTS internal line numbers. A maximum of 100000 records can be stored for each subregion. Presently the number of records assigned to each subregion varies between 0 and approximately 100.

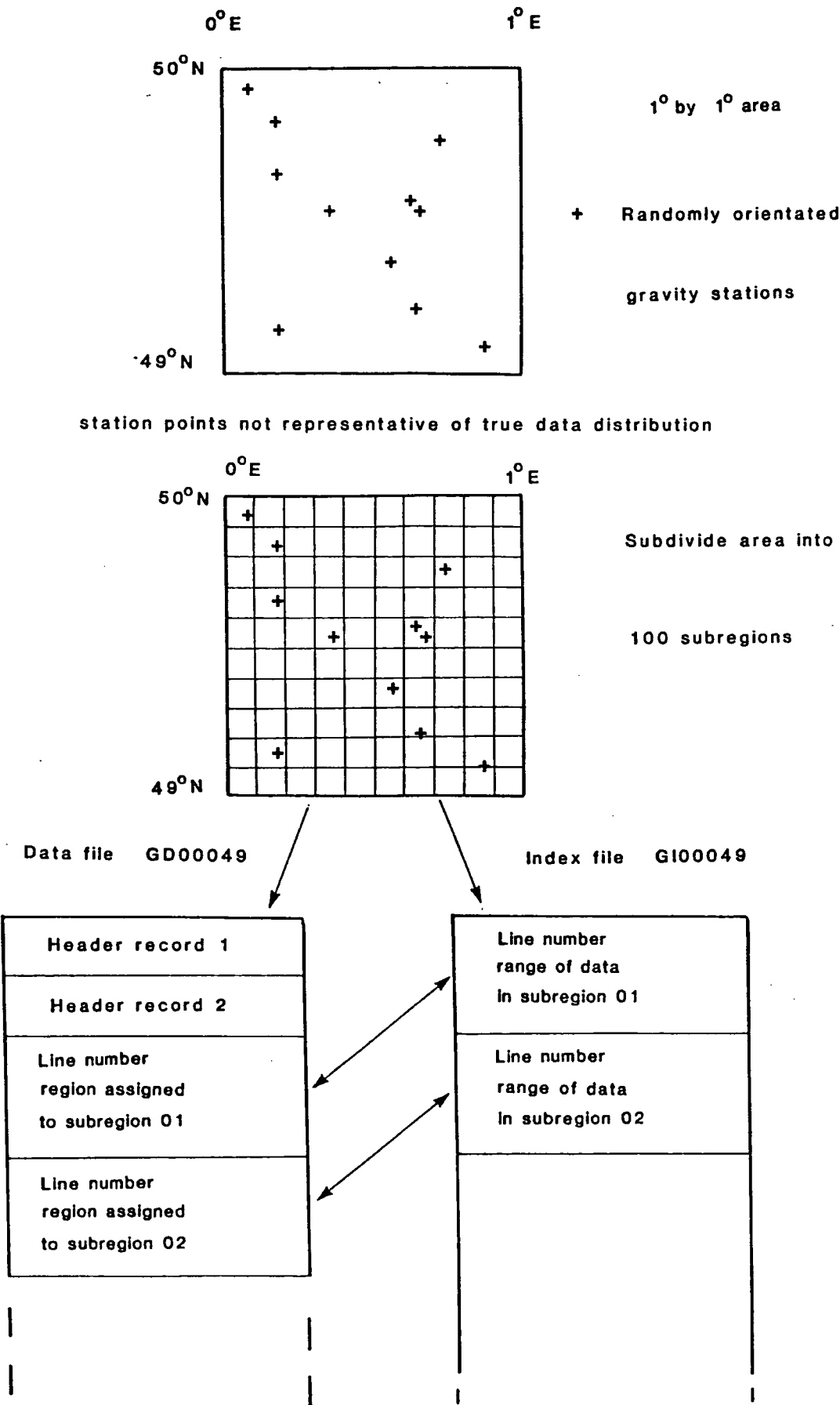
The line numbers are very large, but the datafile will be no larger than required because under the MTS operating system only those lines exist that are explicitly written. The index file is required because the data file contains no information describing the number of records assigned to each subregion. Each index file contains 100 records. One record for each subregion. Each record consists of three data fields, namely a subregion identifier code and the first and last line numbers for the data records within the subregion. If there are no records for a subregion both line number codes are set to zero. A schematic outline of the storage mechanism is shown in figure 2.4.

Each data file contains two header records. The first record notes the date on which the file was created. The second record gives a brief description of the data in the file. This record stores the total number of records in the file, average values of latitude, longitude, topography, observed gravity, free air gravity, Bouguer gravity and terrain corrections for the data in the file and the RMS deviation of the topography, free air gravity, Bouguer gravity and terrain corrections.

The storage mechanism allows the data for any subregion to be retrieved using only two sets of direct access input/output (I/O) operations. Firstly the appropriate index file record is read to determine the location of the subgroup of interest. Then the required records are retrieved from the main data file by a set of direct access reads. In database terminology, the database may be described as a two level nondense indexed database (Date, 1981). Nondense indexing occurs when numerous records are grouped under a single key, such as the file name and the subregion code. The indexing occurs on two levels because the subregion subgroups are nested within the initial 1° by 1° file grouping.

Figure 2.4

A schematic outline of
the database data structure



2.7 Database generation

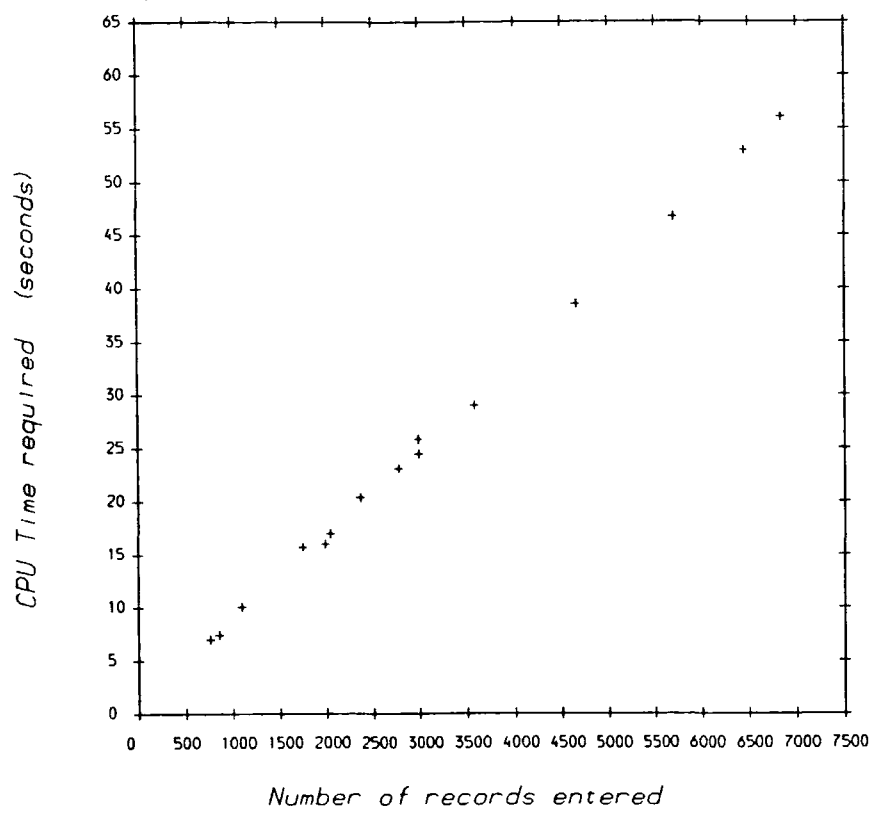
The databank preprocessing produces a common input format for the database. The database data structure is generated by the programme DBIN. 2. DBIN. 2 sequentially processes each record. For each record the required data file, and index file, are automatically opened, or created if they do not exist. The record is then written to the data file and the data file header record and index file are updated.

Figure 2.5 shows that for the input files tested at least, the central processing unit (CPU) time required to generate the storage structure approximates to $O(N)$, where N is the number of records entered. This is a little unexpected because the calculation of the subregion code from the latitude and longitude data fields in each records requires complex operations such as multiplication and subdivision as well as addition and subtraction. Also new data and index files may have to be created and initialized, and old data and index files opened and closed during the data input. The calculation of the RMS deviations of some of the data fields in each file is also complex. Therefore, the CPU time required to enter each record is expected to vary. However, overall the average input time for each record appears to be roughly constant.

One possible explanation is that the test input files were taken from the national gravity and topography databank and the data records were already sorted according to the OSGB grid reference data fields. However, the data records would still have to be rearranged according to the latitude and longitude data fields and the file header records updated. A series of input files containing more randomly distributed data points would provide a more thorough test of the CPU time required to generate the database file structure.

Most of the storage space used by the database is taken up by the data files. The size of each datafile is linearly proportional to the number of records within the datafile. Therefore, the storage space utilized is roughly $O(N)$. The current database contains about 9300 pages of data (25/4/88). A page corresponds to 4096 bytes. The data files comprise 8800 pages which is approximately 36Mb and the index files a further 500 pages (2Mb). The additional storage space needed for the index files is about 5% of

Figure 2.5. Plot of the central processing unit time required to enter the data records within an input data file into the database against the number of data records within the input data file for a series of test input data files taken from the national gravity and topography databank compiled by the Department of Geophysics, University of Edinburgh.



the total space required. As the density of data coverage increases with time this figure will decrease.

2.8 File listing programmes

Storing the data records in unformatted format is very efficient with respect to the storage space required and the speed of I/O operations. To enable the contents of the files to be studied visually two programmes have been written to provide formatted listings. Programme Dbinwrite writes out the contents of the data files (table 2.1). The two header records are written first to allow the nature of the records within the file to be quickly assimilated. The line number of each record is included to enable a further check on the index/data file interface. The contents of any index file may be listed using Ibinwrite (see table 2.2).

2.9 Data Retrieval Performance

The data retrieval performance of the data structure has been measured and compared with that of a system similar to the Lamont database. The data retrieval performance tests measured the amount of CPU time required by the databases to retrieve all the data located within a specified area. This form of retrieval is fundamental to both automatic profile and map generation.

The initial tests concerned the retrieval of data from within a 1° by 1° region. Starting with a search area of exactly one square degree the CPU time for the data search and for the data to be written out to an external file was measured for both systems. Subsequently, the search area was reduced to 0.81, 0.64, 0.49, 0.36, 0.25, 0.16, 0.09 and 0.01 square degrees. Each search area took the form of a "square", except for meridian convergence, centred upon the midpoint of the initial 1° by 1° region.

The first test was applied to the region 54° N–55° N/0° E–1° E. This comprised a marine region with a medium density of data coverage (507 points); the stations being fairly evenly distributed. This test comprised two parts. In the first part the retrieved data was written out to a formatted file and in the second part to an unformatted

Table 2.2. Formatted listing of the database index file GI00857

FILE:GI00857		

BOX CODE	FIRST RECORD	LAST RECORD
-----	-----	-----
85700	0	0
85701	0	0
85702	0	0
85703	0	0
85704	0	0
85705	600000	600001
85706	700000	700001
85707	800000	800006
85708	900000	900005
85709	1000000	1000003
85710	0	0
85711	0	0
85712	0	0
85713	0	0
85714	0	0
85715	0	0
85716	0	0
85717	1800000	1800000
85718	1900000	1900001
85719	2000000	2000000
85720	0	0
85721	0	0
85722	0	0
85723	0	0
85724	0	0
85725	0	0
85726	0	0
85727	0	0
85728	0	0
85729	0	0
85730	0	0
85731	0	0
85732	0	0
85733	0	0
85734	0	0
85735	0	0
85736	0	0
85737	0	0
85738	0	0
85739	0	0
85740	4100000	4100003
85741	0	0
85742	0	0
85743	0	0
85744	0	0

Table 2.2. continued

85745	0	0
85746	0	0
85747	0	0
85748	0	0
85749	0	0
85750	5100000	5100009
85751	0	0
85752	0	0
85753	0	0
85754	0	0
85755	0	0
85756	0	0
85757	0	0
85758	0	0
85759	0	0
85760	6100000	6100016
85761	6200000	6200005
85762	0	0
85763	0	0
85764	0	0
85765	0	0
85766	0	0
85767	0	0
85768	0	0
85769	0	0
85770	7100000	7100010
85771	0	0
85772	0	0
85773	0	0
85774	0	0
85775	0	0
85776	0	0
85777	0	0
85778	0	0
85779	0	0
85780	8100000	8100014
85781	0	0
85782	0	0
85783	0	0
85784	0	0
85785	0	0
85786	0	0
85787	0	0
85788	0	0
85789	0	0
85790	9100000	9100007
85791	9200000	9200007
85792	0	0
85793	0	0
85794	0	0
85795	0	0
85796	0	0
85797	0	0
85798	0	0
85799	0	0

file. This enabled the relative output speeds to be compared. The results are shown in figures 2.6 and 2.7. When the search area was precisely one square degree all 507 records had to be output to the external file. For the 0.01 square degrees test only 2 records were written out. The difference in the CPU time measured for the two search areas for the Lamont system depends only on the time required to output the records. Therefore, we can deduce from the results that the unformatted output operates on average nearly twice as rapidly as the formatted output.

The results of the unformatted output test show the basic relationships between the two databases. The simplicity of the Lamont mechanism makes it most efficient when the search area is bounded by integer coordinates. As the search area is reduced in areal extent the Durham system becomes more efficient. The retrieval time approaches zero as the extent of the search area tends to zero. This occurs because as the search area decreases the number of records that have to be interrogated decreases. As the density of data coverage increases the advantages of the Durham system become more pronounced. This can be observed in the results for a set of similar tests for the region $54^{\circ}\text{ N}-55^{\circ}\text{ N}/2^{\circ}\text{ W}-1^{\circ}\text{ W}$, which contains 3477 records shown in figure 2.8.

Plotting the number of points retrieved against the CPU time required for the Durham system shows that the search time is roughly proportional to the number of points retrieved (figure 2.9). The asymptotic analysis search time is, therefore, $O(N)$, where N = number of records retrieved.

From the tests for small search areas the retrieval performance for larger regions may be estimated. If the search area is bounded by integer coordinates the Lamont system will be marginally more efficient. An arbitrary region will comprise both whole integer 1° by 1° sections and partial sections of 1° by 1° areas. This balances the advantages of the two methods. The small geographical extent of the UK and the high density of data coverage should cause the Durham system to be more efficient. This observation is supported by a series of retrieval tests for arbitrary search areas within northern England (figure 2.10). A further advantage is that as more data is collected and the density of data coverage increases the advantage of the Durham system will be

Figure 2.6. Plot of the central processing unit time required to retrieve and write out to a formatted output file all of the data records lying within a specified geographical region associated with the marine data file GD00054 against the areal extent of the specified region for both the Durham database file structure and a data file structure similar to the Lamont Doherty Geological Observatory binning system.

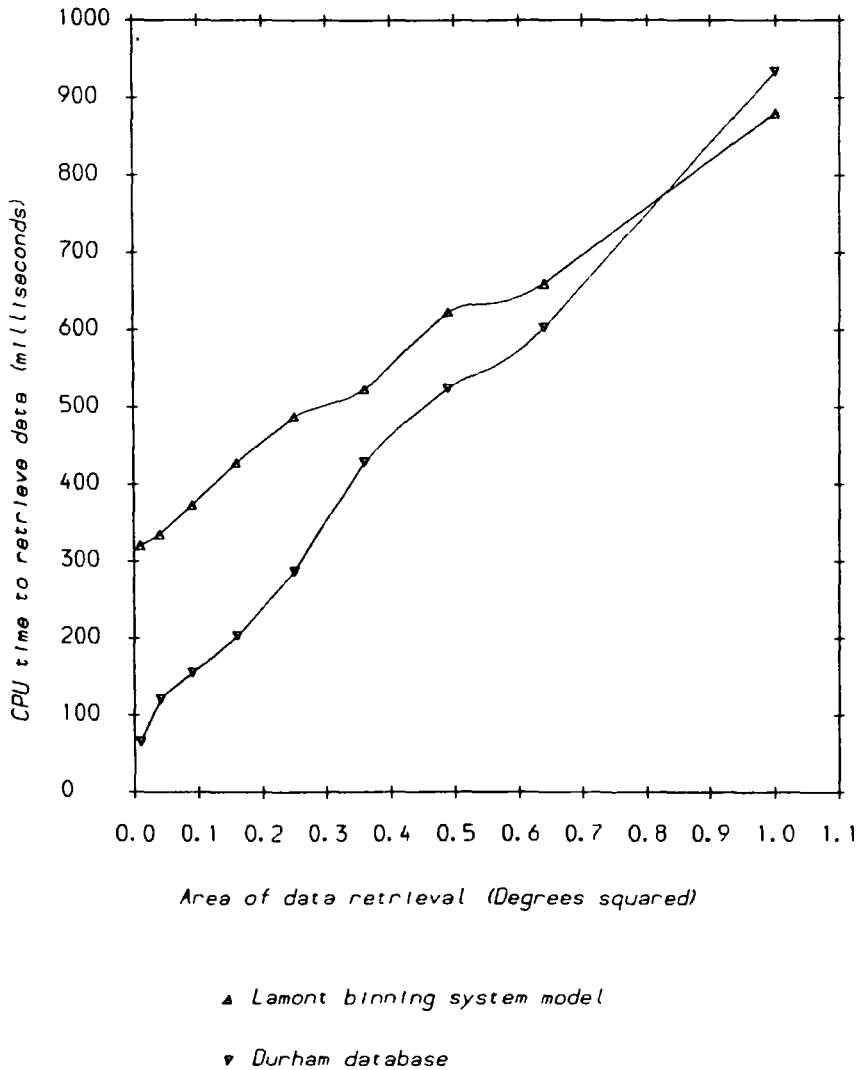


Figure 2.7. Plot of the central processing unit time required to retrieve and write out to an unformatted output file all of the data records lying within a specified geographical region associated with the marine data file GD00054 against the areal extent of the specified region for both the Durham database file structure and a data file structure similar to the Lamont Doherty Geological Observatory binning system.

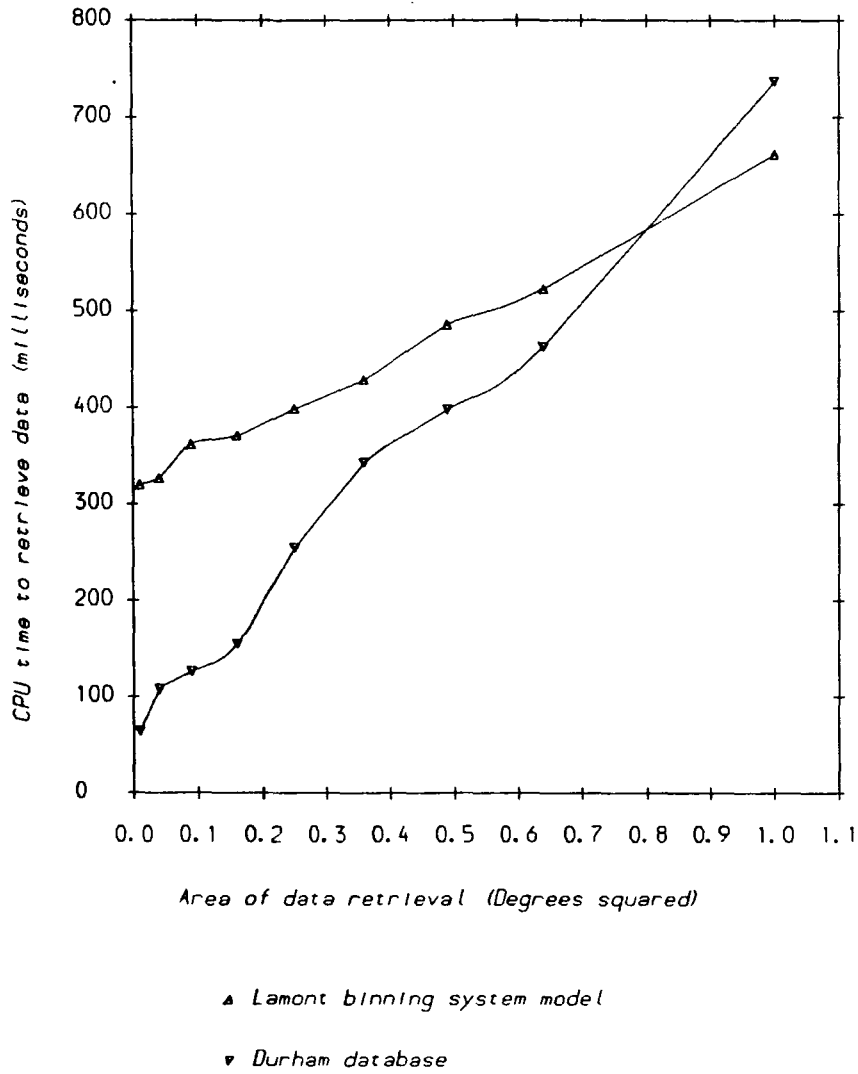


Figure 2.8. Plot of the central processing unit time required to retrieve and write out to an unformatted data file all of the data records lying within a specified geographical region associated with the land/marine data file GD35854 against the areal extent of the specified region for both the Durham database file structure and a data file structure similar to the Lamont Doherty Geological Observatory binning system.

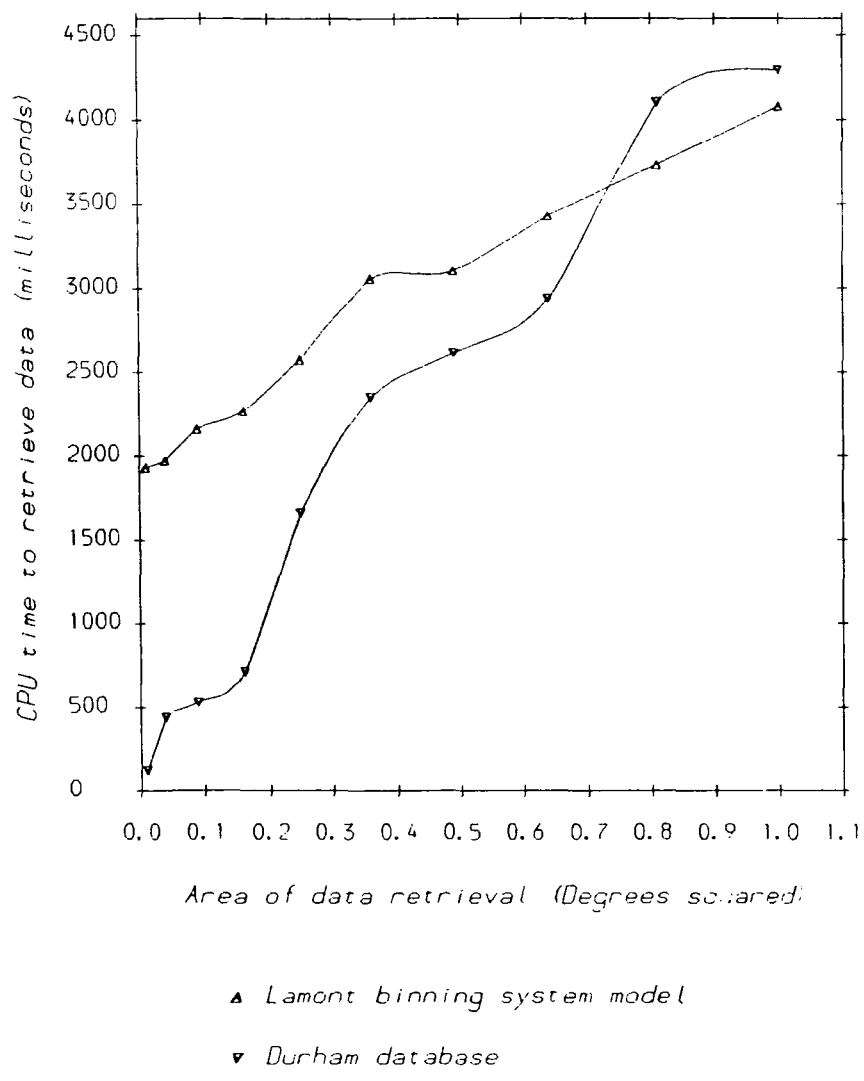


Figure 2.9. Plot of the central processing time required to retrieve and write out to an unformatted output file the data records lying within a specified geographical region against the number of data records retrieved.

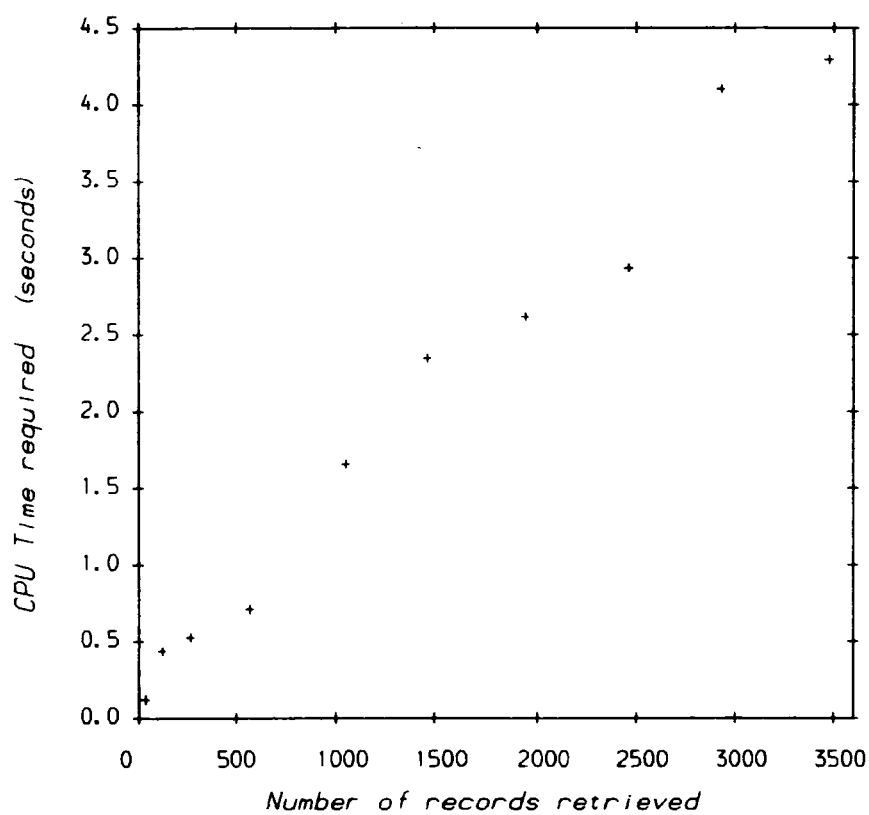
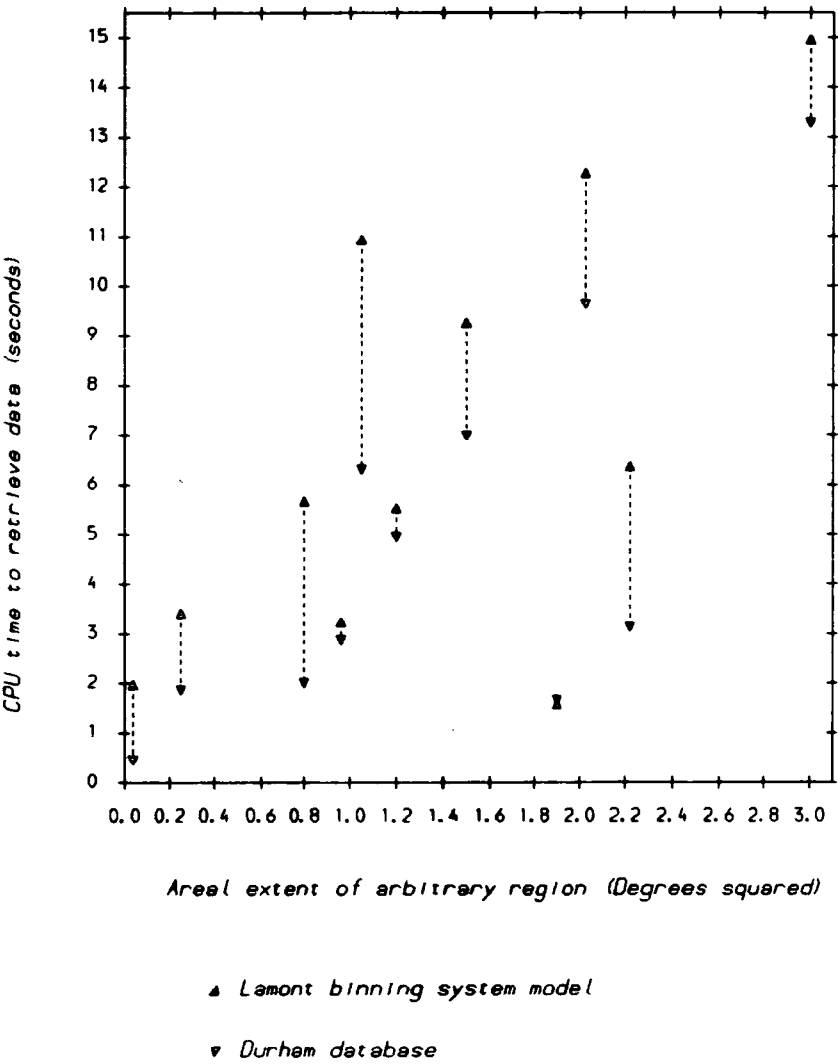


Figure 2.10. Plot of the central processing unit time required to retrieve and write out to an unformatted output file all of the data records lying within a series of arbitrary search regions in northern England.



enhanced.

The speed of data retrieval is not the only consideration. The Durham database requires an additional 6% extra storage space for the index files. Despite this the Durham data structure has been maintained because of its superiority in generating profiles. The method of forming long profiles (> 100 km) is described later, but in essence it requires the retrieval of the data located within a geometrically complex region. This form of operation is far more efficiently executed by the Durham data structure. In summary, the new data structure appears to more effective than the binning system because of the greater flexibility generated by the smaller regions of data grouping.

2.10 Data Update

The database is designed to store a substantial amount of information. The information is only useful as long as it remains accurate. The techniques developed for maintaining the integrity of the information are commonly grouped under the heading of data update. When developing any database it is important to consider the characteristics of the stored data so that the update facilities are capable of overcoming future problems (King, 1981).

There are three main kinds of update operation, namely insertion, change and deletion. Data insertion is easily accomplished by processing the new data records with the database generation programme DBIN. 2. Change and deletion require careful consideration. An important characteristic of the gravity data is its lack of volatility. Providing that the gravity data is initially reduced correctly no further modifications should be needed. This stability is one factor that allowed a complex data structure to be designed around data retrieval based upon locality. However, a certain degree of flexibility must be provided.

For example, a few incorrectly processed records could be entered into the database. To counter this the database provides a facility to delete a single, specified record from the database files. The deletion is complicated because the associated data file header

information and index file must be updated. Part of the datafile may also have to be renumbered. Another problem that may be encountered is that a marine cruise or land survey is systematically in error. For example, it is not unusual for the Marine Geophysics Unit of the B. G. S. to reprocess the results of a specific cruise. This type of problem can only be resolved if the database can find all of the data from a particular cruise or survey. This has been achieved by operating a contributor/datafile index. Part of this index is shown in table 2.3. The index lists each contributor and the files to which the contributions have been made. In response to a request to retrieve the data for any given contributor all of the indexed files are examined and the required data records written to an external file. This method is not particularly efficient but it is considered that this sort of request will only occur occasionally.

The deletion mechanism described earlier has been merged with the contributor index to allow the data from a given contributor to be simultaneously written to an external file and removed from the database. The data in the external file may be corrected and re-entered into the database. To date only one incorrectly processed data set has had to be removed (25/4/88).

These techniques have maintained the integrity of the database fairly effectively since its inception. However, future difficulties may require new solutions. For example, it may be necessary to remove all the data from a specific region if a better data set becomes available. This could be achieved by merging the line deletion mechanism with the area search programme. A more serious problem would involve a revision of the gravity reference network, NGRN73. The primary base station for each measurement has not been recorded and so the whole databank would require reprocessing.

2.11 Data Presentation

The importance of the database depends upon its ability to display the gravity and topography data it contains in a form suitable for further analysis. This is achieved by a second set of programmes designed to construct profiles, contour maps and false colour images of the gravity and topography data. These facilities are often described

Table 2.3. Formatted listing of part of the contributor index file CNTIDX

TOTAL NUMBER OF CONTRIBUTORS=104

MGU81 5	17						
GD000049	GD000050	GD00149	GD00150	GD00151	GD00152	GD00251	GD00252
GD35549	GD35550	GD35650	GD35749	GD35750	GD35849	GD35850	GD35949
GD35950							
MGU76 1	14						
GD000049	GD000050	GD35249	GD35250	GD35349	GD35350	GD35449	GD35750
GD35849	GD35850	GD35949	GD35950	GD35248	GD35348		
87C ****	0						
MGU80 2	4						
GD000050	GD00150	GD00151	GD35950				
MGU78 2	36						
GD000050	GD000052	GD000053	GD000054	GD000056	GD000057	GD000058	GD00150
GD000151	GD000152	GD000153	GD000154	GD000155	GD000156	GD000157	GD000158
GD000251	GD000252	GD000253	GD000254	GD000256	GD000257	GD000258	GD35749
GD35850	GD35854	GD35855	GD35857	GD35858	GD35950	GD35953	GD35954
GD35956	GD35957	GD35958	GD000357				
-67H ****	42						
GD000050	GD000051	GD000052	GD000053	GD00151	GD00152	GD35355	GD35356
GD35357	GD35451	GD35455	GD35456	GD35551	GD35552	GD35553	GD35557
GD35650	GD35651	GD35652	GD35653	GD35654	GD35655	GD35657	GD35750
GD35751	GD35752	GD35753	GD35754	GD35755	GD35756	GD35757	GD35850
GD35851	GD35852	GD35853	GD35854	GD35855	GD35950	GD35951	GD35952
GD35953	GD35954						
A1OC ****	23						
GD000050	GD000051	GD000052	GD000053	GD00151	GD35650	GD35651	GD35652
GD35653	GD35750	GD35751	GD35752	GD35753	GD35850	GD35851	GD35852
GD35853	GD35854	GD35950	GD35951	GD35952	GD35953	GD35954	
G-67 ****	34						
GD000051	GD00151	GD35357	GD35449	GD35450	GD35457	GD35458	GD35550
GD35551	GD35552	GD35553	GD35554	GD35555	GD35556	GD35557	GD35558
GD35650	GD35651	GD35652	GD35653	GD35654	GD35655	GD35656	GD35657
GD35658	GD35753	GD35754	GD35755	GD35756	GD35757	GD35851	GD35852
GD35854	GD35855						
MGU 7720	25						
GD000053	GD000054	GD000055	GD000056	GD00153	GD00154	GD00155	GD00156
GD00157	GD00253	GD00254	GD00255	GD00256	GD00258	GD35656	GD35755
GD35756	GD35854	GD35855	GD35856	GD35857	GD35954	GD35955	GD35956
GD35957							
MGU 7770	9						
GD000054	GD000056	GD000057	GD35854	GD35855	GD35856	GD35954	GD35955
GD35956							

as the applications environment of the database (King, 1981).

2.12 Data distribution

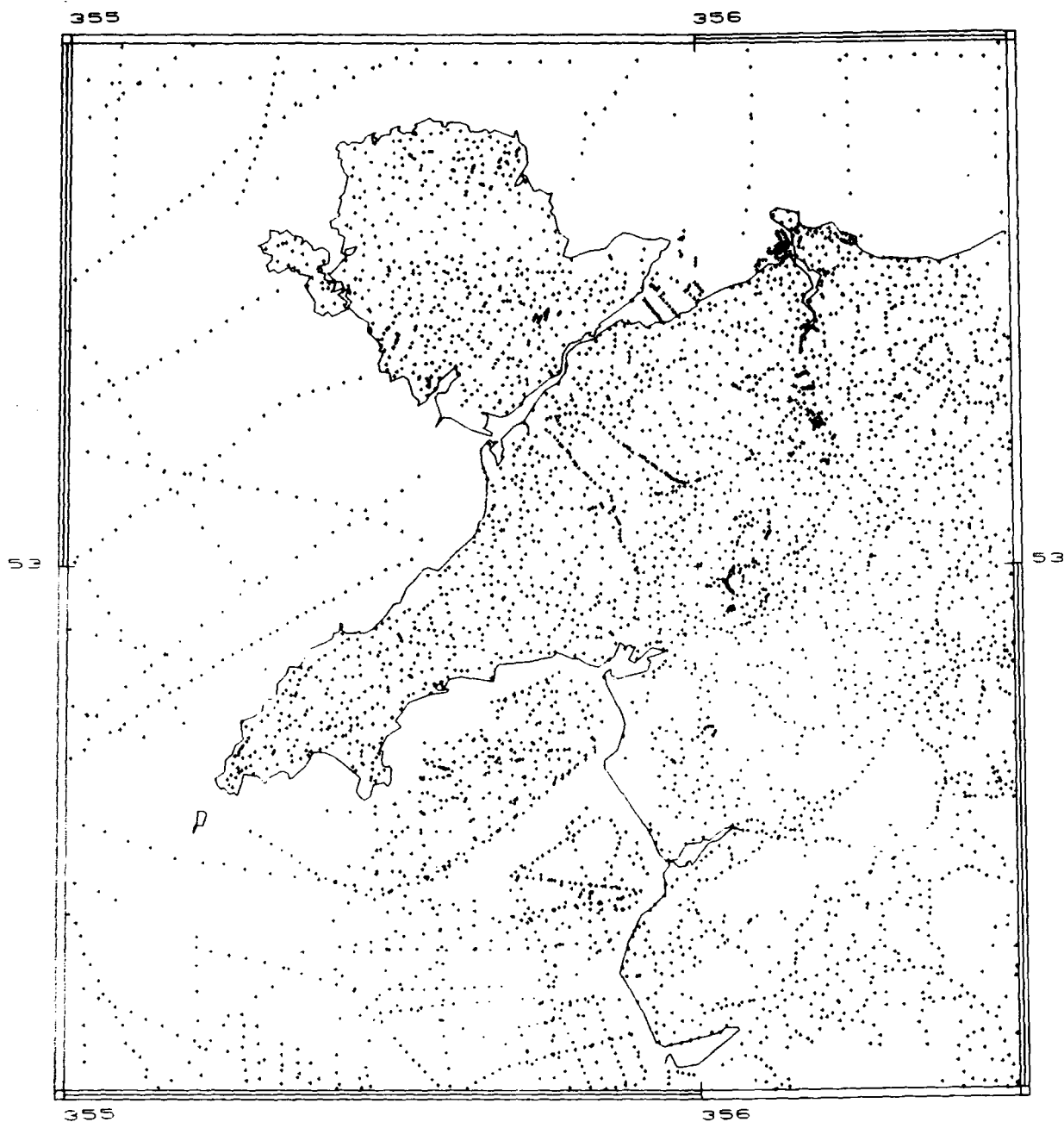
Before using automatic computer routines on a large geographically distributed data set it is important to be able to assess the density of the data coverage. The quality of the resulting contour maps and false colour images is critically dependent on the density of data coverage. A very effective method of assessing the data coverage for a given region is to mark the location of all the recorded stations on a paper plot. The database can generate such plots using either the mercator projection or the OSGB transverse mercator projection (figure 2.11).

In addition to the station position marker one of a number of the data fields within each record may be plotted. This enables manual interpretation of the original data and also allows ship track cross over errors to be assessed.

2.13 Profile Representation

Profiles are a very common method of displaying geophysical observations. They are particularly useful where the data coverage is poor and contour maps are unreliable. The database provides a facility for generating long profiles (> 100 km) using a spherical Earth approximation. To construct a profile the database prompts the user to enter the end points of the profile and the width of a window about the profile from which the profile data is to be taken. The central profile and the edges of the window are then traced out along geodesic curves (Richardus and Adler, 1972). The $6'$ by $6'$ subregions lying within and around the window are then identified. The data records from these subregions are systematically processed using an oblique mercator projection (Snyder, 1984) which converts the latitude and longitude of each record into uv space. u defines the distance of the station along the profile and v gives the perpendicular distance of the station from the central profile. If the absolute value of v is less than the half width of the window the data point is included in the profile. No weighting is assigned to the data. All three main data fields (i.e. Free air gravity, topography and Bouguer gravity)

Figure 2.11. Example plot of the database facility to display the distribution of the gravity and topography point observations for any specified geographical region.



Ordnance survey of Great Britain transverse Mercator projection. Latitude and longitude marked every degree around border. Approximate scale 1 700,000.

may be plotted together (figure 2.12) or a single field only. The relationship between the user defined window and the records processed by the oblique mercator projection is shown in figure 2.13.

2.14 Map Representation

When the data coverage for a region approaches a spatial distribution, contour maps and false colour images can be generated. The presentation techniques usually require that the gravity and topography data is represented by a regular matrix. This is commonly termed a digital terrain model. Despite the development of triangulation techniques in automatic contouring procedures (Green and Sibson, 1978; McCullagh and Ross, 1980; Watson, 1982), digital terrain models are still widely used to represent isarithmic surfaces (Devereux, 1985). The advantages of gridding the data lie in the compatibility with other raster formatted information and the ease with which computational models can be applied to digital terrain models for surface comparison and analysis (Devereux, 1985). However, digital terrain models can be inefficient with respect to storage utilization if the data contains large regions of uniform slope (De Floriani et al., 1985).

Two approaches to map generation have been implemented. The first method produces a grid of data values based on latitude and longitude. The second approach converts the latitude and longitude of each station location into grid coordinates before gridding. The map projections currently available are the OSGB transverse mercator, the Lambert Conformal and the O. S. of Ireland transverse mercator projection. The two transverse mercator projections use the Airy (1849) spheroid. The spheroid used for the Lambert Conformal projection is specifiable.

Many techniques have been proposed to interpolate the information contained in a set of randomly orientated data points onto a regular grid. The interpolation techniques may be classified into three main groups, namely local, global and hybrid. Global methods involve fitting a mathematical function to the data points and using the function coefficients to estimate the value of the data at the grid points. Local procedures

Figure 2.12. Multiple profile plot of the free air gravity, topography and Bouguer anomaly gravity point observations along a profile from Morecambe Bay to the North Yorks.,Cleveland district across the Pennine fells of northern England.

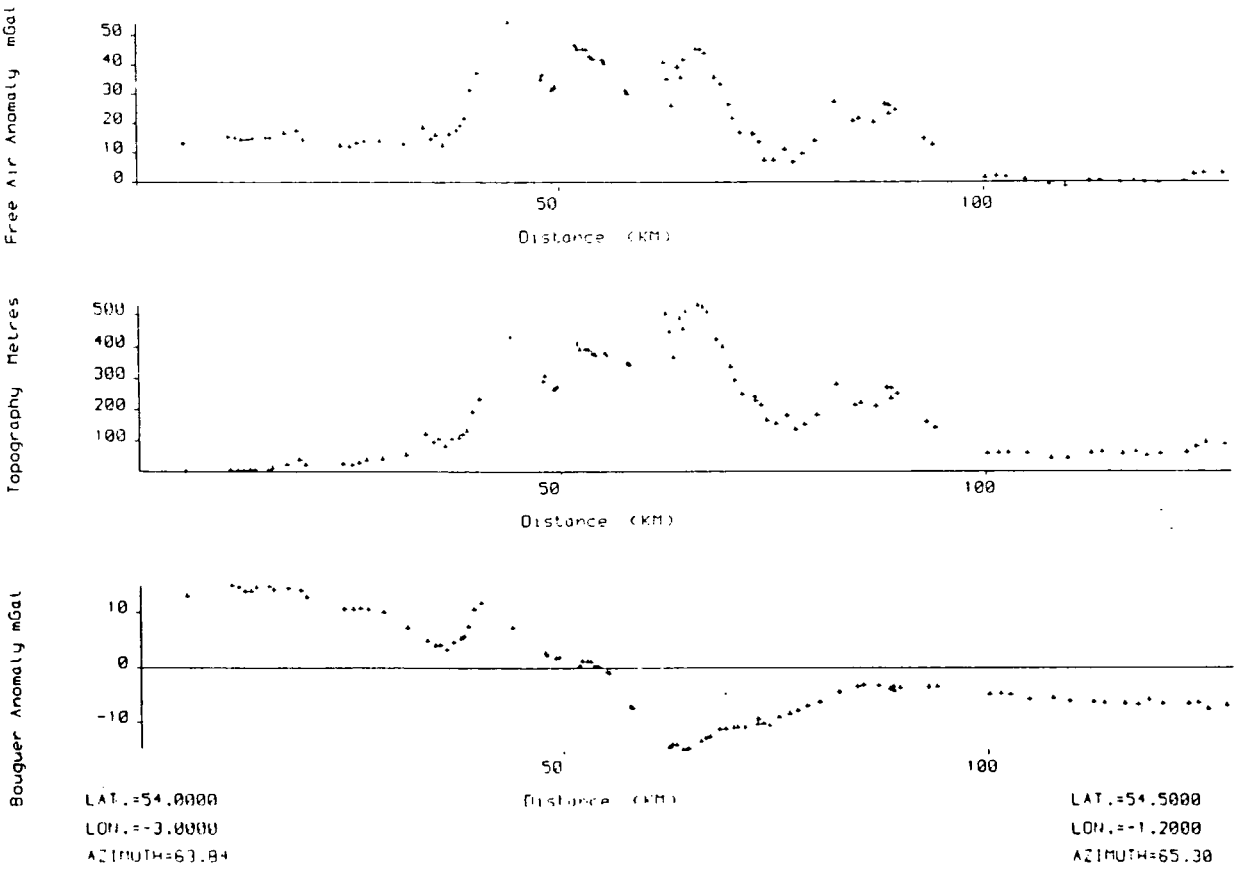
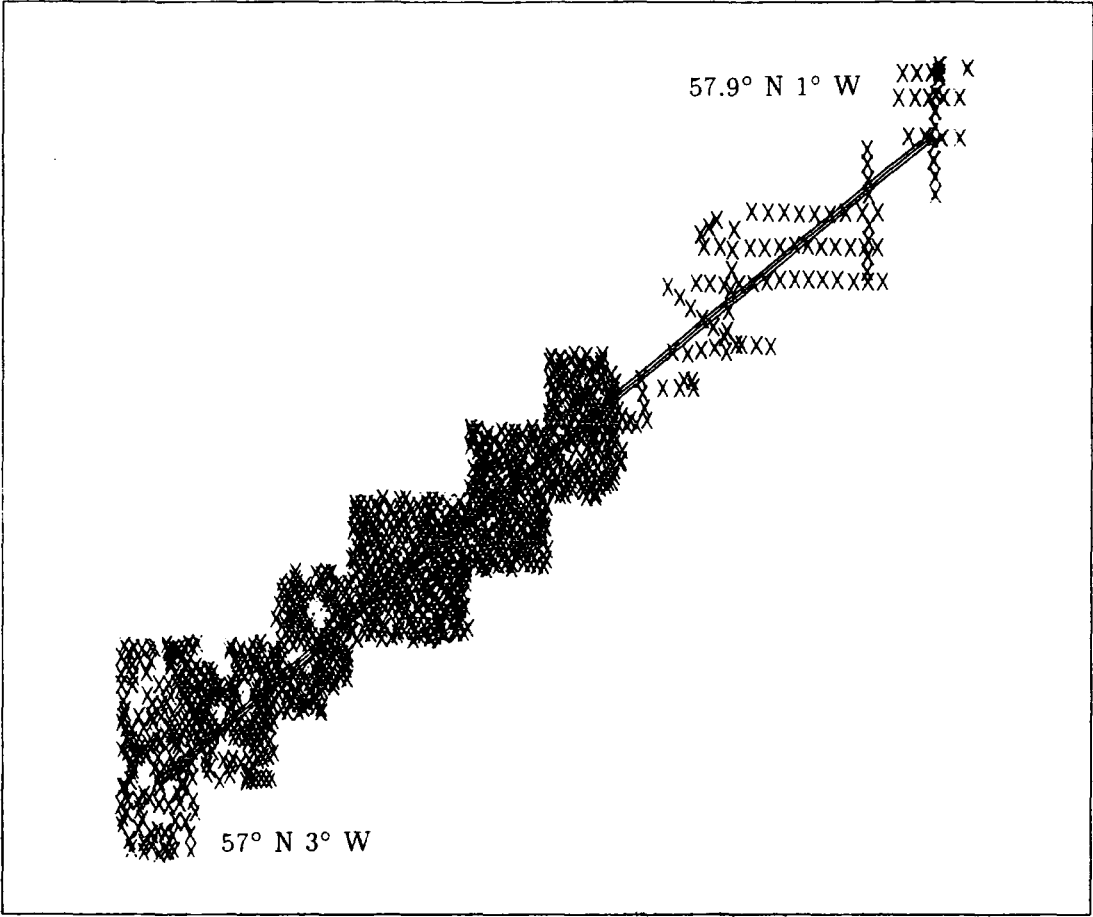


Figure 2.13. Relationship between the user defined window for automatic profile generation and the location of the gravity and topography point observations retrieved from the database for processing with the oblique Mercator projection algorithm.



use only those data points within the immediate locality of each grid point for the interpolation. Hybrid techniques use local data values to refine global estimates (Cole, 1969).

The database uses a form of local interpolation. A regular grid is superimposed over the randomly orientated gravity stations and local estimates for each data field are obtained by averaging the pertinent data within each grid square (Karner, 1983). Each average is assigned to the centre point of the grid square. The simplicity of this technique makes it very efficient, which is important if a very large number of data records need to be processed. The technique is also numerically stable. The size of grid squares used depends upon the density of the data coverage and the intended use for the grid. A 2 km by 2 km grid is useful for image processing, whereas a 10 km by 10 km grid is more appropriate for isostatic studies. The gridding method can only represent wavelengths in the data greater than $2\Delta x$, where Δx is the horizontal sampling interval.

In general finer grids can be used on land (> 2 km) than for marine regions (> 4 km). To enable a constant grid size to be used either a larger than necessary gridding interval must be used on the land data or a form of interpolation must be applied to assign estimates to the undefined marine grid squares. Provided that the sampling interval is not made too fine, the second alternative will produce acceptable results.

Estimates for the data free grid squares are calculated using a weighted average of the neighbouring grid points (Karner, 1983). The maximum half width of the interpolation sampling region can be defined by the database user. Typically a half width of 10 grid squares is sufficient. The method of interpolation is non-linear because a smaller sampling region is utilized if the data coverage is adequate. The interpolation works best if the original data points are randomly distributed and it is wise to keep the total number of interpolated grid points below 20% of the total number of points. Marine ship tracks are not always suitable for the form of gridding and some artificial noise may occur. This is particularly apparent when digital image processing methods are applied.

A more complicated interpolation technique uses bicubic splines (Cox, 1972). Bicu-

bic splines are fitted to the three data field grids in the locality of each data hole. The coefficients of the splines can then be used to estimate the value of each data field at the central grid point. The accuracy of the estimates depends upon the data coverage and the complexity of the splines. Although more rigorous, this method is more time consuming than the weighted average and may become unstable in regions of poor data coverage. Therefore, it can only be applied to regions with very good data coverage and consequently few data holes. In practice, the weighted average is usually preferred.

2.15 Contour Maps

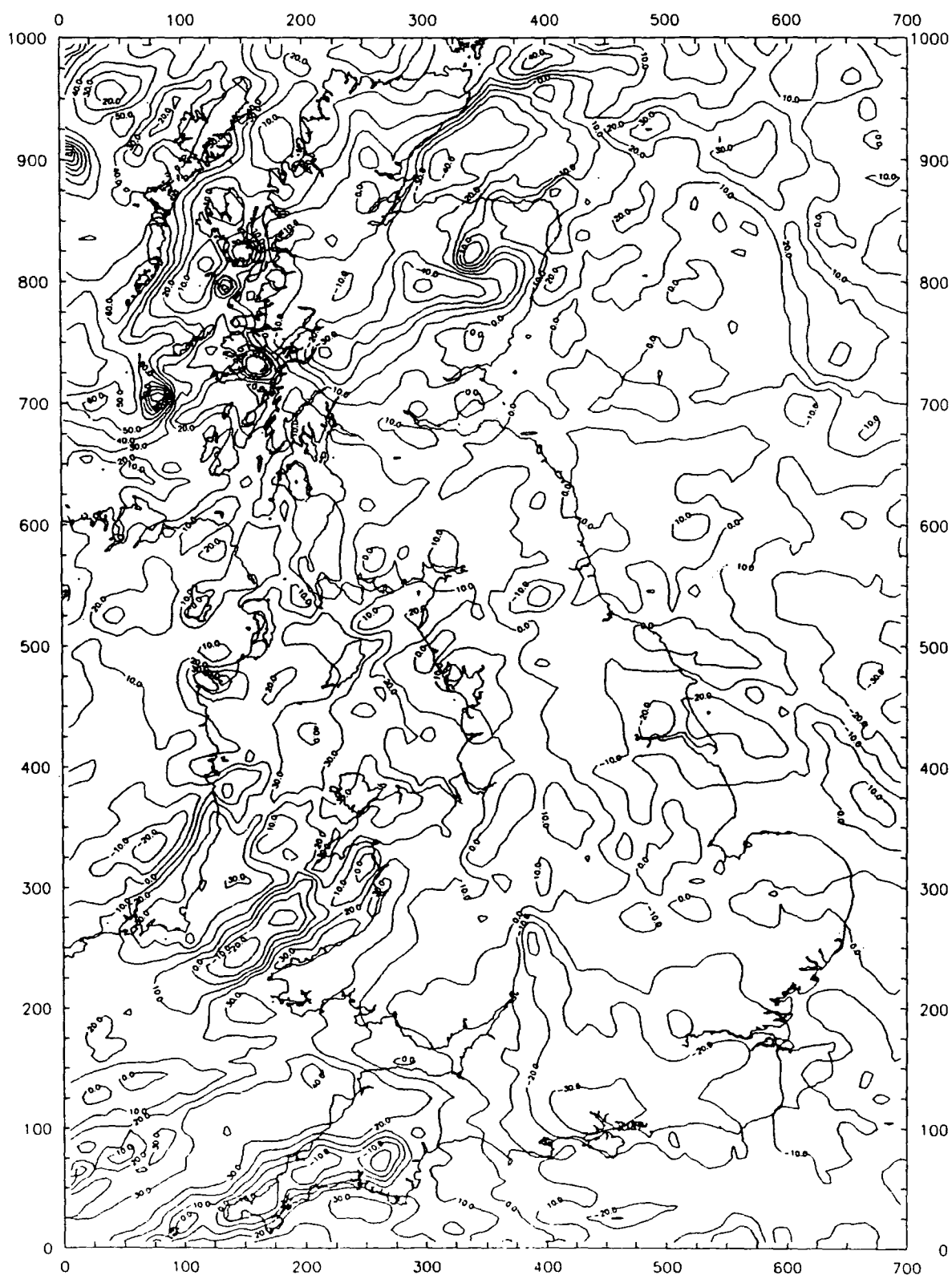
Contour maps are an important form of displaying spatial data sets because they enhance trends within the data. Both grid types may be contoured. The lat. /lon. grids are contoured by firstly defining the contours in coordinates of latitude and longitude and then transforming the contours using a suitable geographical projection before plotting. Numerous projections are available. Spherical Earth projections include azimuthal, cylindrical and miscellaneous projection types. Ellipsoidal projections include the mercator projection and the transverse mercator projection. The database contouring software was developed by Karner (1983) and implemented at Durham by the author. The specific mechanism of the contouring package is not important, but it is useful to note that the technique uses linear approximations of the gridded data between grid points. If the contoured data is very noisy the contours produced may be smoothed using a simple smoothing filter.

The projection based grids may be contoured using either the database routine or commercial contouring packages. The diagrams presented in this thesis generally use the Surface II graphics system (Sampson, 1975). A contour map of the Bouguer gravity of the British Isles is shown in figure 2.14.

2.16 Other forms of representation

The matrix representation of the data fields can also be displayed using isometric projections and false colour computer images. The application of digital image

Figure 2.14. Bouguer anomaly map of the British Isles. The grid sampling interval is 10 km. The contouring interval is 10 mGal. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance survey grid coordinates in km.



processing techniques to Bouguer gravity data is discussed in the next chapter.

2.17 Data manipulation

The gridded representations of the gravity field are amenable to digital filtering. Modification of the data in the wavenumber domain through the use of the Fast Fourier Transform (FFT) (Cooley and Tukey, 1965) is particularly useful. Two low pass filters have been developed to remove high wavenumber noise from the grids. The upward continuation wavenumber operator is defined by $e^{-|k|h}$, where k is the horizontal wavenumber

$$|k| = 2\pi \left(\frac{1}{\lambda_x^2} + \frac{1}{\lambda_y^2} \right)^{\frac{1}{2}} \quad 2.8$$

The upward continuation operator is applied by first transforming the data into the wavenumber domain using the FFT, multiplying the real and imaginary coefficients of the transform at each discrete wavenumber by the operator for that wavenumber and finally performing the inverse transform. If the initial data was recorded on a plane S , lying above the causative density contrasts, the product of the upward continuation operation represents the potential field on the plane S_1 at a height h above the original plane S .

The second filter is a gaussian low pass filter defined by the wavenumber operator $e^{-|k|^2\lambda^2}$. The constant λ is defined so that

$$k_c = \frac{0.588}{\lambda} \quad 2.9$$

where k_c is the cut off wavenumber (Meskó, 1984). The cut off wavenumber is chosen so that

$$S(k_c) = e^{-k_c^2\lambda^2} = -3\text{dB} \quad 2.10$$

The amplitude of any wavenumber component with a wavenumber greater than the cut off value will be attenuated by more than -3 dB. The application of the gaussian operator in the wavenumber domain is comparable to convolving a two dimensional gaussian weighted filter with the original data grid. This smooths the grid values, blurring individual features within the data.

Before the FFT is applied to the grids, the grid edges are smoothed to zero using a cosine taper. This reduces the noise introduced by discontinuities in the FFT's periodic representation of the grid and counters the effects of spectral leakage (Brigham, 1974). However, the modification degrades the accuracy of the final results around the edge of the map.

The effects of the two wavenumber domain filters can be seen in figures 2.15 and 2.16, which show the Bouguer gravity map of the British Isles displayed in figure 2.14 after upward continuation to 25 km and after the application of a 150 km cut off wavelength gaussian filter.

2.18 System dependence

The gravity and topography database can only operate efficiently under the Michigan terminal system operating system because the database takes advantage of the MTS direct access file structure. Under most operating systems the size of each direct access file and the length of the direct access records to be stored in the file must be specified when the file is created and they cannot be altered subsequently. Under the MTS operating system neither the size of the direct access file nor the length of the direct access records need to be specified when the file is created. New data can be written to the data files when required and the files will expand to accommodate the data. This enables the database to use only as much storage space as is required for the data currently held in the database, whereas for most operating systems a large amount of storage space must be set aside for the addition of new data in the future. The MTS operating system direct access file structure is, therefore, ideally suited to the development of computer databases such as the gravity and topography database. However, unfortunately the MTS operating system is not widely used and, hence, the portability of the database with respect to the use of the database at other installations is restricted.

Figure 2.15. Bouguer anomaly map of the British Isles after upward continuation of the potential field to a height of 25 km. The grid sampling interval is 10 km. The contour interval is 10 mGal. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance survey grid coordinates in km.

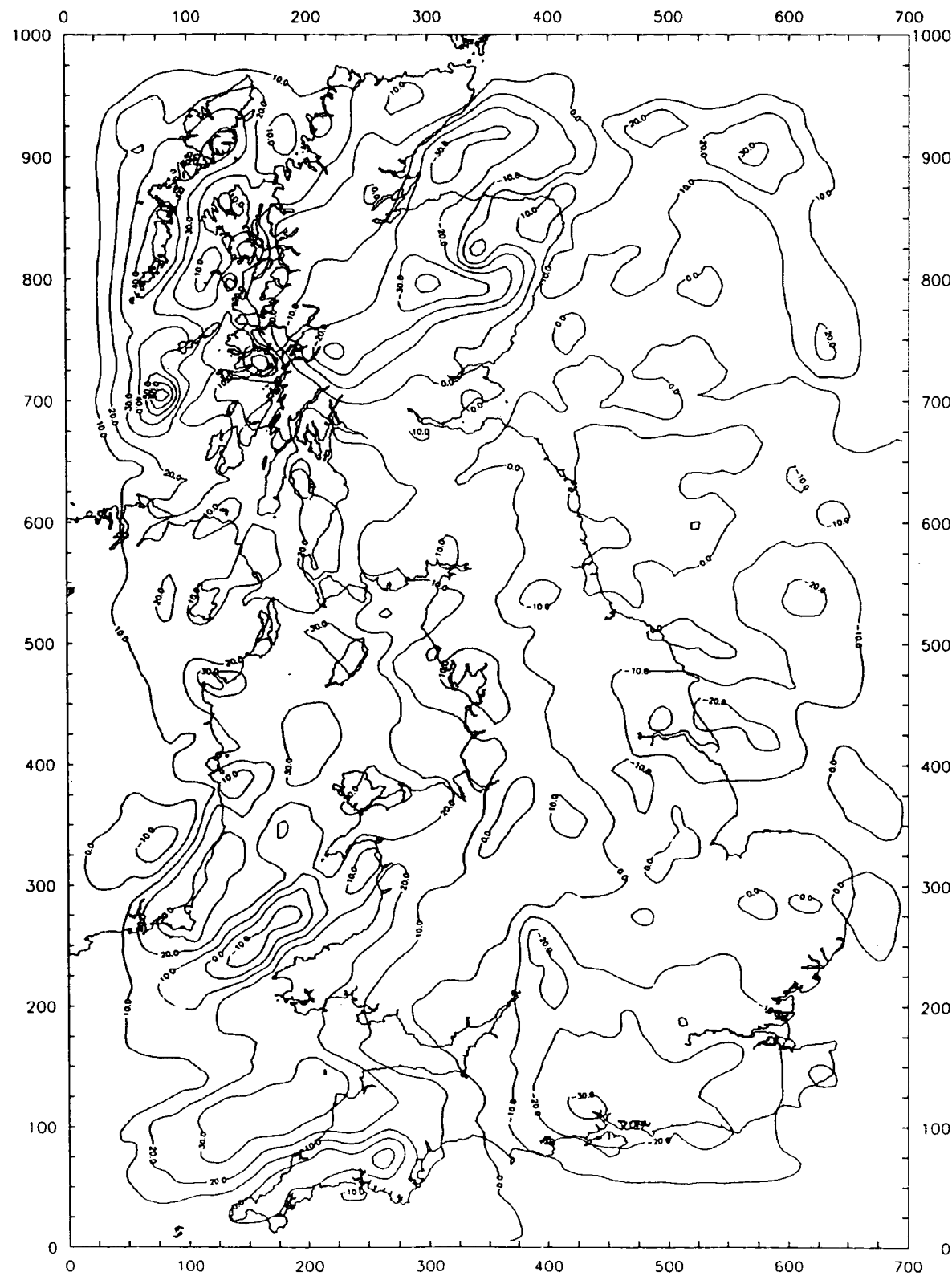
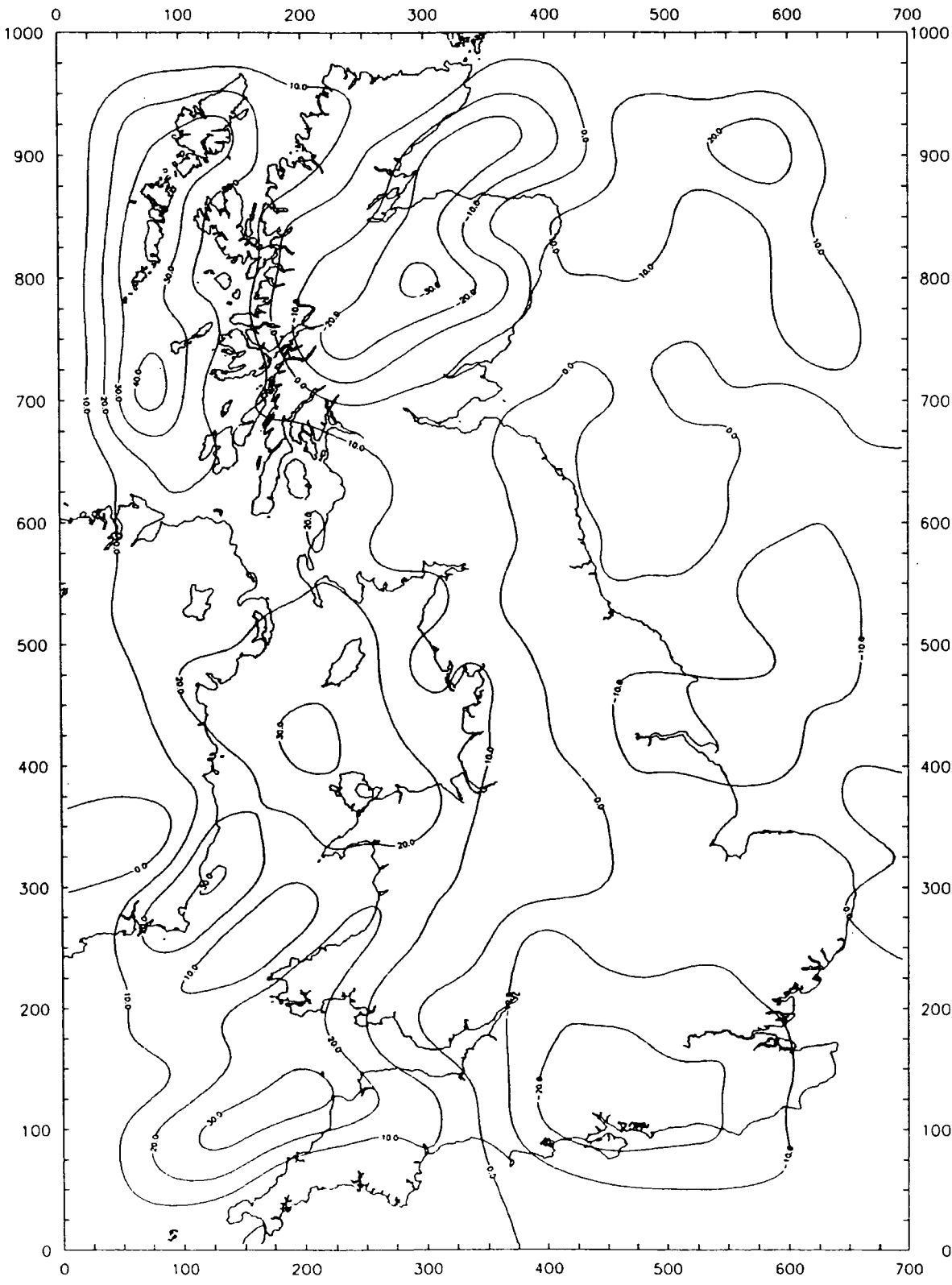


Figure 2.16. Bouguer anomaly map of the British Isles after the application of a 150 km cut off wavelength low pass gaussian filter. The grid sampling interval is 10 km. The contour interval is 10 mGal. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance survey grid coordinates in km.



CHAPTER 3

The application of digital image processing techniques to Bouguer anomaly data for the United Kingdom region

3.1 Introduction

Digital image processing techniques are commonly used to display and analyse the large spatial data sets acquired by remote sensing. These techniques can be modified and applied to the reduction and display of any large, geographically distributed data set. The vast store of gravity and topography data contained within the Durham gravity and topography database is one such data set. This chapter is a report on the application of digital image processing techniques to the Bouguer gravity data recorded for the UK and the northwest European continental shelf.

Digital image representations of the information contained within spatially distributed data sets complement and improve upon the traditional forms of contour maps. False colour images create a strong visual impact. Trends in the imaged data are easy to interpret. Most image processing systems can display up to 256 different shades, which can be used to enhance subtle anomaly trends not obvious in contour maps (Guinness et al., 1982). This feature has also been described as increasing the inherent granularity of the data (Arvidson et al., 1984). Cordell and Knepper (1987) observed that digital images of magnetic field data retain much of the high frequency content of the data lost in contour map representations.

In addition to providing an effective visual display, digital image processing techniques may be used to enhance trends within the data. Of particular importance is the ability to enhance “discontinuities” within the data observed over sharp anomaly edges and lineaments. This improves the interpretation of subtle trends and patterns. For example, the boundaries between different tectonic domains are clearly defined where

tectonic fabrics of different orientation and wavelength converge (Arvidson et al., 1984). Another advantage of digital image processing is that several pertinent data sets may be integrated into a single image, such as lithology and Bouguer anomalies (Guinness et al., 1982). The value of applying digital image processing techniques to potential field data was concisely expressed by Cordell and Knepper (1987), who observed that the images “represent a qualitatively different form of analysis, rooted in visual perception rather than deterministic physical theory”.

3.2 Previous work

Early work in this field began in the USA and Australia. Arvidson et al. (1982, 1984) applied digital image processing techniques to gravity and topography data covering the USA. This work led to the tentative identification of a Precambrian rift in Missouri (Guinness et al., 1982) from digital images of gravity, magnetic and enhanced thermal infra-red remote sensing data. Moore and Simpson (1982) imaged a digital terrain model (DTM) of the topography of Australia. These images were used to analyse regional geological structures, especially the relationship between topographic lineaments and ore deposits (Harrington et al., 1982). Prior to this work O’Driscoll and Keenihan (1980) had shown that five of the largest Australian ore deposits (Kalgoorlie, Kambalda, Roxby Downs, Broken Hill, and Mount Ida) were located along lineaments visible within Bouguer anomaly maps.

Cordell and Knepper (1987) used grey tone images of aeromagnetic data to gain a fresh insight into the buried basement of the Rolla quadrangle in southeast Missouri (37° N–38° N/92° W–90° W). They observed that the Geological Survey of Finland has for some time produced high quality, grey tone aeromagnetic maps (Korhonen and Airo, 1983).

The recent completion of the UK gravity and topography databank has facilitated the application of digital image processing techniques to the United Kingdom gravity field. Karner et al. (1987) produced several images of the Bouguer gravity (land) and free air gravity (sea) anomalies of NW Europe including the UK. Terrestrial free

air gravity measurements were integrated with free air gravity values determined from SEASAT altimetry data (Haxby, 1985). The sampling rate of the SEASAT data constrained the image resolution to a picture element (pixel) size of $5' \times 5'$. The images were accompanied by a preliminary tectonic interpretation of the regional geology and a discussion of the effects of lithospheric flexure within the region.

The Regional Geophysics Research Group of the B. G. S. (formerly the Applied Geophysics Unit) has recently produced several digital images of the Bouguer gravity data for mainland Great Britain (Chacksfield, 1987). However, little interpretative work has been carried out. Several more detailed local studies have been reported. The structure of the basement of the English Lake District has been investigated using a combination of gravity and aeromagnetic data (Lee, 1987).

3.3 Digital image processing techniques

A digital image is a digital representation of a picture. A monochrome (grey tone) image can be defined as a two-dimensional light intensity function $f(x, y)$, where x and y denote spatial coordinates and the value of f at any point (x, y) is proportional to the brightness of the image at that point (Gonzalez and Wintz, 1977). Digital images are formed by discretizing images both in spatial coordinates and in brightness (grey level). Digital images can be expressed by matrices. The rows and columns specify points within the images and the corresponding matrix element values define the brightness of the digital image at these points. The elements within the matrix are termed picture elements, or pixels. Most image processing systems can usually display up to 256 different grey levels. Low pixel values correspond to low intensities (dark grey) and high values to high intensities (light grey). Colour digital images require more information for each pixel. In addition to pixel intensity, values are required for hue (dominant wavelength) and saturation (degree of purity).

The gridded representations of the gravity data produced by the Durham gravity and topography database can easily be converted into grey level digital images. Each grid square value is represented by a pixel in the grey level digital image. The pixel

values are constrained to range between 1 and 255. Therefore, the data to be imaged must be rescaled. After rescaling, the individual pixel values may be stored in a single byte of data. The complete digital image is represented by a matrix of bytes. Byte matrices are a common form of representing digital grey scale images within image processing systems, such as the I²S System 500 Image processing system located at Durham University.

The images developed from the gravity grids use a simple linear rescaling which maps the minimum input value to 1, the maximum input value to 255, and intermediate input values to intermediate pixel values. This produces a raw grey level digital image which may be enhanced by further processing. Many different techniques of digital image enhancement may be applied but most of the digital images developed for this study use a common enhancement process particularly suited to interpreting tectonic structures which is outlined below.

The amplitude of the Bouguer gravity field is represented by a colour contour map. Suitable contour levels (in mGal) are converted into their corresponding pixel values. These pixel levels define a series of intermediate pixel ranges each of which is assigned a separate hue. Approximately 10–15 different hues are usually required.

Remote sensing terrain interpretations of aerial photographs and satellite imagery have shown that shadows are useful for detecting topographic lineaments (Moore and Simpson, 1982). Similarly a shaded relief digital image of the gravity field “terrain” will enhance lineaments that strike perpendicular to the direction of illumination. A very useful form of digital image representation is to merge shaded relief images with colour contour maps of the gravity data. This can be achieved by letting the amplitude of the gravity anomaly control the hue and saturation of the digital image, whilst the local gradient (from the shaded relief model) controls the intensity (Pettengill et al., 1980). The advantage of this technique is that information is presented concerning both the amplitude and the local gradient of the gravity field.

3.3.1 Shaded relief digital images

Shaded relief representations of digital terrain models can be generated using the

reflectance map method (Horn and Bachman, 1978). A reflectance map is a plot of surface gradient against surface reflectance for a particular type of surface and illumination direction. The technique gives acceptable results if the terrain is rough and the elevation of the source of illumination is low. The techniques does not account for mutual illumination between surfaces or cast shadows (i.e. one surface overshadowing another) but these shortcomings can be neglected.

Digital terrain models comprise an array of terrain elements (e.g. gravity anomaly values in this case). Consider a terrain model with an easterly pointing x axis, a northerly pointing y axis and an upward directed z axis. The array elements are denoted by z_{ij} . Discrete approximations of the surface gradients of the terrain model at the element z_{ij} are given by

$$p = (z_{(i+1)j} - z_{ij})/\Delta$$

$$q = (z_{i(j+1)} - z_{ij})/\Delta$$

where p is the gradient from west to east, q is the gradient from south to north and Δ is the digital terrain sampling interval. The reflectance map technique assumes that the terrain is viewed from the z axis and that the location of the illumination source is defined by an azimuth θ (measured clockwise from north) and an elevation ϕ . The reflectance of any individual surface element can be expressed as a function of three angles, namely the incident angle (i), the emittance angle (e) and the phase angle (g). These angles are defined in figure 3.1. A very simple reflectance model for a surface material is given by

$$\Phi_1(i, e, g) = \rho \cos i \quad 2.1$$

The surface is considered to be a perfect diffuser appearing equally bright from all viewing angles. The constant ρ is an “albedo” factor which can be taken to be the ratio of the reflectance of the surface to that of a perfectly diffuse surface (see Horn and Bachman, 1978). The cosine of the incident angle i is required to account for the foreshortening of the surface as viewed by the illumination source.

The incident angle for any given surface element can be more conveniently expressed in terms of the gradient of the surface element (p, q). If the distances from

Figure 3.1. Light reflection from a surface element. The angles are defined as follows:
 i the incident angle; e the emittance angle; g the phase angle.

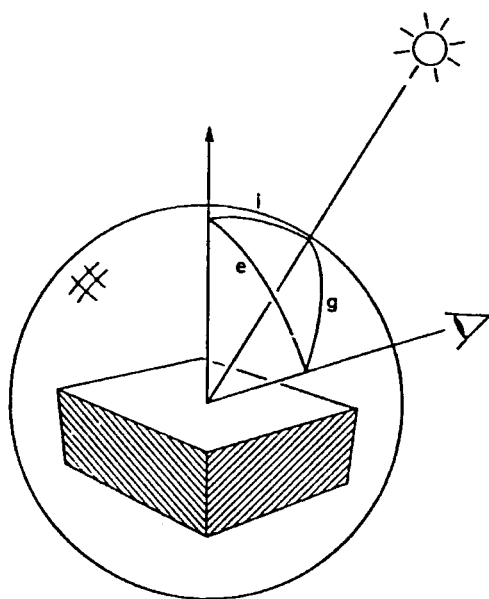


Diagram taken from Horn and Bachman (1978)

the surface to the illumination source and the viewing point are large compared to the areal extent of the terrain model the phase angle g is constant. The cosine of the incident angle can be determined from the dot product of the local normal to the surface gradient $(-p, -q, 1)$ and the unit vector pointing to the light source $(-p_s, -q_s, 1)$. $p_s = \sin \theta \cot \phi$ and $q_s = \cos \theta \cot \phi$. The reflectance at any surface element of gradient (p, q) is then given by

$$\Phi(p, q) = \frac{\rho(1 + p_s p + q_s q)}{\sqrt{1 + p_s^2 + q_s^2} \sqrt{1 + p^2 + q^2}} \quad 2.2$$

The shaded relief digital image is produced by calculating the reflectance for each pixel of the terrain, except the edge rows and columns where the surface gradient cannot be determined, and converting the reflectance values into byte form. The final digital image very effectively highlights trends and patterns in the imaged data that are orientated roughly perpendicular to the direction of illumination.

A similar digital image to the shaded relief image can be obtained by applying a Prewitt edge filter to the grey level Bouguer gravity image (International Imaging Systems Inc., 1984). The Prewitt edge filter is a simple 3×3 element convolution filter. The filter elements are weighted to enhance particular trends within the imaged data.

3.3.2 Isotropic filters

The techniques discussed above are anisotropic. They enhance trends in digital images characterized by a common orientation. Two important isotropic enhancement methods are based around image differentiation. If a monotone image is represented by the function $f(x, y)$ an isotropic filter produces the same effect if f is first rotated and then filtered or if f is filtered and then rotated (Rosenfeld and Kak, 1976). An isotropic, derivative filter will enhance features, such as edges or lines running in any orientation. Rosenfeld and Kak (1976) have shown that

- (1) an isotropic linear derivative operator may only include derivatives of even orders;
- (2) arbitrary isotropic derivative operators may only include derivatives of odd orders if they are raised to even powers.

A useful arbitrary derivative operator is the magnitude of the gradient. For a monotone

image defined by $f(x, y)$ this is expressed by

$$|grad f(x, y)| = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2} \quad 2.3$$

The magnitude of the digital gradient can be determined from

$$|grad f_d| = \sqrt{(\Delta x f_d)^2 + (\Delta y f_d)^2} \quad 2.4$$

where

$$\Delta x f_d = (f_d(i+1, j) - f_d(i, j))/\Delta$$

$$\Delta y f_d = (f_d(i, j+1) - f_d(i, j))/\Delta$$

$f_d(i, j)$ = value of digital image at the point i, j

Δ = sampling interval

Imaging the digital gradient highlights regions characterized by strong gradients subduing the long wavelength information within the digital image. A second image enhancement technique is to calculate the Laplacian of the image f (Rosenfeld and Kak, 1976). The Laplacian linear, derivative operator is defined by

$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \quad 2.5$$

For a digital image f_d the discrete approximation to the Laplacian is

$$\begin{aligned} \nabla^2 f_d(i, j) &= \Delta x^2 f_d(i, j) + \Delta y^2 f_d(i, j) \\ &= (f_d(i+1, j) + f_d(i-1, j) + f_d(i, j+1) + f_d(i, j-1)) - 4f_d(i, j) \end{aligned}$$

In this study the discrete approximation has been calculated from

$$= f_d(i, j) - \frac{1}{5}((f_d(i+1, j) + f_d(i-1, j) + f_d(i, j) + f_d(i, j+1) + f_d(i, j-1)))$$

which is proportional to the Laplacian, by a factor of $-\frac{1}{5}$. The rescaling of the data into byte format makes this factor irrelevant. It is useful to note that the Bouguer anomalies obey Laplace's equation and the product of the two dimensional Laplacian operator on a digital image of the Bouguer anomalies is equivalent to the the second vertical derivative of the Bouguer anomalies. The discrete calculation subtracts an average of $f_d(i, j)$ and

its four immediate neighbours from $f_d(i, j)$, which may be described as subtracting a blurred version of the image from the original.

The effect of imaging the Laplacian differs from that of imaging the magnitude of the gradient. The Laplacian tends to enhance lines, line ends and points within the image, whilst imaging the magnitude of the gradient tends to enhance steps and edges in the data (Rosenfeld and Kak, 1976). The different effects of applying the two techniques to a ramp in the imaged data are shown in figure 3.2.

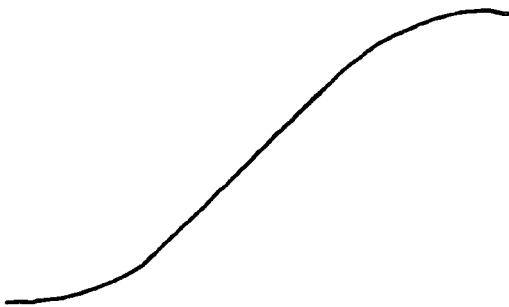
Any enhancement technique based on image differentiation will tend to enhance the high frequency content within the imaged data at the expense of the low frequency content. Therefore, any noise within the image will similarly be accentuated. This means that caution must be exercised when interpreting the resulting images.

3.4 Imaging the Bouguer gravity data for the UK region

The digital image processing techniques discussed in the previous section have been applied to the Bouguer gravity field of the UK in an attempt to discover further information on the tectonic framework and evolution of the region. A series of regional geotectonic digital images have been produced from a single grid of Bouguer anomaly values. The gravity digital terrain model has been illuminated from four directions to enhance all of the important tectonic lineaments and fabrics of the UK. A Laplacian image is also presented.

The distribution of the gravity stations used in generating the geotectonic images is shown in figure 3.3. Note that the data set displayed is not as complete as the final data set displayed in figures 2.1, 2.2 and 2.3. The initial grid representation of the Bouguer gravity field covered the region 49.9° N– 58.8° N/ 7.5° W– 2.3° E and was sampled at 4' intervals. The grid comprised 19832 grid squares 2444 of which required estimated values to be assigned using the weighted average technique. The weighted average is numerically stable and this accounts for the smooth nature of the geotectonic images in the vicinity of regions of very poor data coverage (i.e. the Hebridean and north Celtic Sea regions).

Figure 3.2. Comparison between the magnitude of the gradient and the Laplacian of a ramp in the imaged data



Ramp in data



Magnitude of the gradient



Laplacian

Figure 3.3. Distribution of the gravity and topography point observations used to generate the digital images of the Bouguer anomaly gravity of the UK and adjacent regions.



Before entry into the I²S image processing system, the grid values were linearly rescaled to range between 1 and 255 and converted into byte format. The original minimum and maximum grid values were -54.75 mGal and $+136.88$ mGal respectively. Four shaded relief and one Laplacian digital image were also prepared. Using the I²S image processing system the digital images were magnified by a factor of 2.0 in the sample (x) direction and 3.8 in the line (y) direction. These magnification factors allow the images to approximate a conformal mercator projection. The magnification process was based around a bicubic spline interpolation. A colour contour map of the Bouguer gravity was produced by assigning 13 different hues. The contour levels were assigned in a non-linear distribution and are concentrated around the mean value of the Bouguer gravity for the grid (approximately 5–10 mGal).

This provided a further method of image enhancement. The majority of the grid square values representing the Bouguer gravity lay close to the mean value. Therefore, numerous contour levels were assigned around the mean value and relatively few contour levels were assigned to the extreme regions of the Bouguer gravity value range (e.g. < -40 mGal and > 30 mGal). This created a good distribution of contour levels across the digital image rather than concentrating the contour levels around isolated minima and maxima, which are usually associated with limited areal extents.

The four shaded relief digital images were used to control the intensity of the 13 hues within each digital image. The shaded relief digital images depict the Bouguer gravity digital terrain model illuminated from the NW, NE, N and W. Rotating the illumination direction by 180° serves only to invert the shaded relief image and produces little new information. Therefore, the four chosen illuminations should enhance the majority of the important tectonic trends present. The Laplacian digital image enhances lineaments and fabrics of all orientations providing a summary of the main tectonic features.

Each image has been overlaid with a digitized coastline of the UK and Ireland and a $1^\circ \times 1^\circ$ marker grid. Regions of particularly poor data coverage where artificial features were developed within the digital images have been masked and appear black.

Before analysing and interpreting the digital images, I shall discuss the definition and origin of lineaments in the gravity field and present a description of the major features of the Bouguer gravity field of the UK and adjacent regions. The definition of lineaments will allow a greater appreciation of the digital images, whilst the description of the gravity field will enable the importance of the lineaments to be evaluated within the overall tectonic framework of the UK region.

3.5 Definition and origin of lineaments within the gravity field

The form and distribution of lineaments imaged by satellite and aerial photography have been analysed and interpreted by Earth scientists working in remote sensing. However, the terminology applied to describe linear features as linears, lineaments and lineations has often been confused. In this chapter I shall use the definition of lineament proposed by O'Leary et al. (1976) which defines the term as follows: "senso stricto in a geomorphological sense as a mappable simple or composite, linear feature of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differ distinctly from the pattern of adjacent features and presumably reflect a subsurface phenomenon". Conceptually, lineaments may be considered to be the product of the intersection of two subplanar surfaces (Hall, 1986). Three main forms of lineaments are recognized in remote sensing (Gold, 1980):

- (1) segment and/or point alignments;
- (2) linear truncations and offset contours;
- (3) linear boundaries in derived maps such as facies variations, tectonic domains or shear zones.

Doré and Gage (1987) described major lineaments corresponding to known major crustal discontinuities as alignments. Examples of alignments in the UK region are the Highland Boundary fracture zone and the Tornquist alignment (Pegrum, 1984). Doré and Gage (1987) suggested that these alignments played important roles in the tectonic evolution of the North Sea region.

3.5.1 Origin of lineaments

Lineaments identified from remotely sensed electromagnetic radiation usually relate to surface or near surface features (Hall, 1986). These features may be tentatively interpreted as the expressions of deeper structures. Lineaments derived from imaging potential field data, excluding the free air anomaly, are more likely to relate directly to subsurface phenomena. In particular, lineaments within the Bouguer gravity field must delimit subsurface density contrasts.

The simplest form of lineament to be imaged in the gravity anomaly field is the anomaly gradient generated at a fault. However, because the interpretation of the sources of Bouguer anomalies is often ambiguous the precise origin of many lineaments is obscure. Constraints imposed by a knowledge of the local geology can often aid interpretation.

A significant proportion of the Earth's upper crust in the UK region can be broadly described as a two layer model with a relatively low density Upper Palaeozoic/Mesozoic/Cainozoic cover of sediments overlying an older, higher density Precambrian/Lower Palaeozoic basement. Within this basement-cover model there are three main types of density contrast that can generate lineaments:

- (1) density contrasts within the cover, such as lithologies of particularly low density including evaporites and Tertiary sediments or erosion channels filled with recent drift deposits;
- (2) variations in the depth to basement such as those associated with horsts, graben and sedimentary basins;
- (3) basement features such as acid and basic intrusions, which may be irregularly orientated or exploit a line of crustal weakness, density contrasts between domains of different basement type such as the Scourian-Laxfordian contact (Bott et al., 1972).

Lineaments associated with the latter two groups are useful for the interpretation of tectonic features. The density contrast associated with a basement fracture may be small. However, if the fracture controls the location of another source of density contrast, such as intruded granitic material or the development of a later fault, an

important lineament may be produced.

It is important to be able to separate the lineaments generated within the cover from those originating from the basement. Several methods can be used to help distinguish between the two types of lineament. An examination of the surface geology in the vicinity of any lineament will expose surface features likely to contribute to the distortion of the gravity anomaly field. The geomorphology of the lineament is also useful. Lineaments of considerable length which continue across many different types of outcrop lithology are unlikely to be associated with sources within the cover. Similarly lineaments running obliquely to the general outcrop strike are more likely to be associated with sources beneath the cover.

Further information can be obtained from complementary aeromagnetic data. Unless significant amounts of magnetite are present within the cover in lavas, sills or rare magnetic sediments the cover is generally not magnetic by comparison with the basement. Therefore, aeromagnetic data can often be used to check whether the gravity lineaments are caused by basement features.

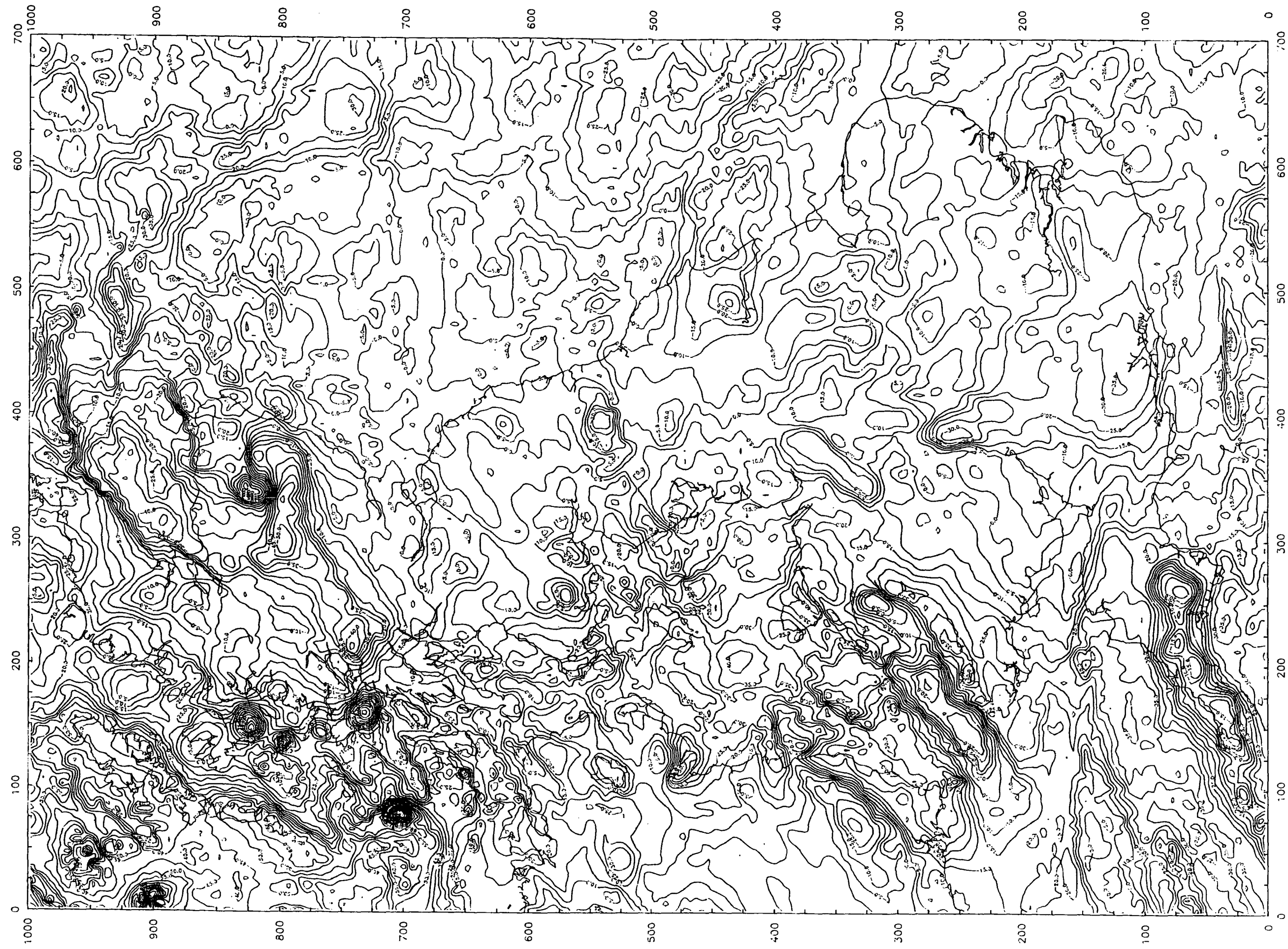
The interpretation of the lineaments within the gravity data is complicated by a number of factors. The upward continuation of potential field anomalies suppresses the high wavenumber content. Lineaments become more diffuse and difficult to identify.

The digital image enhancement techniques also enhance high wavenumber noise in the digital images. The dense concentration of gravity stations on land makes the information reasonably reliable. However, the poorer sampling and widely spaced ship tracks of the marine surveys can induce noise in the digital images.

3.6 Major features of the Bouguer gravity field of the UK and the NW European continental shelf

3.6.1 Introduction

This section discusses the major features of the Bouguer gravity field. To enable a more conventional interpretation to be given before studying the digital images a contour map of the Bouguer gravity is displayed in figure 3.4.



The observed Bouguer anomalies originate from a number of different types of source. Long wavelength regional anomalies can be produced by density variations within the upper mantle. These density variations mainly result from changes in temperature and may be associated with local convective motion.

Changes in crustal thickness affect the measured anomalies. Major mountain chains compensated by thick crustal roots are marked by negative Bouguer anomalies. Smaller changes in crustal thickness also produce significant anomalies. Similarly lateral changes in the relative thicknesses or mean densities of the lower and upper crust can produce Bouguer anomalies (e.g. Setto and Meissner, 1987).

Bouguer anomalies are noticeably affected by the depth to the upper crustal basement. In regions of shallow or outcropping basement moderately high anomalies are often observed. When the basement lies at depth beneath thickened sedimentary sequences, low anomaly values occur. The thickened sedimentary sequences usually occur within local sedimentary basins. In the UK region two main types of basin can be recognized. Intensely negative local anomalies with steep marginal gradients occur over sedimentary basins containing Mesozoic and younger sediments. The large anomaly amplitudes are a result of the significant density contrasts between the young sediments, characterized by densities in the region of 2400 kg m^{-3} for the Mesozoic and $2050\text{--}2250 \text{ kg m}^{-3}$ for the Tertiary, and the underlying basement which has a density of 2700 kg m^{-3} or greater (Zervos, 1987). Thus a Mesozoic basin 2 km thick with a density contrast of -300 kg m^{-3} with the basement produces a negative anomaly approaching -25 mGal . Basins characterized by steep margins are marked by steep anomaly gradients. The precise densities depend upon the actual lithologies present.

Less conspicuous anomaly lows occur over older Upper Palaeozoic basins which are usually associated with smaller density contrasts with the basement. Bott (1967) estimated that the density contrast between the Carboniferous successions of basin facies in the Northumberland and Stainmore troughs and the basement rocks lay between -100 and -200 kg m^{-3} . Some Coal Measure sequences are of particularly low density because of a preponderance of sandstones and generate quite significant anomalies

(Cook et al., 1951).

Igneous intrusions within the basement are associated with both positive and negative Bouguer anomalies. Granitic intrusions are generally less dense than the surrounding host rocks and produce significant anomaly lows such as the -50 mGal local low over Dartmoor. For example, Bott and Scott (1964) considered the Bodmin Moor granite to have a density of roughly 2600 kg m^{-3} compared to a density of approximately 2750 kg m^{-3} for the country rocks. Basic intrusions are usually denser than basement and can produce local positive Bouguer anomalies of amplitudes about 50 mGal, such as those observed over the Tertiary igneous complexes of the Hebrides. Gravity anomalies can also be caused by lateral density variations within the metamorphic basement. An example of this is the density contrast between the Scourian and Laxfordian basement in the Caledonian foreland of northwest Scotland (Bott et al., 1972).

The density contrasts outlined above cannot always be studied in isolation. The loading of the lithosphere by the density contrasts is compensated through the process of isostasy and the gravity effect of the compensation will modify that of the original load. Isostatic equilibrium may be achieved through a number of mechanisms, but an important process is regional compensation which occurs when a load is compensated by the regional deflection of the lithosphere (Vening Meinesz, 1941). The response of the lithosphere to loads of geological duration can be quite accurately modelled by the loading of a thin elastic plate overlying an inviscid fluid substratum (Walcott, 1970b; Watts, 1978).

The lithospheric flexure hypothesis predicts that the form of isostatic compensation varies with the wavelength of the applied load (Banks et al., 1977). An isostatic response function for the UK region (see Chapter 5) suggests that loads with wavelengths less than 200 km do not cause significant lithospheric flexure. These features may appear to be uncompensated because of the high apparent strength of the lithosphere at short wavelengths or because they are compensated by a different process. For example, additional investigations into the relationship between topography and gravity over the Cornubian batholith suggests that the associated high topography is

locally compensated at shallow depth by the batholith and is not significantly compensated by present day flexure. For longer wavelengths, 200 to about 1000 km, depending on flexural rigidity the observed relationship between gravity and topography can often be explained by flexure. The amount of compensation depends on the flexural rigidity of the lithosphere and the wavelength of the load. For loads of very long wavelength (> 1000 km) the apparent strength of the lithosphere is insignificant and the loads thus appear to be supported according to simple Airy isostasy, except near the edges of the loads. Loads out of apparent isostatic equilibrium may be supported by dynamic processes such as convection within the mantle, or the sinking of the lithosphere.

3.6.2 The long wavelength background anomaly

The United Kingdom is located on the NW edge of the European continental shelf, close to the NE Atlantic continental margin. The long wavelength, regional Bouguer gravity field is characterized by a marked gradient with the anomaly values increasing from east to west. The average Bouguer anomaly value for the southern North Sea is approximately -20 mGal, whereas anomaly values for the NW Approaches average $30-40$ mGal and those of the SW Approaches average $20-30$ mGal. Karner et al. (1987) explained the general positive from the Hebridean shelf break to the Pennines, observed in a merged free air (marine), Bouguer gravity (land) image of the NW European continent and shelf, as a combination of two major influences:

- (1) an extended free air gravity “edge effect” along the shelf break;
- (2) the formation of major sedimentary basins within the North Sea and the accompanying lithospheric flexure in the adjacent continental regions.

The free air edge effect at continental margins is generated by the incomplete cancellation of the gravity anomalies produced by changes in the topography of the surface and Moho interfaces. The maximum wavelength of this effect is roughly $100-200$ km (Karner and Watts, 1982). The positive anomaly of the NE Atlantic continental margin is much wider than this. Karner et al. (1987) suggested that the additional positive anomaly may be caused by two further effects:

- (1) footwall uplift produced by isostatic unloading of the crust across major normal

faults;

- (2) loading of the continental lithosphere by Tertiary plateau lavas and the associated central igneous complexes.

However, the overall wavelength of the regional variation across the UK is of the order of 1000 km. The effective strength of the lithosphere is almost insignificant at such wavelengths. Therefore, the regional gradient is probably caused by the dynamic support of the lithosphere by processes such as convection within the underlying mantle or by deep isostatic compensation. The regional gradient may then be associated with the location of the UK region on the edge of the geoid high centred over the Icelandic hotspot. This feature will be examined in more detail in Chapter 5.

3.6.3 Tectonic domains and Bouguer anomaly classification

The observed Bouguer anomalies of the UK and the continental shelf can be grouped into a set of regional domains associated with differing tectonic evolution. The most important domains are the Caledonian foreland of NW Scotland and the Outer Hebrides, the dominant NE–SW trending Caledonian foldbelt of northern Britain and Ireland, a domain of mixed tectonic trends covering central, eastern and southeastern England, the Variscan foldbelt of south and southwest England, and the North Sea province.

3.6.4 The Caledonian foreland

The Caledonian foreland of NW Scotland and the Outer Hebrides is marked by a regional anomaly high which forms part of the long wavelength feature discussed above (3.6.2). This is associated with a slightly thinned crust and the high density Lewisian basement ($> 2800 \text{ kg m}^{-3}$ for Scourian). Local highs occur over very shallow and outcropping basement, particularly over the Scourian pyroxene granulites. The regional high of the NW Approaches is punctuated by three NE–SW trending lows associated with the Minches basin and the Sea of the Hebrides and the Inner Hebrides troughs (McQuillin and Binns, 1979). The troughs have been described as simple half graben infilled by Mesozoic and some Upper Palaeozoic sediments formed by the reactivation of Caledonian thrusts as extensional faults (Smythe et al., 1982; Brewer and Smythe,

1986). However, at least in the Minches basin the relatively low density Torridonian sediments which underlie the Mesozoic contribute substantially to the anomaly low (Fellows, 1986).

High positive Bouguer anomaly values are observed over the Tertiary igneous complexes; Skye +73 mGal (Bott and Tuson, 1973), Mull +67.2 mGal (Bott and Tantrigoda, 1987), Rhum +76.3 mGal (McQuillin and Tuson, 1963) and Blackstones bank +135 mGal (McQuillin et al., 1975). The majority of these complexes are intruded into the Caledonian foreland but the Mull, Arran and northeast Ireland complexes penetrate the Caledonian foldbelt.

3.6.5 The NE–SW Caledonian foldbelt

The NE–SW Caledonian foldbelt forms a broad tectonic domain which sweeps across northern Britain into northern and central Ireland. Along strike the Bouguer anomaly pattern varies significantly over the major structural components of the foldbelt.

In northern Scotland, to the east of the Moine thrust, the Lewisian basement is overlain by the Moine group. In this region the LISP seismic refraction project (Bamford et al., 1978) identified a refractor of velocity 6.4 km s^{-1} at a depth of approximately 8–10 km. This refractor has been tentatively interpreted as the high density granulite facies Lewisian basement. The refractor displays lower than usual velocities in the region of the Laxfordian basement in the vicinity of the Ben Stack line. This may result from a lower density unit in the Precambrian basement identified by Bott et al. (1972). The low density unit, which generates a distinct NW–SE trending Bouguer anomaly low over the Lewisian of Sutherland, may be the result of localized granitic and/or pegmatitic invasion of the basement. Towards the southeast, the trough broadens into an oddly shaped low overlying the Grudie and Rogart granites.

The region of negative Bouguer anomalies northwest of the Great Glen fault may be caused by a series of granitic intrusions including the Strontian granite and a belt of low density migmatites. The low amplitude of the anomalies suggests that these granites are either less extensive in depth, or of a higher density than the granites of

the Grampian Highlands. The LISP seismic refraction profile identified a relatively thin crust in this region. Therefore, the observed Bouguer anomalies cannot be explained by a thickened crust.

The Inner Moray Firth is characterized by an extensive Bouguer anomaly low with a minimum value of approximately -40 mGal delimited by steep gravity gradients (Sunderland, 1972). The steep anomaly gradients reflect control of the basin subsidence by bounding extensional faults, such as the reactivated Great Glen fault, the Helmsdale fault and the Banff fault. The low anomaly values are mainly the product of 3–4 km of low density Upper Palaeozoic and Mesozoic sediments, but detailed gravity modelling by Dimitropoulos and Donath (1981) indicates the possible presence of a granitic intrusion beneath the central ridge.

The Grampian Highlands of Scotland located between the Great Glen fault and the Highland Boundary fracture zone are characterized by an extensive regional anomaly low. The lowest Bouguer anomaly values recorded for the UK, approximately -55.0 mGal, occur over the Cairngorm granite complex. The extent of the anomaly low roughly corresponds to the outcrop of the Moine group. The anomaly low is abruptly terminated to the southwest by a line running (NW–SE) from the Isle of Mull to Loch Lomond termed the Cruachan lineament. In the northeastern Highlands a series of intense local positive anomalies are caused by the Younger Gabbroic intrusions (McGregor and Wilson, 1967). A Bouguer anomaly maximum of $+44$ mGal occurs over the Cabrach basic mass.

The origin of the major low is controversial. Original interpretations assumed three main rock groups of differing density: the high grade Lewisian basement ($2750\text{--}2800$ kg m $^{-3}$), the Torridonian, Moine and Dalradian ($2670\text{--}2750$ kg m $^{-3}$) and the low density granitic intrusions ($2630\text{--}2670$ kg m $^{-3}$). Dimitropoulos (1981) explained the anomaly low in terms of large scale ‘granitization’ of the Highlands. However, Hipkin and Husain (1983) proposed that a further density contrast may exist between the Moine and Dalradian groups. In a modification of the method introduced by Nettleton (1939), the density of the surface rocks was estimated by varying the applied Bouguer correction

density until the correlation between the Bouguer anomaly and the surface topography was minimized. The estimated mean values for the densities of the Dalradian and Moine groups were found to be 2830 kg m^{-3} and 2738 kg m^{-3} respectively. Although these results have not been substantiated by laboratory measurements, Hipkin and Hussain (1983) observed that there is a close correlation between the Bouguer anomaly gradients and the outcrop boundary between the Moine and Dalradian groups in Perthshire. Hipkin and Hussain (1983) concluded that the observed Bouguer anomaly was caused by a wedge of Moines, with the cross sectional form of a downpointed triangle, roughly 15 km in depth. The possibility of the widespread 'granitization' of the Highlands was considered unlikely because an Airy isostatic anomaly map for northern Britain suggested that the low density Caledonian granites were separated into two main groups namely the Cruachan-Loch Etive complex and the Monadhliath, Cairngorm and Lochnagar group.

However, this interpretation may not be correct. The localized anomaly minima may be the result of granitic cupolas above a more extensive batholith. The anomaly gradients surrounding the main anomaly low are uncommonly large for the typical magnitude of density contrasts occurring within metamorphic basement material. Some earlier density measurements of Dalradian group rocks from the northeast Highlands suggest a much lower mean density of 2740 kg m^{-3} (McGregor and Wilson, 1967). Further measurements of outcrop densities are required to distinguish between the two hypotheses.

A significant density contrast between the two groups would be useful to explain the curious contrast between the intensely negative Bouguer anomaly values over the Scottish mountains and the moderately high Bouguer anomaly values over the same orogenic belt in NW Ireland where Moine group rocks are absent. Karner et al. (1987) explained this association as the product of different tectonic evolutions, the Scottish Caledonides being the remains of a thick skinned orogenic structure and the Irish Caledonides the result of a thin skinned orogenic belt. Alternatively, the granitic intrusions of NW Ireland may be volumetrically much less abundant than those of the Grampian

Highlands.

South of the Highland Boundary fracture zone, a broad regional high is recorded over the Midland valley. The LISP seismic refraction project (Bamford et al., 1978) imaged a 6.4 km s^{-1} velocity refractor at 7 km depth beneath the Midland valley. This shallow basement, which has been associated with a thinned upper crust, may be the origin of the broad anomaly high. Local anomaly variations in the Midland Valley are caused by sedimentary basins and intrusives.

The shallow 6.4 km s^{-1} basement refractor terminates to the south of the Southern Uplands fault. The anomaly pattern over the Southern Uplands is complex, the observed anomaly troughs and highs probably resulting from both variations in the basement and the intrusion of granitic material. The granitic intrusions form a NE–SW trending belt across the Uplands. Important intrusions are the Cairnsmore of Fleet granite (Parslow and Randall, 1973), the Loch Doon granite, the Criffell granodiorite (Bott and Masson-Smith, 1960) and the proposed Tweeddale batholith (Lagois and Hipkin, 1979). The Cheviot granite lies to the south of the main Southern Uplands belt. A number of local negative anomalies occur over Permo–Trias basins. These include the Dumfries and Lochmaben basins and the Luce Bay and Galloway troughs (Bott and Masson-Smith, 1960; Mansfield and Kennett, 1964). The amplitudes of the anomalies over the Dumfries and Lochmaben basins are each roughly 15 mGal. This indicates a thickness of roughly 1100m of Permo–Triassic infill (Bott and Masson-Smith, 1960). All of these basins display a pronounced NW–SE elongation.

A second more extensive chain of granites extends from the Leinster granite in southeastern Ireland across the Irish Sea to the Lake district batholith (Bott, 1974) and the Weardale granite beneath the northern Pennines (Bott, 1967). Other granites in this chain include the Isle of Man granites (Cornwell, 1972) and a number of granites tentatively proposed to underlie the mid North Sea high (Donato et al., 1983).

During the Lower Carboniferous, the northern Pennine granites were associated with buoyant blocks of basement bounded by slowly subsiding sedimentary troughs (Bott, 1967). The thickened sedimentary sequences of the Northumberland, Stainmore

and Bowland troughs produce Bouguer anomaly lows but these are difficult to distinguish because of the large anomaly gradients generated by the granitic intrusions.

The Irish Sea is characterized by a broad, regional anomaly high culminating in a maximum anomaly of approximately +40 mGal. The Bouguer anomalies over both the Lower Palaeozoic succession of Wales and the Upper Palaeozoic of eastern Ireland are dominated by the regional gradients associated with the high. A series of local anomaly minima ranging in amplitude from 20–40 mGal are superimposed on the regional high. The local minima occur over Upper Palaeozoic and Mesozoic basins. The more northerly basins include the East Irish Sea basin, the Solway basin and the Kish Bank basin (Bott, 1964; Bott and Young, 1971). The Solway and Carlisle basins and the Carboniferous Northumberland trough may be extensional features related to the Iapetus suture. The East Irish Sea basin can be traced onshore into the Permo-Triassic of the Cumbria and Lancashire coasts. The basins commonly comprise 2–4 km of Carboniferous/Permo-Trias infill lying on Lower Palaeozoic basement. The Central Irish Sea basin is bounded by two distinctly Caledonian basement ridges, namely the mid Irish Sea uplift and the Irish Sea geanticline. Gravity and seismic investigations indicate that the basin contains at least 2500 m of sedimentary infill (Al-Shaikh, 1970). In the south Irish Sea an anomaly low of 70 mGal amplitude is recorded over the NE–SW trending St. George's Channel basin (Dimitropoulos and Donato, 1983). The basin may contain up to 10,000 m of mainly Mesozoic infill (Blundell et al., 1971). To the northeast, the trough continues into the Cardigan Bay basin and to the southwest into the North Celtic Sea graben.

The source of the regional anomaly high over the Irish Sea may be a thinned crust or a denser basement (Bott and Young, 1971). Recent seismic reflection surveys (BIRPS and ECORS, 1986) have imaged the Celtic Sea graben as simple, asymmetric, half graben overlying normally reactivated Variscan thrusts. Karner et al. (1987) suggested that the regional positive anomaly may result from the relaying of upper crustal extension responsible for the basin formation in the Irish Sea, down into the lower crust, via major detachment zones. The lower crustal extension thus generated may produce

the required crustal thinning.

3.6.6 Central, eastern and southeastern England

This is a complex tectonic domain dominated by three major basement fabrics. A marked NW–SE tectonic trend controlled the Upper Palaeozoic evolution of eastern England. This was partly Charnian in origin, but was partly caused by a NW–SE trending branch of the Caledonides (see 3.8.2). This is particularly prominent in east Yorkshire and Lincolnshire. The third fabric is associated with the N–S Malvernian axis. This trend exerted a strong control on the Upper Palaeozoic and Mesozoic evolution of the west Midlands district.

A broad Bouguer anomaly high centred over the Derbyshire dome is characterized by anomaly values around 20 mGal (Maroof, 1976). The apparent anomaly high is the product partly of a shallow Precambrian basement and partly a reflection of the adjacent anomaly lows over the Cheshire basin and the East English shelf. The broad anomaly low over the East English shelf is the result of a number of factors including:

- (1) the thickening of the Mesozoic sediments towards the southern North Sea;
- (2) postulated granitic intrusions such as the Market Weighton granite (Bott et al., 1978) and two nearby granites just offshore which may cause the conspicuous offshore low northeast of the Humber estuary (Donato, 1988);
- (3) thickened Lower Carboniferous and Namurian sequences in the Gainsborough and Widmerpool gulfs and elsewhere (Kent, 1966).

A complex series of local anomaly maxima and minima is observed over the Wash district and the east Midlands to the west. Recent work suggests that the localised anomaly lows over the Wash district, near Glington, Wisbech, Boston, Hunstanton and Saxthorpe may be caused by granite cupolas rising from an extensive batholith at depth (Chroston et al., 1987). Localised highs in the east Midlands are commonly the product of shallow Precambrian or Lower Palaeozoic basement, as observed at the Nocton high, southeast of Lincoln (White, 1948). The south Leicestershire diorites and the Mountsorrel and Melton Mowbray granodiorites display little difference in density from the local basement and are not obviously represented in the Bouguer anomaly

data (Allsop, 1987).

A very broad Bouguer anomaly high traverses roughly E–W from the Ardennes region to Wales. This corresponds to the region of the Carboniferous Midland Barrier and the Mesozoic London–Brabant landmass. Karner et al. (1987) interpreted the high as a remnant flexural bulge to the thrust sheets of the Variscan orogeny. In the English Midlands this regional anomaly high is modified by local anomaly highs over horsts of Coal Measures and anomaly lows over the intervening graben, which are filled with low density Permo–Trias deposits (Cook et al., 1951). To the east the horsts are controlled by basement faults of the Charnian trend (NW–SE), whilst further to the west the N–S Malvernian trend becomes more prominent.

The N–S Malvern axis forms the western boundary of the Worcester basin. Over the basin, anomaly values decrease to a local Bouguer minima of -32 mGal. The basin may contain as much as 7000 m of Permo–Triassic infill (Whittaker, 1985) overlying a basement of Cambrian to Carboniferous age (Smith, 1987). Further north the influence of the Malvern axis can possibly be recognised in the northeastern margin of the Cheshire basin. East of the Worcester basin, local Mesozoic basins are not as conspicuous as they are in the other domains, although there is a gradual thickening of the Mesozoic strata towards the North Sea.

3.6.7 The Variscan Foldbelt

The tectonic framework of southwestern and southern England is dominated by the Variscan foldbelt. A broad regional high overlies southwestern England and the Southwestern Approaches with Bouguer anomaly values rising towards the continental margin. The regional high is punctuated by a number of important anomaly minima. A series of intense, local anomaly minima are observed over the granite cupolas of the Cornubian batholith (Bott et al., 1958).

The ENE–WSW trending North Celtic Sea graben is marked by a Bouguer anomaly minima of -7 mGal (Davey, 1970). To the northwest of the graben, anomaly values rise to a maximum of over 40 mGal off the southeast coast of Ireland. The South Celtic Sea graben is separated from the North Celtic Sea graben by two basement highs namely

the Pembrokeshire ridge and the Labadie bank. The South Celtic Sea graben is marked by a Bouguer anomaly minimum of -5 mGal and may contain up to 7,000 m of mainly Mesozoic sediments. To the east, the South Celtic Sea graben continues into the Bristol Channel basin.

Bouguer anomaly values decrease sharply to the north over Exmoor and west Somerset. Bott et al. (1958) explained the regional gradient in terms of the thrusting of Devonian sediments to the north over less dense Upper Palaeozoic rocks extending southwards from the Bristol channel. Brooks et al. (1977) proposed a simple ESE–WNW anticline characterized by a Lower Palaeozoic–Devonian density inversion as an alternative explanation for the observed anomaly gradient. Further evidence for the thrust model has been presented by Donato (1987). A seismic reflection survey imaged a southerly dipping event beneath the Somerset anticline tentatively interpreted as a thrust.

The extensive Wessex basin complex of southern England (Kent, 1949) is characterized by a regional Bouguer anomaly low, with localized anomaly minima down to -36 mGal. The anomaly extends across the English channel, over the English Channel basin and to the Paris basin.

The central province of the English Channel is marked by a linear Bouguer anomaly low associated with the mid-Wight Axis. The axis comprises a monoclinal downturn to the south of the order of 1000 m (Smith and Curry, 1975). The anomaly minimum is presumably caused by a thickened Mesozoic/Tertiary sequence to the south of the axis.

3.6.8 The North Sea

The North Sea region experienced extensive lithospheric extension and sedimentary basin formation during the Mesozoic with thermal subsidence during the late Cretaceous and Tertiary. The region is characterized by a long wavelength Bouguer anomaly low which is especially well marked over the southern North Sea basin. The Central graben, the Viking graben and the Buchan and Witchground graben of the Outer Moray Firth are not marked by intense Bouguer anomaly minima. Seismic refraction data from Sclater and Christie (1980) and Wood and Barton (1983) indicate that these basins

are compensated by an underlying thinned crust as predicted by the sedimentary basin formation model of McKenzie (1978).

The mid North Sea high is characterized by a broad, diffuse anomaly high (0–20 mGal). The anomaly high reflects an E–W elongated basement high. Anomaly values decrease towards the east as the high becomes progressively buried under sediments. Further to the southeast, Bouguer anomaly values fall to between –15 and –20 mGal over the southern North Sea basin. The amplitude and shape of this anomaly low can be satisfactorily explained by extensive sediment accumulations within the basin (Donato and Tully, 1981).

A NW–SE trending Bouguer anomaly high occurs over the *Solepit* trough. The *Solepit* high represents a Permian to Late Cretaceous basin that was inverted in the Late Cretaceous and Early Tertiary (Glennie and Boegner, 1981). The apparent anomaly high is probably a reflection of a region of normal basement depth sandwiched between the Southern North Sea basin and the granitic intrusions of the East English shelf and the Wash district.

3.7 Lineament analysis

In this section I describe and discuss the possible origins of the lineaments imaged in the digital images of the Bouguer gravity field. The interpretation of the tectonic significance of the lineaments is deferred to the next section. Although each digital image is discussed individually, the morphology of any given lineament is best assessed by studying several of the images presented.

To aid in the interpretation, the imaged lineaments were digitized and redrawn at a scale of 1:625,000 on the OSGB national grid. This allowed the lineaments to be compared directly against the previously published Bouguer anomaly map of the British Isles North sheet (Hussain and Hipkin, 1981) and South sheet (Hipkin and Chacksfield, 1986), the aeromagnetic map (Sheets 1 and 2 of the aeromagnetic map of Great Britain, 1972; 1965), and surface geology maps (Geological Survey 1:625,000 map, North and South sheets, Third edition, 1979).

Throughout this discussion specific lineaments are identified by lower case letters. More general features are denoted by capital letters.

3.7.1 Northwestern illumination

Plate I displays a digital image of the Bouguer gravity of the UK. The digital image has been enhanced by superimposing a shaded relief representation of the digital terrain illuminated from the northwest. This enhances the important NE–SW trending tectonic structures associated with the Caledonide orogeny, which are *prevalent* in the northern and western regions of the UK and Ireland.

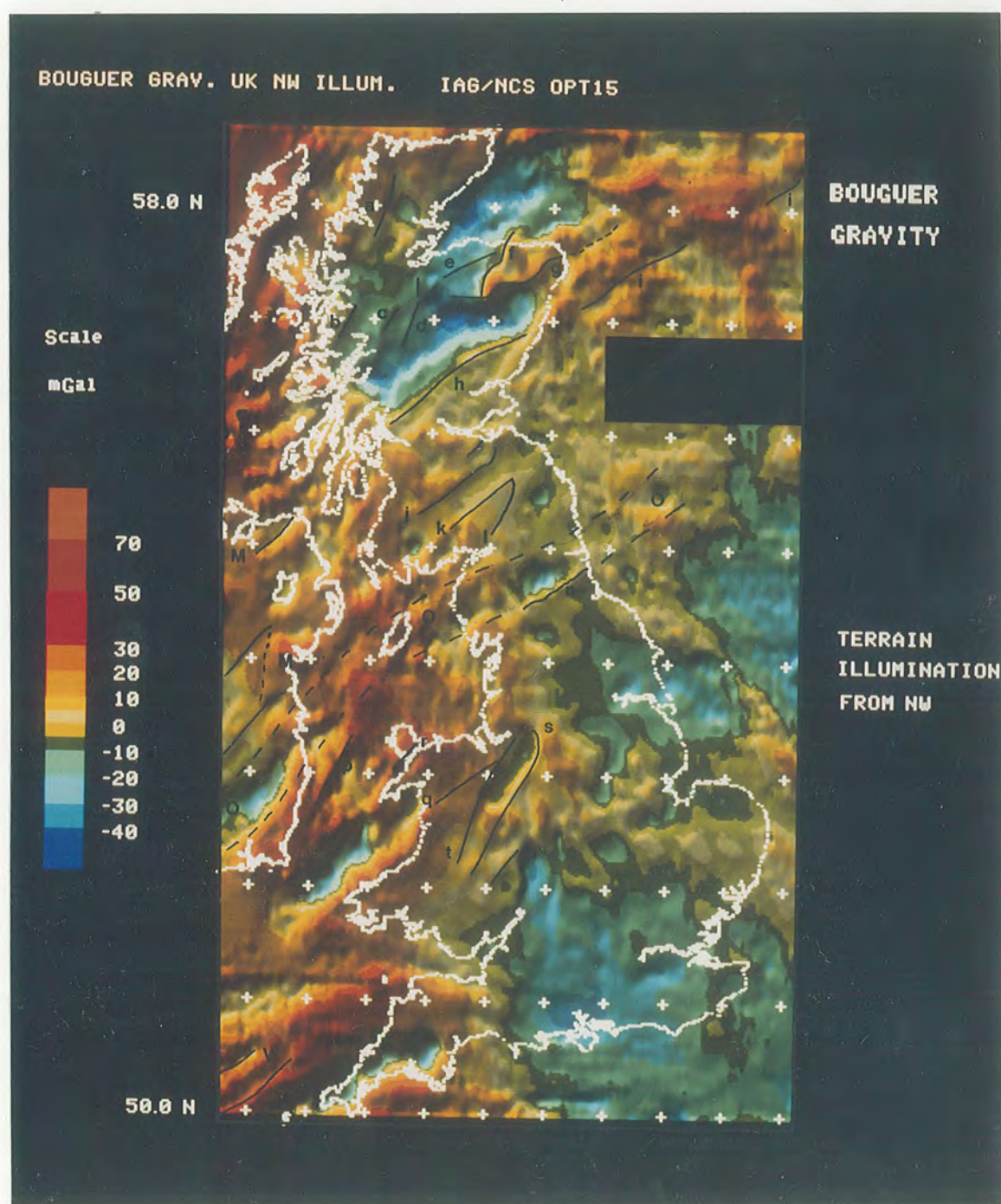
The Northern Highlands of Scotland are characterized by strong NNE–SSW lineaments. A prominent anomaly gradient is imaged running subparallel to and slightly to the east of the Moine thrust (lineament a). This gradient marks the western edge of an oddly shaped anomaly low, associated with a Bouguer anomaly minima of -18 mGal, centred over the Grudie granite. This anomaly gradient may, therefore, delimit the western margin of the subsurface granite and its extension to the southwest. To the northwest, the anomaly low traverses towards the Laxfordian front.

A similar anomaly gradient is imaged close to the Sgurr Beag slide (b). The gradient marks the western margin of a trough of low Bouguer anomaly values which lies between the slide and the Great Glen fault. The low Bouguer anomalies may be caused by acidic intrusions. The Strontian granite is located at the southwestern edge of the trough and a belt of granitic gneiss runs along the western edge of the trough from Scotstown to Loch Quoich.

The Great Glen fault is marked by slight anomaly gradients in the northeast, near Inverness, and in the southwest along Loch Linnhe but is not strongly imaged in the central region. As discussed later, the major gravity anomalies in this region appear to be associated with granitic intrusions. Therefore, the poor definition of the fault in this region suggests that it does not control the subsurface distribution of any significant intrusions. However, this is not the case further southwest where motion on the fault provided space for the intrusion of the Strontian granite (Watson, 1984).

A faint NNE–SSW trending anomaly high lies slightly to the southeast of the Great

Digital image of the Bouguer anomaly gravity of the UK and adjacent regions with terrain illumination from the northwest



Glen fault (c). This lineament can be discerned in the Bouguer anomaly contour map as a broad high of roughly 10 mGal amplitude. According to the surface geology map, the lineament traverses across Moinian quartz feldspar granulites but a thin strip of Dalradian schists and limestone correlates with the southeastern edge of the high. The fact that the Dalradian outcrop only partially correlates with the Bouguer anomaly high suggests that the possible higher density of the Dalradian is not the origin of the high. Further to the southeast, a series of NE–SW elongated granites have intruded the quartz granulites. These granites include the Allt Crom and Corrieyairack complexes. Therefore, a more plausible explanation of the observed anomalies is the presence of a region characterized by relatively little low density intrusive material at shallow depth compared to the surrounding areas.

A similar lineament traverses from Ben Alder to the northwestern margin of the Monadhliath mountains (d). This lineament correlates closely with the Loch na h'Erba fault, also known as the Laggan fault, but runs a few degrees closer to north–south. Towards the north–northeast, the lineament appears to bifurcate forming a 'V' shaped structure. The western part of this structure is formed by a NNW–SSE elongated anomaly high, of maximum amplitude 6 mGal, which runs from the Monadhliath mountains towards Inverness. The second branch is generated by a saddle in the anomaly field between intense local Bouguer anomaly minima over the Moy granite (–34 mGal) to the north and the Monadhliath granite (–44 mGal) to the south. The cause of the lineament appears to be related to the surrounding granite intrusions in a similar manner to lineament c. The Allt Crom and Corrieyairack granites lie to the northwest and to the southeast the lineament is bounded by the steep gradient into the Bouguer anomaly low between the Cairngorm and Moor of Rannoch granites. The southwestern end of the lineament terminates against the Strath Ossian granite.

A faint NE–SW lineament traverses across Moray and Banff from Ferness towards Lhanbryde, near Elgin (e). The local surface geology offers no explanation for this lineament. For most of its length the lineament runs across outcropping Moine quartz feldspar granulites, except for the extreme northeastern section which overlies sediments

of Middle Old Red Sandstone age. The lineament is roughly subparallel to the Moine–Middle/Upper Old Red Sandstone unconformity that runs close to the coast of the Inner Moray Firth. Therefore, the lineament may be associated with an underlying structure which controlled the southern boundary of the Devonian Orcadian basin and the Mesozoic Inner Moray Firth basin.

The western boundary of the anomalous Buchan block of the northeast Highlands is characterized by steep anomaly gradients. Anomaly values over the Buchan block are unusually high owing to the presence of a buried sheet of high density ($> 2900 \text{ kg m}^{-3}$) mafic material (McGregor and Wilson, 1967). The southern and western margins of the mafic sheet are formed by the Belhelvie, Inch and Huntly masses (Brown, 1983). The southerly location of the Morven–Cabrach mass suggests that it is not part of the mafic sheet but it may have been a feeder pipe (Allan, 1970). The steep E–W anomaly gradient between Portsoy and Morven (f) forms part of the Portsoy–Duchray Hill lineament described by Fettes et al. (1986). To the west, the lineament is flanked by the northern part of the Dalradian–Moine boundary sigmoid of northeast Scotland. Here the general NE–SW trend of the Dalradian–Moine boundary is deflected into a NW–SE direction between Balmoral and Tomintoul, forming a distinct kink or sigmoid (Watson, 1984).

A major N–S anomaly gradient is imaged between the northern flank of the extensive Cairngorm granite complex and the southern boundary of the Inch gabbro. Further west the anomaly values fall by roughly 50 mGal off the southern flank of the Morven–Cabrach anomaly high into the Cairngorm low. These gradients form part of an en echelon set of lineaments, traversing roughly WSW–ENE across NE Scotland (g). However, the lineaments are of a composite form being generated partly by the low over the Cairngorm and Aberdeenshire granites and partly by Bouguer anomaly highs over the Morven–Cabrach, Inch and Maud gabbros. The lineament may be tentatively continued out into the North Sea from the Fraserburgh district.

The Highland Boundary fracture zone is imaged as a series of local highs (h). An elongate high of length 50 km, width 6 km, with a maximum anomaly value of +10

mGal northwest of Alyth may be produced by local occurrences of ultrabasic rocks. The origin of a similar high near Comrie is less clear. This anomaly high may correspond to unexposed ultrabasic rocks or, perhaps, a thin sliver of denser than usual Dalradian pelites. Towards southwestern Scotland, the linear high diverts to the northwest of the surface trace of the Highland Boundary fracture zone following a thin sliver of Dalradian slates marked by a small density contrast of roughly 100 kg m^{-3} with the surrounding Upper Dalradian grits (Qureshi, 1970).

To the northeast, the Highland Boundary fracture zone can be clearly discerned striking NE–SW across the central North Sea (i). The lineament intersects the broad regional anomaly high over the Montrose–Forties basement high (Tully and Donato, 1985) and continues to the Ling graben (Doré and Gage, 1987). The nature of this lineament is different from that observed onshore. Offshore the lineament forms a boundary between a region of broad, low amplitude features to the southeast and higher wavenumber, positive anomalies to the northwest. The location of the fault is more easily discernable from aeromagnetic data (I. G. S. , 1972), which shows a complex anomaly pattern to the northwest indicating a shallow basement and a much smoother set of anomalies to the southeast indicating a deeper basement (Tully and Donato, 1985). The markedly different anomaly values over the central sector of the North Sea and the Grampian Highlands suggests a significant change in the nature of the basement, presumably located within or at the edge of the anomalous Buchan block.

The Southern Uplands fault is characterized by a slight, linear ridge in the Bouguer anomaly values (maximum value approximately 16 mGal), flanked by a small fall in anomaly values to the southeast (j). McLean (1966) observed that south of Dalmellington the Southern Uplands fault has little effect on the Bouguer anomaly values and that the principle anomaly is a broad high culminating roughly 0.8 km southeast of the fault. The northwestern Southern Uplands are characterized by a trough in the anomaly values, bounded by the Southern Uplands fault and a subparallel lineament to the southeast (k). Lineament k runs for approximately 25 km from the Lochmaben

Permo-Trias basin in the southwest to Galashiels in the northeast.

The structure of the Southern Uplands was poorly defined by the LISP seismic refraction profile (Bamford et al., 1978). Hall et al. (1983) have shown that crystalline rocks of continental affinity lie at shallow depths (1–5 km) in at least two zones, which strike roughly parallel to the NE–SW Caledonian strike. The basement of the Southern Uplands appears to comprise NE–SW orientated blocks characterized by marked differences in seismic velocities. High velocity refractors (approximately 6 km s^{-1}) are located 15–20 km southwest of the Southern Upland fault as a continuation of the basement beneath the Midland Valley and in a 10–20 km wide block beneath Eskdalemuir. Between these blocks a sliver of basement characterized by a seismic velocity of 5.6 km s^{-1} is observed. The southern edge of this block correlates well with the second lineament that runs subparallel to the Southern Uplands fault. The curling lineament trace to the south may mark the southern boundary of the Eskdalemuir block.

A further factor must be considered with respect to the northwestern anomaly trough between the Southern Uplands fault and lineament k. Lagois and Hipkin (1979) tentatively identified a granitic intrusion, known as the Tweeddale batholith, underlying the northeastern section of the anomaly trough. Further southwest, a strong negative closure occurs over the Cairnsmore of Fleet granite. Lagois and Hipkin (1979) have suggested that the anomaly trough may reflect a regionally extensive batholith beneath the Southern Uplands. However, the steepness of the anomaly gradient at the southern lineament indicates a shallow density contrast (Hipkin and Hussain, 1983). The imaged anomalies, therefore, probably reflect both significant variations in basement type and widespread acidic intrusions within the region.

A curling lineament trace is imaged running from Langholm to just east of Melrose (l). In the southwest this lineament corresponds to the boundary between the Wenlock of the Southern Uplands and the Lower Carboniferous of the Northumberland trough and to the northwest to the boundary between Llandoverly and Upper Old Red Sandstone rocks. The origin of the lineament (l) most probably corresponds to the density contrasts between these formations.

The Iapetus suture (Phillips et al., 1976) does not generate a marked Bouguer anomaly lineament in the Irish Sea, northern England or southern Scotland, but the suture can be distinguished in eastern Ireland. The proposed suture coincides with the northeastern section of the southeastern lineament of the group marked M. The change in the nature of the lineament along strike may reflect a change in the form of the suture from a sinistral transpressive structure in eastern Ireland to a subduction-accretion feather edge in northern England and Scotland (Karner et al., 1987).

The Irish Midlands along strike from the Southern Uplands are characterized by several strong NW-SE striking lineaments (M). These lineaments are the product of a block and trough structure within the Lower Palaeozoic basement of central Ireland (Brown and Williams, 1985; Garland, 1987).

The Lunedale-Butterknowle fault system (n) is imaged as a series of linearly aligned highs between the anomaly lows over the Weardale granite, and the Stainmore trough and Wensleydale granite (Bott, 1967).

The Leinster-Isle of Man-Lake District-North Pennine chain of granites forms a strong, arcuate belt (O). This chain of acidic intrusions may continue further northwest in the form of two roughly, circular anomaly lows imaged off the Northumberland coast. The outermost low has been tentatively interpreted as a granitic intrusion by Donato et al. (1983).

South of the Lunedale fault NE-SW Caledonian trends are imaged only in the western English Midlands, Wales, the Irish Sea and Ireland. The mid Irish Sea uplift (Barr et al., 1981) is marked by a strongly imaged lineament running from the Wicklow Head shelf towards the central Irish Sea anomaly high (p). The uplift, which is characterised by positive anomalies up to 40 mGal, is defined by steep anomaly gradients into the Kish bank basin anomaly low (Bott and Young, 1971) and the Central Irish Sea basin low.

The Cardigan Bay and St. George's Channel basins form two distinctly Caledonian NE-SW trending anomaly lows. To the northwest they are bounded by the Irish Sea geanticline and to the southeast by the Lower Palaeozoic terrains of the Cardigan coast

shelf and the St. Bride's Bay shelf (Barr et al., 1981). The southeastern boundary of the basins is delimited by the Bala fault. On land the Bala fault is very weakly imaged traversing from Tywyn to Chester (q). A major Bouguer anomaly high (+40 mGal) runs across southeast Anglesey, parallel to the Menai Straits (r). This high corresponds to an uplifted block of Precambrian glaucophane schists lying between the Berw faults and the Dinorwic fault (Griffiths and Gibb, 1965).

A complex series of lineaments occurs in the Welsh Midlands and Borders where the southeastern edge of the Caledonide foldbelt impinges upon the Midlands microcraton. A marked NNE–SSW low of approximately 18 mGal amplitude occurs over the Cheshire basin (White, 1948). The Cheshire basin is associated with a complex set of NNE–SSW trending lineaments. The faulted southeastern margin of the basin is characterized by a steep WNW–ESE anomaly gradient, in places steeper than $2.56 \text{ mGal km}^{-1}$. For part of its length this lineament follows the surface trace of the Hodnet fault. Towards the south–southwest, the lineament continues over the Precambrian Long Mynd complex and then swings southwestwards towards Clun before diverting towards the Church Stretton fault near Knighton and Old Radnor (s). The outcrop of Precambrian rocks at Old Radnor suggests that a buried ridge of Precambrian rocks may produce the segment of the lineament south of the Cheshire basin (Griffiths and Gibb, 1965). This segment of the lineament is enhanced by a gravity low over a Silurian basin west of Ludlow.

A second lineament is imaged running along the northwestern margin of the Cheshire basin and across the Lower Palaeozoic succession of central Wales (t). Within central Wales the lineament runs through Welshpool and Kerry to Abbeycwmnir. Southwest of Abbeycwmnir the lineament may connect with the Tywi lineament (see Woodcock, 1984).

The region of low Bouguer anomaly values between these lineaments southwest of the Cheshire basin indicates a slight thickening of the Lower Palaeozoic succession. This is particularly apparent in the Clun Forest region (Woodcock, 1984). This thickening may reflect early subsidence facilitated by extensional faulting along the lineament

traces.

A faint lineament is imaged running NW–SE from Bewdley–Kidderminster towards Hope under Dinmore (u). On the Bouguer anomaly contour map the lineament is represented by a series of local anomaly highs flanked by a broad low to the southwest. The lineament traverses across outcropping Lower Old Red Sandstone sediments. Cook and Thirlaway (1955) suggested that the local anomaly values in this region reflect the buried surface topography of the underlying Precambrian basement. The lineament is, therefore, most probably generated by a shallow basement ridge of Caledonian trend. The broad low towards the southeast can similarly be explained by a thickening of the sedimentary cover. Towards the southwest, the NE–SW lineament may curl southwards towards the Usk anticline. The precise position of this lineament does not appear to agree with the postulated traces of either the Vale of Neath disturbance or the Swansea valley disturbance.

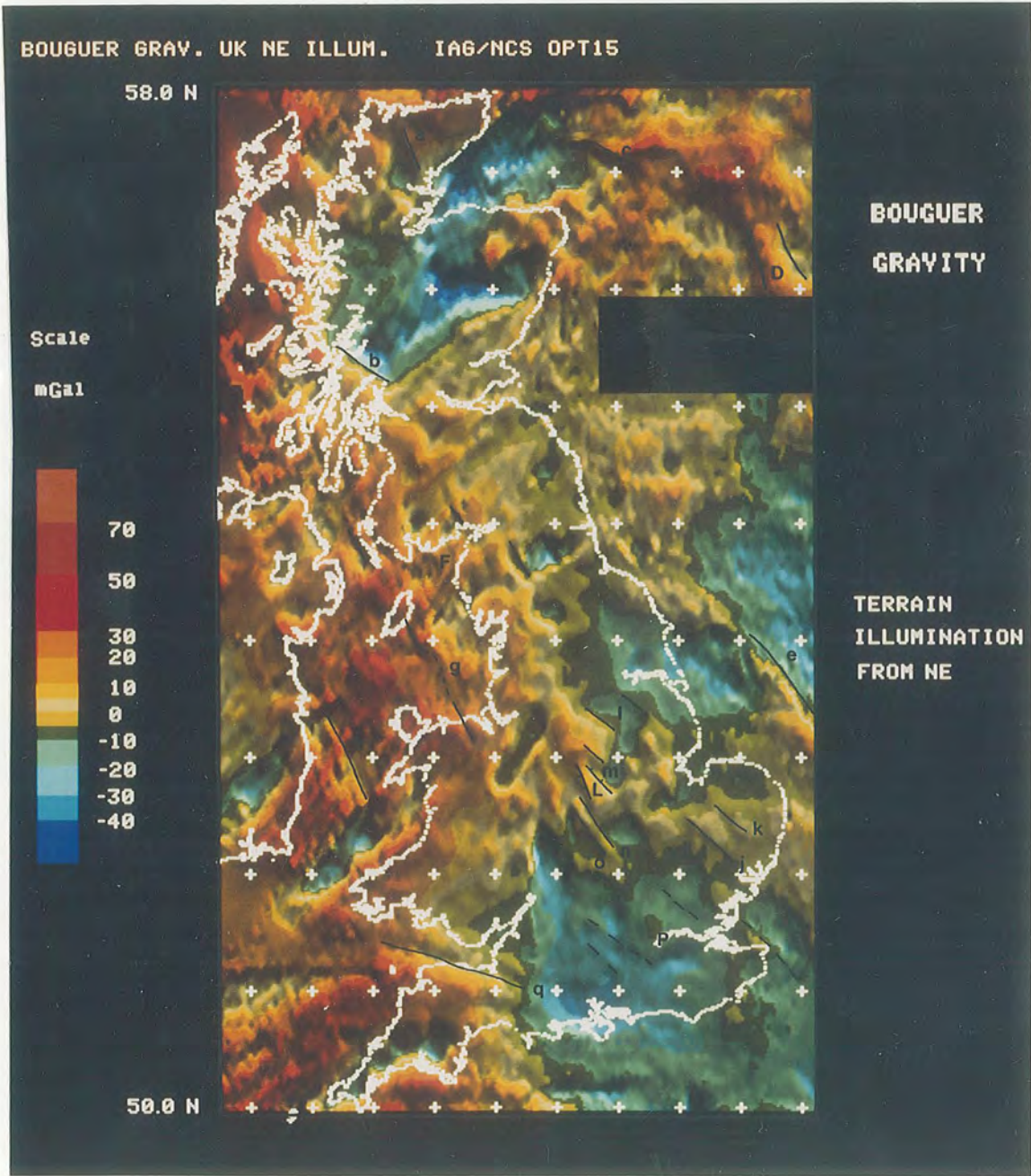
Several NE–SW anomaly troughs are imaged within the SW Approaches region (V). The trend of these lineaments closely matches that of the Cornubian batholith. The Celtic Sea grabens, which are not clearly imaged here because of a lack of data, are characterized by a strong Caledonian trend. Gardiner and Sheridan (1981) interpreted this in terms of the dominant effect of Caledonian basement structures beneath the Variscan front.

3.7.2 Northeastern illumination

Plate II displays a digital image of the Bouguer gravity illuminated from the north-east. This enhances trends striking NW–SE. There are four major tectonic fabrics with this orientation: the Lewisian trend of the northwest Caledonian foreland, the Precambrian Charnian trend observed in the eastern Midlands of England, the more speculative NW–SE Caledonian branch crossing eastern England and the adjacent North Sea, and the Variscan front of southwest England.

The geology of the Caledonian foreland of northwest Scotland is marked by a strong NW–SE structural trend. Approximately 2200 Ma ago a swarm of NW–SE trending tholeiitic dolerite dykes were intruded. The later Laxfordian deformation of about

Digital image of the Bouguer anomaly gravity of the UK and adjacent regions with terrain illumination from the northeast



1900–1700 Ma ago (Anderton et al., 1979) was characterized by NW–SE trending major folds with steep axial planes. A distinct NW–SE striking lineament in the Northern Highlands of Scotland is generated by a strong NE–SW gradient (a). This lineament lies to the northeast of the gravity anomaly trough which traverses from Alness, near the Moray Firth, to the Ben Stack line north of Assynt. Hipkin and Hussain (1983) considered this anomaly trough to be the product of a continuation of the Laxfordian front (Bott et al., 1972). However, lineament a is offset from a continuation of the Ben Stack line and the large amplitude of the Bouguer anomaly low indicates a significant mass deficiency in the basement. The most plausible explanation of the mass deficiency is a granitic complex. The structural trend of the Lewisian basement may have influenced the subsurface shape of the complex to form the observed lineament at the edge of the granite. Watson (1984) suggested that this lineament may mark the possible projection of an old shear zone within the *autochthonous* basement beneath the Moine Thrust.

The Cruachan lineament is defined by a strong SW–NE gradient along the southwestern limit of the main Grampian Highlands anomaly low (b). The lineament traverses from the southwestern part of the Loch Etive granite complex to Loch Lomond, near the Highland Boundary fracture zone. Hall (1986) considered that the southwards termination of a buried mass of low density Moine group rocks at the Cruachan lineament may explain the observed anomaly gradient (figure 3.5). Alternatively, the gradient may represent the southwestern termination of a region of widespread upper crustal granites controlled by an underlying line of weakness. Both the Loch Shin line (part of lineament a) and the Cruachan lineament are associated with anomalous zones within the upper crust marked by the intrusion of numerous appinite pipes (Watson, 1984). Plant et al. (1984) suggested that the lineaments may represent important trans-Caledonian zones extending to considerable depth within the crust and that these weaknesses may have aided the rise of the appinitic material.

The NW–SE trend of these lineaments correlates with the marked NW–SE fabric of the Lewisian basement. Therefore, weaknesses in the underlying Lewisian basement

Figure 3.5. Bouguer anomaly gradient across the Cruachan lineament. (a) Bouguer anomaly profile across the Cruachan lineament; the solid line shows the observed anomaly and the broken line displays the model results. (b,c) Two simple two-dimensional models of the possible subsurface structure of the lineament. The two models give identical results.

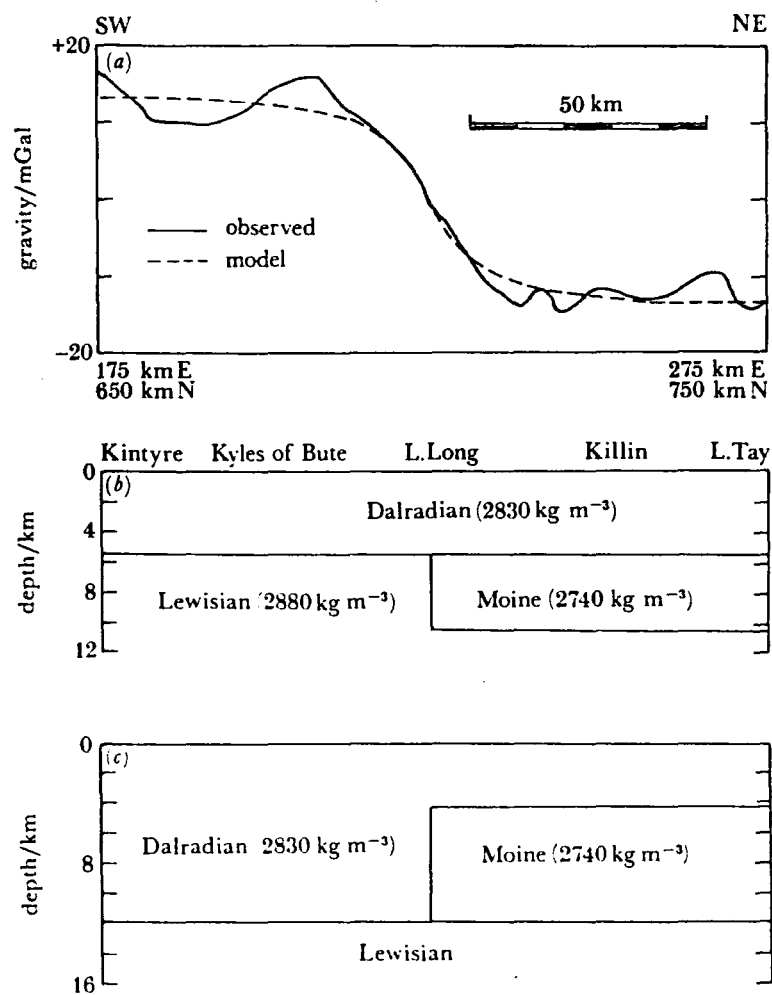


Diagram taken from Hall (1986) and the rock densities from Hipkin and Hussain (1983).

may have exerted an important control on the intrusion of igneous material during the later Caledonian orogeny.

Several NW–SE trending structures are imaged in the North Sea. A distinct lineament defines the southwestern margin of the Halibut horst (c). The Halibut horst is an E–W elongated horst of Devonian rocks bounded to the north and south by thick sequences of Mesozoic sediments (Tully and Donato, 1985). A NNW–SSE elongated anomaly high overlies the Central graben (D). Anomaly values over the graben range from +25 to +35 mGal. The association of positive anomalies with sedimentary basins is unexpected, but can be explained in terms of the response of the crust to extension and thinning (Watts et al., 1982).

The southwestern edge of the Southern North Sea basin has a distinct NW–SE trend, possibly controlled by the Swartz Bank hinge zone (e). Between the Swartz Bank hinge zone and the Dowsing fault zone positive Bouguer anomalies are observed over the inverted Solepit high. The trend of these structures suggest that their evolution may have been influenced by the speculative NW–SE branch of the Caledonian orogeny which has a similar orientation according to observations in eastern England (Pharaoh et al., 1987).

Although much of western Britain is dominated by NE–SW Caledonian trends, a number of small Permo–Triassic basins produce NW–SE elongated anomaly lows. These basins include the Galloway trough, the Stranraer basin, the Vale of Eden basin, the Dumfries basin, the Lochmaben basin and the Vale of Clwyd graben (F). The eastern margin of the East Irish Sea basin also displays a marked NW–SE trend. A faint lineament trace may connect the anomaly low over the Vale of Clwyd with a similar low southeast of the Isle of Man (g). Another similar lineament can be tentatively identified within the Central Irish Sea basin anomaly low (h). These lineaments define a sub-fabric which strikes roughly perpendicular to the main Caledonide framework. This sub-fabric probably represents a conjugate line of weakness to the main NE–SW tectonic fabric. This sub-fabric is not apparent further west in Ireland where no important NW–SE trending lineaments are imaged.

NW–SE trending lineaments are of particular importance in central and eastern England. This has led to the tentative identification of a NW–SE trending foldbelt associated with the Caledonide orogeny which traverses from northern England across the North Sea to the Ardennes region (Turner, 1949; Evans, 1979; Ziegler, 1982; Pharaoh et al., 1987). The central section of the anomaly low over the Gainsborough gulf displays a strong NW–SE trend (I). The anomaly low is the product of an expanded Millstone grit and possibly Lower Carboniferous sequence (Kent, 1966). The gulf is flanked to the northeast by the NW–SE/WNW–ESE trending Askern–Spital high. This is a high standing, complex anticlinal belt that traverses for 50 km from Askern and Lindholm, near Doncaster, to Spital in north Lincolnshire (Lees and Taitt, 1945).

The NW–SE trend continues southeast from the Gainsborough gulf, via the Nocton high, into two distinct lineaments imaged in East Anglia (j and k). Both of these lineaments run obliquely to the strike of the outcropping chalk strata. In an interpretation of the Devonian sedimentary basins underneath the Mesozoic cover in eastern England, Allsop (1985) stripped off the gravity effects of the Mesozoic cover and removed a regional background. The resulting residual anomaly map did not retain the two imaged lineaments. Therefore, these lineaments may originate from density contrasts associated with the Mesozoic cover. However, the development of these density contrasts may have been influenced by deeper basement structures. The continuity of these NW–SE trending structures indicates that they may be controlled by deep basement fractures associated with the tentative branch of the Caledonian orogeny.

The structure of the east Midlands is strongly influenced by the NW–SE Charnian trend of Precambrian origin. Later Variscan events modified the basement structure to generate a marked horst–graben structure within the English Midlands. A ridge of high anomaly values runs from Derby to Ashby de la Zouch (L). The ridge is approximately 35 km long, 4.5 km wide and strikes at roughly 315° . The anomaly high occurs over the Leicester coalfield block and the uplifted Precambrian basement of Charnwood Forest. The northwestern margin of the Widmerpool gulf anomaly low is deformed by a NW–SE anomaly high traversing southeastwards off the Derbyshire dome high (m).

However, this feature may be related to the NW–SE branch of the Caledonides. A third ridge of relatively high anomaly values is delimited by lineaments (n) and (o). The rhombohedral-shaped anomaly low to the east of this ridge is probably caused by a low density acidic intrusion because a NCB exploration borehole, near Hollowell, Northamptonshire, showed little evidence for a significant thickness of sediments beneath the anomaly low (Allsop et al., 1987).

A series of faint lineaments are just discernable in southeastern England (P). In this region lineaments reflecting basement tectonics may be poorly imaged because of the blanketing effect of the younger Mesozoic and Cainozoic cover.

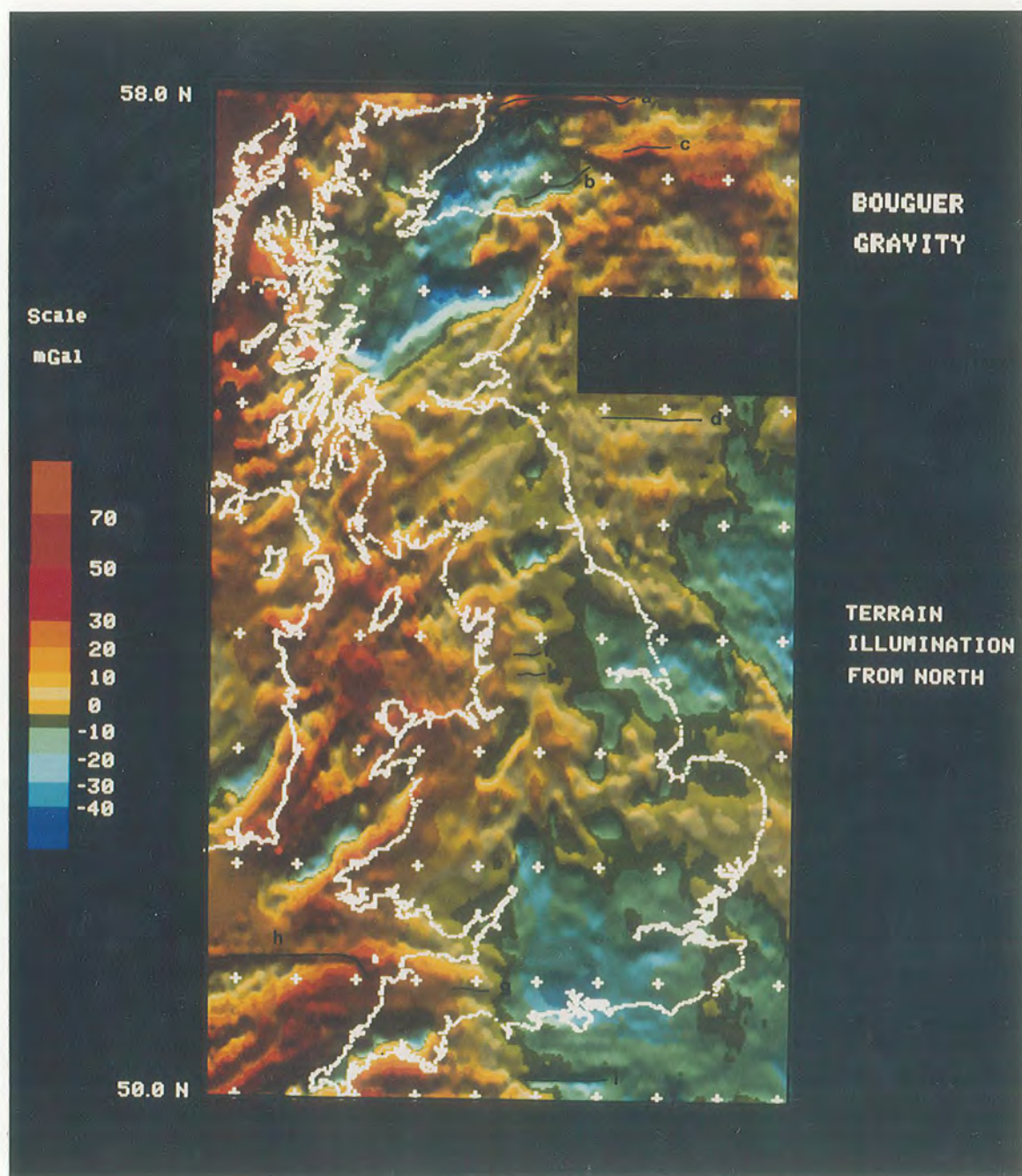
The strong Exmoor anomaly gradient is clearly imaged as a WNW–ESE trending lineament (q). The lineament is imaged traversing from the Pembrokeshire ridge anomaly high to the west–northwest and to the Somerset basin towards the east–southeast.

3.7.3 Northern illumination

The Bouguer gravity digital image with illumination from the north is shown in Plate III. East–west trending structures are not particularly *prevalent* within the tectonic structure of the UK, but some interesting structures are imaged.

The northern margin of the Inner Moray Firth basin anomaly low is defined by a distinct E–W ridge of high Bouguer anomaly values (maximum 44 mGal). This marks the Caithness ridge (a) (Tully and Donato, 1985). To the south, the Banff fault, defined by a steep anomaly gradient north of Fraserburgh, marks the southern margin (b). Both the southern margin of the Halibut horst and the mid North Sea high show evidence of E–W trend (c and d). A possible E–W lineament lies north of the mid North Sea high roughly on the same latitude as the Fife region. The lineament is not shown because of the masking of a region of noisy data. The lineament is of interest though, because from the aeromagnetic map the Southern Upland fault appears to assume an ENE–WSW strike offshore and if this swing in strike were to continue the Southern Upland fault could run into alignment with the E–W lineament. Together with the trend of the mid North Sea high this evidence suggests that the NE–SW Caledonian trend of

Digital image of the Bouguer anomaly gravity of the UK and adjacent regions with terrain illumination from the north



northern England and southern Scotland may swing towards a more E–W trend in the central North Sea province.

Two interesting E–W lineaments are imaged in the central Pennines, north of the Derbyshire Dome (e and f). Towards the southeast, the northwestern section of the Gainsborough gulf low assumes a more E–W trend also. The geology of the Dinantian of the central Pennines consists of a series of *asymmetrical* half graben controlled by E–W trending faults (Lee, 1988). The basement comprises a series of tilted fault blocks with downthrow to the north. The two lineaments lie on either side of a region of relatively high Bouguer anomaly values possibly associated with a basement high such as the central Pennine high (Gawthorpe, 1987).

Further lineaments are imaged in southern England, the English Channel and the SW Approaches. A strong anomaly gradient is observed where low density Permo–Triassic sediments abut against the Devonian basement of the Quantock Hills region (g). A very striking lineament is imaged traversing westwards from the Isle of Lundy, along the northern margin of the South Celtic Sea graben (h). The anomaly gradient across this lineament is in excess of 2.6 mGal km^{-1} in places. Towards the west the lineament trends slightly towards the WSW. Towards the east the lineament appears to divert into a NW–SE trend. The NW–SE trend delimits the southwestern margin of a ridge of high Bouguer anomaly values which traverses across the Bristol Channel from the Isle of Lundy to Pembroke.

In the central English Channel a distinct E–W lineament marks the mid–Wight axis (i). The axis comprises a monoclinical downturn to the south (Smith and Curry, 1975). Similar faint E–W lineaments are imaged further north in the northern channel. These E–W trending features may represent Variscan basement structures reactivated by later Alpine movements, in particular the Helvetic (Oligocene–early Miocene) phase (Dewey, 1982).

3.7.4 Western illumination

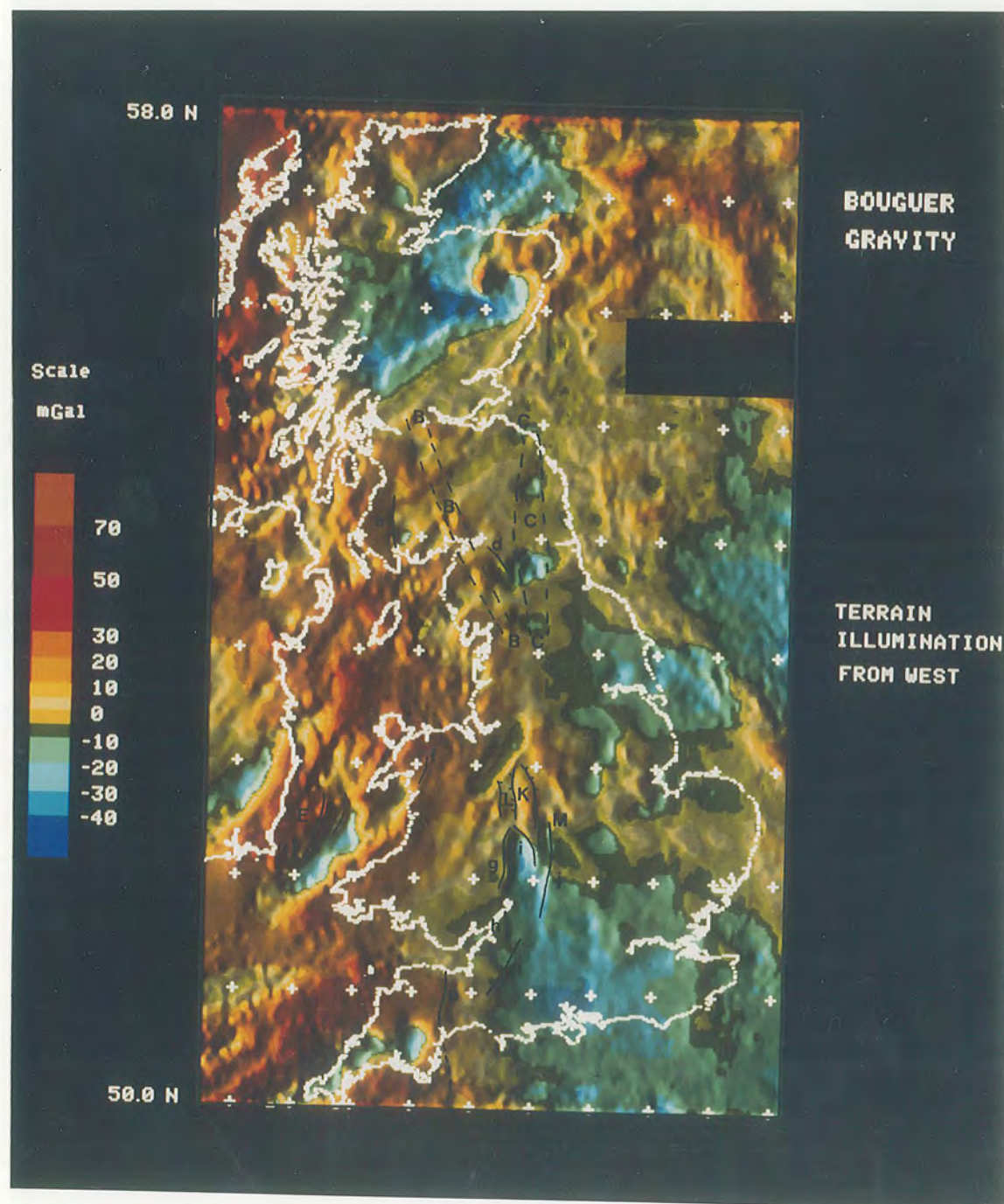
Plate IV displays the digital Bouguer gravity terrain illuminated from the western aspect. The NE–SW trending Bouguer anomaly low over the northern part of the Southern Uplands is terminated abruptly by a N–S lineament traversing the western flank of the Loch Doon granite (a). The lineament is defined by a steep W–E anomaly gradient (approximately 2.9 mGal km^{-1}). Further west the anomaly gradient reduces to roughly 0.8 mGal km^{-1} over the Girvan district. The anomalies over the region between Girvan and Luce Bay are unusually high ($> +20 \text{ mGal}$). Hipkin and Hussain (1983) suggested that the high Bouguer anomaly values reflect the presence of a basic mass at depth, but the anomalies may also be interpreted as a northward continuation of the high anomaly values observed over the Irish Sea.

A curious NNW–SSE lineament, running from the central Midland Valley to Lancashire is formed by the alignment of four individual anomaly minima (B). The origin of the individual anomaly lows have been interpreted as

- (1) a possible acidic intrusion southeast of Hamilton (Davidson et al., 1984);
- (2) the low density Permo-Trias sediments within the Lochmaben basin (Bott and Masson-Smith, 1960);
- (3) the Skiddaw granite (Bott, 1974);
- (4) Permo-Trias and Coal Measure basin sediments within Lower Carboniferous and Namurian strata near High Bentham, Lancashire.

The Skiddaw granite is of late Caledonian origin (Rundle, 1981) and presumably the Hamilton intrusion is of a similar age. The basins are much later Upper Palaeozoic/Mesozoic structures. Therefore, the alignment of anomaly lows may be purely coincidental. However, if not, the lineament may reflect a major weakness within the crust. It is also of interest to note that the anomaly lows associated with the Cheviot, Weardale and Wensleydale granites are aligned to form a N–S chain of lows (C). A fourth aligned low in the Southern Uplands may be caused by a continuation of the Tweeddale batholith but the Bouguer anomalies are complicated by the presence of Devonian sedimentary basins at Lauderdale, near Oldhamstocks and Eyemouth (Lagois

Digital image of the Bouguer anomaly gravity of the UK and adjacent regions with terrain illumination from the west



and Hipkin, 1979).

The Pennine Fault is clearly imaged along the northeastern margin of the Vale of Eden basin (d). A complex series of lineaments are imaged along the western margin of the St. George's Channel anomaly low (E). These appear to be related to the complex anomaly gradients along the western edge of the basin and local anomaly highs over uplifted basement. The complexity of the gradients may be the result of the migration of salt deposits from the centre of the basin towards the basin flanks (Dimitropoulos and Donato, 1983).

In northern Wales a distinct lineament is imaged trending NNE–SSW (f). This lineament intersects the Bala fault lineament near Tywyn. The origin of the lineament is complex. Within the Bouguer gravity field it appears to lie along a saddle between the low over the Tremadoc sub-basin and a region of low anomalies in central north Wales. The surface geology indicates that the lineament traverses the southeastern margin of the Cambrian rocks of the Harlech dome.

The most significant N–S tectonic structures are those associated with the Malvern axis. The axis itself is imaged as a sinuous N–S lineament traversing along the western margin of the Permo–Trias sediments of the Worcester graben (g). The W–E gradient of the western margin of the basin is roughly 6.4 mGal km^{-1} . Further south the Malvern line continues along the Bath axis (h). The Malvern axis has experienced a complex history of tectonic activity. Thrusting over the axis occurred in the early Palaeozoic and the Upper Palaeozoic and the axis was reactivated as an extensional fault in Permo–Trias times (Beckinsale et al., 1986).

The eastern boundary of the Worcester graben is marked by a strong E–W gradient of approximately 1.4 mGal km^{-1} (i). The curvilinear, roughly N–S trending lineament (j) may delimit the eastern boundary of the Malvernian trend in central England.

Further north Malvernian trends control the South Staffordshire coalfield block (K) and the Stafford graben (L). The intense anomaly low between the Birmingham fault and the Western Boundary fault of the Warwick coalfield (M) is formed by a downfaulted wedge of Coal Measures (Cook et al., 1951). The Coal Measures were

estimated to be roughly 1200 m thick and the top of the wedge to be at a depth of approximately 300 m.

The curvilinear lineament (n) may define the western edge of the Mesozoic/Cainozoic Wessex basin. A distinct lineament is imaged where the Mesozoic strata of Devon, Somerset and Dorset abut against the older Upper Palaeozoic massif of southwestern England (o). This lineament traverses from Watchett to Exmouth. A faint continuation of the lineament is imaged to the south traversing across the English Channel.

3.7.5 The Laplacian of the Bouguer gravity data

Plate V is a monochrome digital image of the Laplacian of the Bouguer gravity. The Laplacian of the Bouguer gravity is effectively a map of the second vertical derivative of the Bouguer gravity determined using a wide grid spacing. The Laplacian operator is isotropic. Therefore, this digital image summarizes the major features imaged in the preceding four digital images.

In northern and central Scotland several of the important NNE–SSW lineaments are observed:

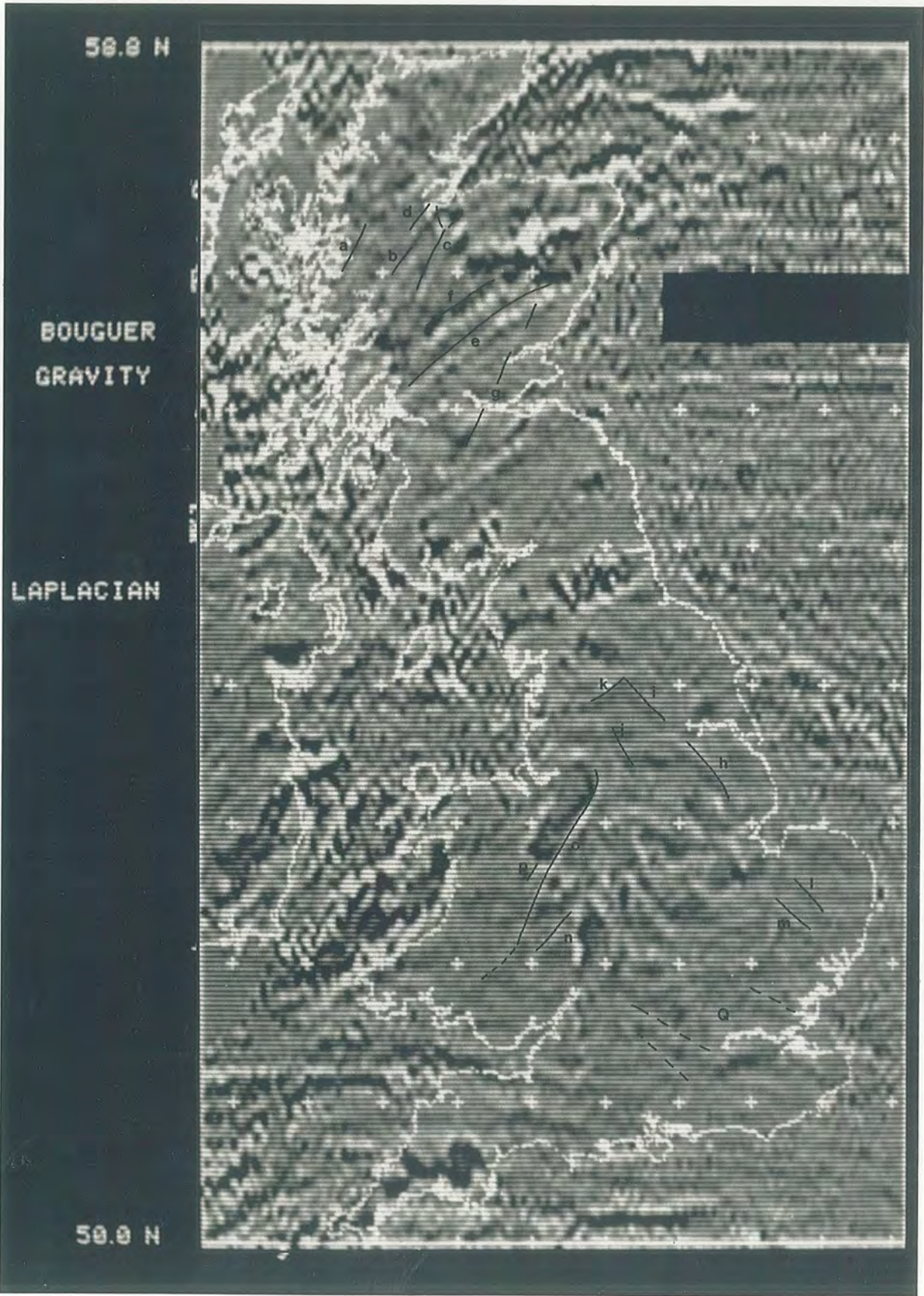
- (1) the Sgurr Beag slide lineament (a);
- (2) the NNE–SSW lineament east–southeast of the Great Glen fault (b);
- (3) the Loch na h'Erba fault lineament (c).

The Great Glen fault is slightly more clearly imaged than before (d). The Highland Boundary fracture zone is clearly imaged (e), as is the sharp anomaly gradient over the southeastern boundary of the major anomaly low over the Grampian Highlands (f). A faint, curling lineament traverses the southern margin of the Hamilton anomaly low, crossing the Devonian andesites of the eastern Midland Valley and passing along the northern edge of the andesites near the Highland Boundary fracture zone (g). The southwestern section of this lineament, south of the Firth of Forth, may follow the course of a NE–SW trending Caledonian anticlinal axis, possibly reactivated during the Variscan orogeny (Anderson, 1978).

The lineaments imaged within the Southern Uplands and northern England correlate closely with those previously described.

Plate V

Monochrome digital image of the Laplacian of the Bouguer
anomaly gravity of the UK and adjacent regions



The most interesting lineaments imaged are located in central and eastern England. The Askern–Spital high is clearly defined (h). Northwest of this high, a second lineament is clearly imaged running NW–SE for approximately 40 km (i). This lineament terminates close to Ilkley. Close examination of the Humber and Trent 1:250,000 Bouguer anomaly map (I. G. S. , 1977) indicates that the imaged gradient slopes from southwest (+ve) to northeast (-ve). Therefore, although the regional gravity anomaly values are slightly negative it is unlikely that the second lineament defines the northeastern edge of a continuation of the expanded gulf facies sediments in the Gainsborough gulf. Instead, the Askern spur may broaden to the west, north of the Don monocline producing an uplifted basement with respect to the Gainsborough gulf. This explains the continuation of the W–E gradient off the eastern edge of the Askern–Spital high.

These two lineaments partially define an anomalous NW–SE trending zone also bounded by the Derbyshire dome to the west (j) and a steep NW–SE gradient to the northwest (k). Towards the southeast, the two NW–SE trending lineaments imaged in East Anglia may form a continuation of this trend (l and m).

This group of lineaments may form an important tectonic feature in eastern and central England. This is probably associated with the NW–SE trending branch of the Caledonides. An important belt of magnetic anomaly highs can be traced across northwestern and eastern England from the southern part of the English Lake District to East Anglia. Local anomaly maxima are measured at Ingleton, Bateley Bridge, Holme upon Spalding Moor, Scunthorpe and Market Rasen. This belt of magnetic anomaly maxima runs only slightly to the northeast of the anomalous gravity zone.

The tectonic history of this feature must be complex because it is characterized by both basement subsidence and presumed basement highs. Along the length of this feature the subsidiary structural trends vary. In the northwestern section, around Sheffield, E–W structures are faintly imaged. Further southeast NW–SE and NNW–SSE lineaments are more important. The strike of these subsidiary structural features may have affected the reactivation of this zone by later compressional phases, such as that associated with the Variscan orogeny.

Numerous lineaments are imaged in central England but these are more clearly defined in the earlier digital images. However, several important Caledonian NE–SW trending lineaments are displayed. The NE–SW trending lineament which intersects the Malvern axis near Kidderminster is clearly imaged (n). The east–southeast margin of the Cheshire basin and its south–southwest extension are also very clear (o). There is a slight indication that this lineament curls towards the southwest in south Wales. In contrast to the earlier digital images, the Pontesford–Linley fault can be detected (p).

Southeastern England displays several faint NW–SE lineaments which may be useful for defining tectonic domains (Q).

3.8 Lineament interpretation

The most effective method of interpreting the imaged lineaments is to consider their orientations and patterns in terms of the tectonic evolution of the UK region. The lineament patterns can be studied at various scales, from local studies to regional interpretations. I shall first discuss the lineament patterns within northern and central Scotland, and central England and then look at the UK region as a whole. Plates VI and VII display simple grey level shaded relief digital images of the Bouguer gravity illuminated from the northwest and northeast respectively. These digital images summarize most of the important lineaments required for this study.

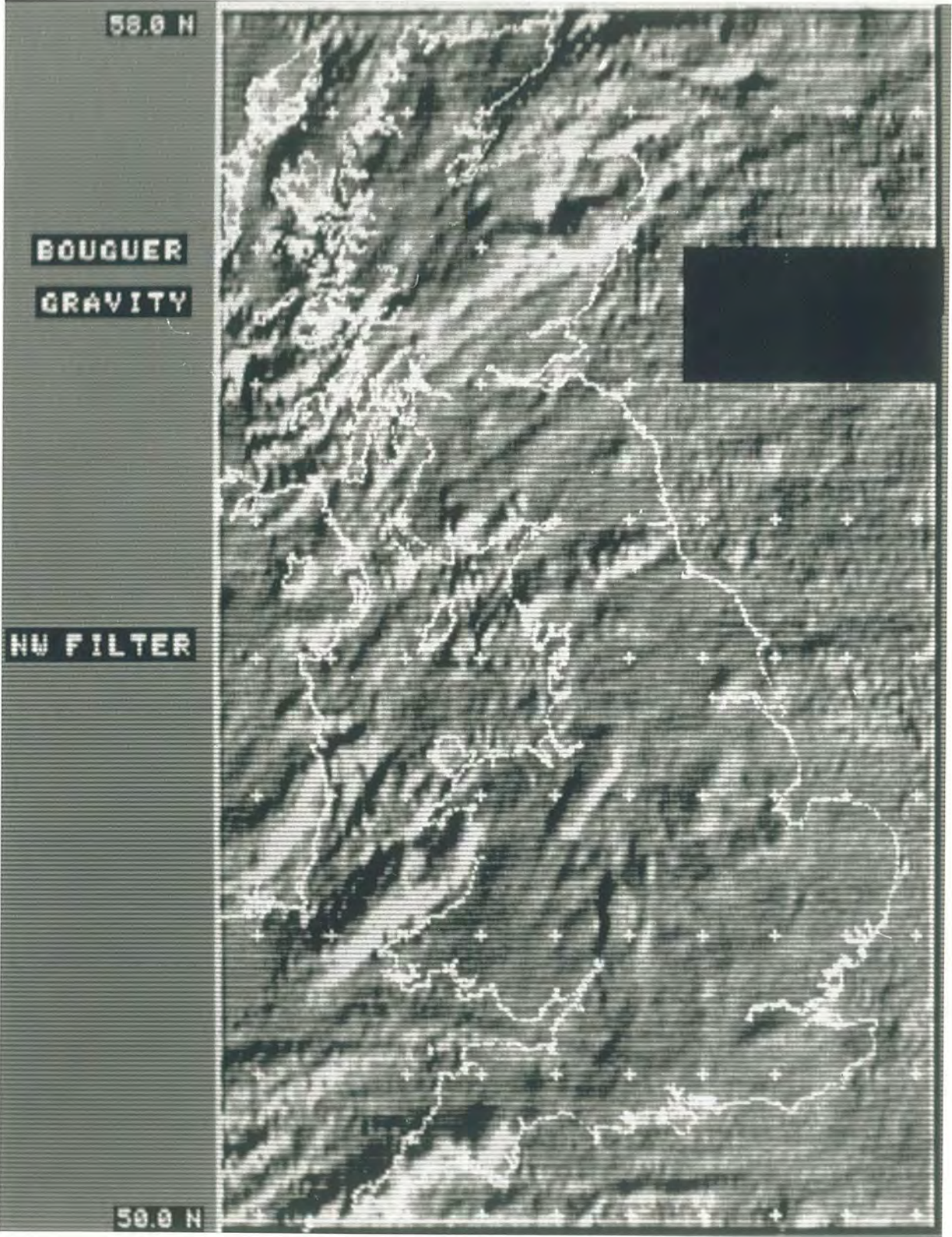
3.8.1 Northern and central Scotland

The Grampian Highlands are bounded to the southeast by the Highland Boundary fracture zone. The fracture zone forms a major lineament or alignment, separating two tectonically distinct regions. On land the fault zone separates the Grampian Highlands, characterized by NNE–SSW lineament orientations, from the Midland Valley which displays few strong lineaments, but is bounded by major NE–SW trending faults. In the North Sea region the fault separates two markedly different tectonic terrains with the northwestern terrain appearing to comprise a shallower basement.

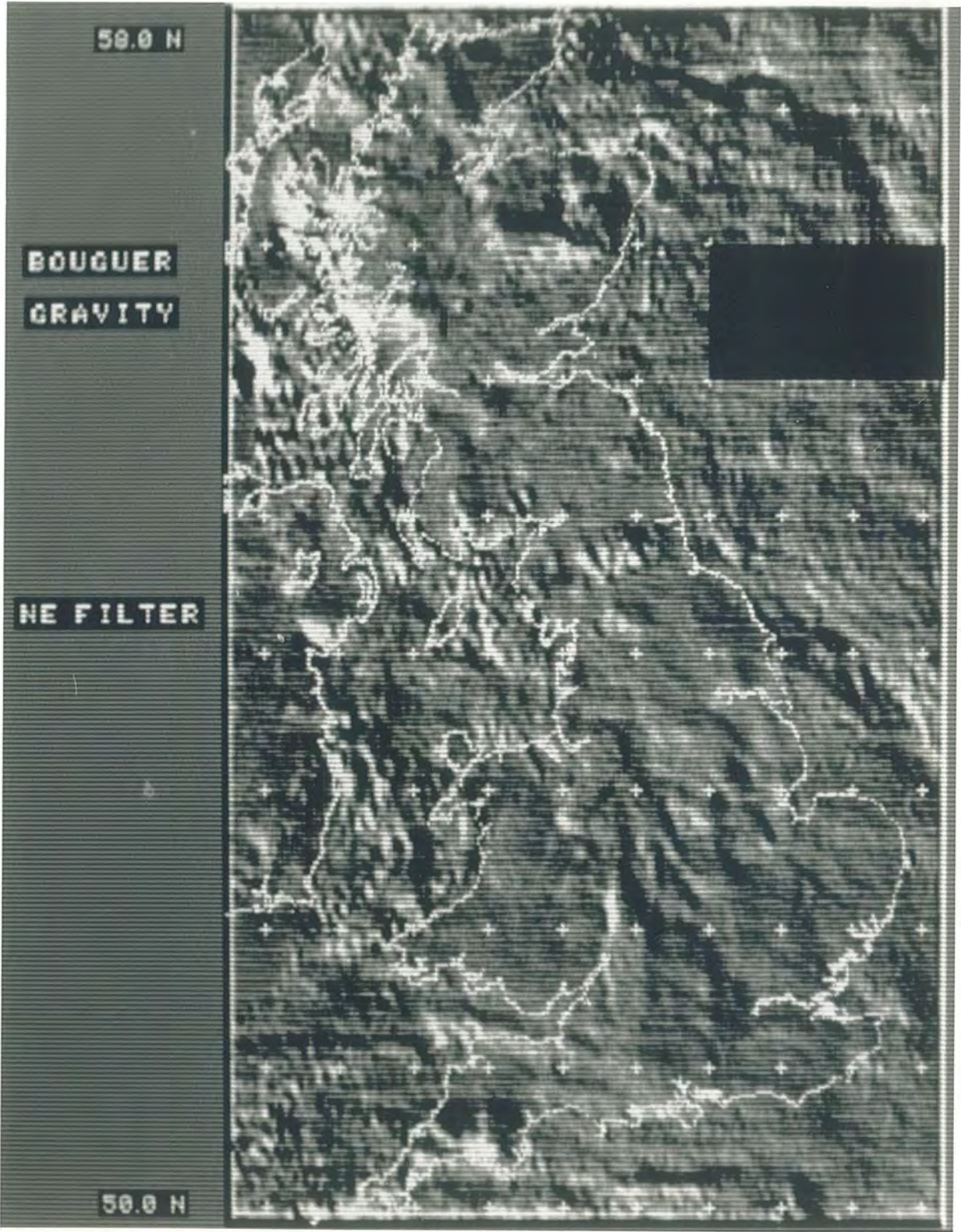
The digital image data suggests that the fracture zone has been a very significant tectonic boundary in the northern UK region. The lineament must have had an impor-

Plate VI

Monochrome shaded relief digital image of the Bouguer gravity of the UK
and adjacent regions with terrain illumination from the northwest



Monochrome shaded relief digital image of the Bouguer gravity of the UK
and adjacent regions with terrain illumination from the northeast



tant influence on the evolution of the North Sea basins because the fracture zone can clearly be seen to intersect the trilete junction of the three main sedimentary basins of the North Sea namely the Central graben, the Viking graben, and the Outer Moray Firth basin. Towards the northeast, the fracture zone continues along the Ling graben alignment (Doré and Gage, 1987).

The Bouguer anomalies of the Grampian Highlands and the southern section of the Northwestern Highlands can be split into two distinct provinces. The northwestern region of the Grampian Highlands and the southern region of the Northwestern Highlands are characterized by a broad region of negative Bouguer anomalies with low amplitude local variations. The anomaly values range between 0 and -20 mGal. The three imaged NNE–SSW trending lineaments of central Scotland are associated with this region.

The second region comprises the belt of negative, large amplitude Bouguer anomalies traversing from the Loch Etive–Moor of Rannoch granites to the Aberdeenshire granites. The origin of the central section of this belt of low Bouguer anomalies is controversial and was discussed in detail in section 3.6.5.

The contrasting patterns of the Bouguer anomalies of the two regions correlates with the differing ages of the granitic intrusions. The region of low relief anomalies correlates with the outcrop of the late orogenic granites of the Caledonides which are the pre–Silurian granites of Brown and Locke (1979). These granites appear to produce only small residual gravity and magnetic anomalies (Brown and Locke, 1979) but these may represent local variation in the roof or density of a deep extending granitic basement. Isotopic and trace element data indicates that much of this granitic material was produced by the partial melting of the crust (Watson, 1984). Watson (1984) estimated the age of the late orogenic granites to be in the region of 435 to 405 Ma.

The distribution of the post–orogenic granites which are the Siluro–Devonian granites of Brown and Locke (1979) corresponds with the region of intensely negative Bouguer anomalies of the Grampian Highlands. The post–orogenic granites comprise large volumes of low density material. Most of the intrusions are also associated with

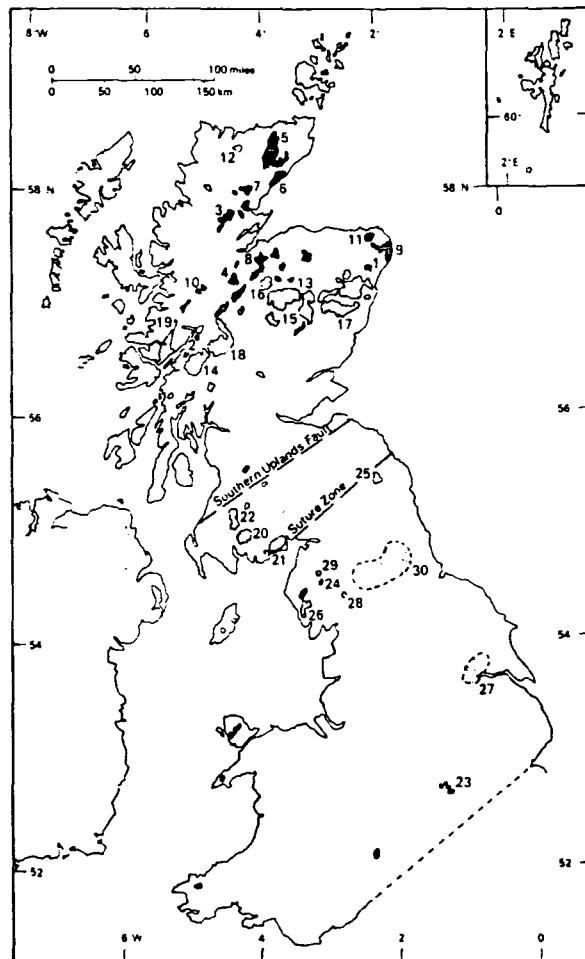
significant magnetic anomalies (650 γ over Etive and 250 γ over the Monadhliath granite) that contain components with wavelengths in the region of 10–20 km suggesting a deep source possibly associated with metamorphic effects in the basement around the root zones of the granites (Brown and Locke, 1979). Simpson et al. (1979) suggested that the post orogenic granites comprise a significant component of juvenile origin. The age of the post orogenic granites ranges between 415 and 400 Ma (Watson, 1984). The distribution of the two granite groups is shown in figure 3.6. Two exceptions to this classification are the late orogenic Moy granite, east of Inverness, which is associated with a Bouguer anomaly *minimum* of -34 mGal and the post orogenic Strontian granite which is marked by a Bouguer anomaly *minimum* of only -20 mGal (Brown and Locke, 1979).

Within the area intruded by the late orogenic granites the NNE–SSW lineaments may represent variations in depth to the concealed granitic material or variations in density of the granite. The possible structures of the density contrasts capable of producing the observed gravity lineaments and their relationships to earlier basement fractures are shown in figure 3.7. The correlation between possible changes in the density of the intrusive material and the basement fractures is speculative. The density contrast between the granitic material and the metamorphic basement is difficult to estimate owing to the variable compositions of the granites at outcrop and the diffuse contacts (Brown and Locke, 1979) but the average density contrast is likely to lie between -80 and -160 kg m^{-3} . Assuming a regional background of roughly $+10$ mGal which may be an underestimate, the broad NE–SW elongated anomaly low directly northwest of the Great Glen fault comprising the Strontian granite low and the region to the northeast has an anomaly amplitude of approximately -28 mGal. The most plausible cause of this region of negative anomalies is a widespread granitic basement because the LISP seismic refraction profile (Bamford et al., 1978) showed little evidence for an anomalously thick crust. Using the density contrasts given above, the slab formula predicts that the minimum thickness of granite required to produce the observed anomalies varies from 4.175 to 8.35 km. The broad NNE–SSW trending lineament

Figure 3.6. The location of the Caledonian granite complexes of Great Britain.

Group 1: Black. The pre-Silurian group of Brown and Locke (1979)—includes the late orogenic granites of Scotland.

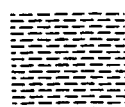
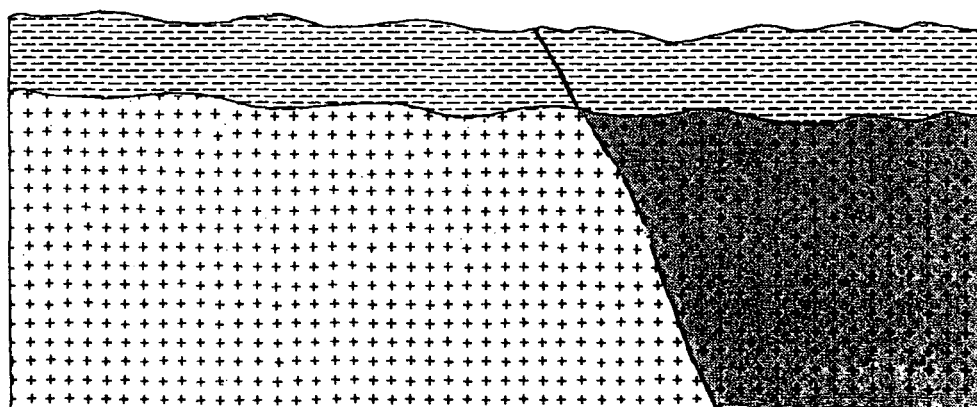
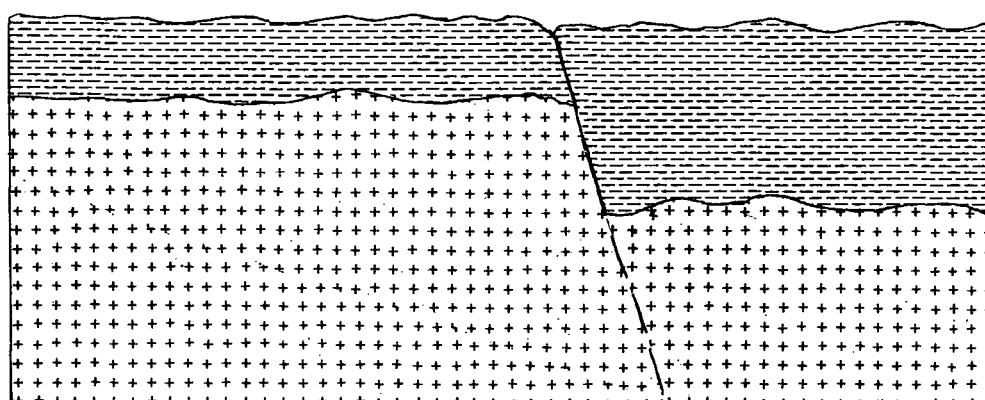
Group 2: Shaded. The Siluro-Devonian group of Brown and Locke (1979)—includes the post orogenic granites of Scotland.



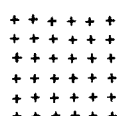
Identification of complexes: 1 = Ardlethan; 2 = Ballachulish; 3 = Carn Chuinneag; 4 = Foyers; 5 = Halladale; 6 = Helmsdale; 7 = Lairg-Rogart; 8 = Moy; 9 = Peterhead; 10 = Ratagain; 11 = Strichen; 12 = Ben Loyal; 13 = Cairngorm; 14 = Etive; 15 = Lochnagar; 16 = Monadhliath; 17 = Mount Battock; 18 = Rannock Moor; 19 = Strontian; 20 = Cairnsmore of Fleet; 21 = Criffell; 22 = Loch Doon; 23 = Mount Sorrel; 24 = Threlkeld; 25 = Cheviot; 26 = Eskdale; 27 = Market Weighton; 28 = Shap; 29 = Skiddaw; 30 = Weardale.

Diagram taken from Brown and Locke (1979)

Figure 3.7. Diagram of the speculative associations between basement fractures and intrusive granite complexes which could generate some of the Bouguer anomaly lineaments observed in the southern Northwestern Highlands and the northern Grampian Highlands. (a) Relationship between an early basement weakness and the topography of the roof of an intrusive complex. (b) Tentative correlation between the location of an early basement weakness and a change in the density of an intrusive complex.



Caledonian basement rocks



Intrusive complex



Intrusive material of a lower or greater density
than the average for the complex

which lies directly southeast of the Great Glen fault has a residual positive anomaly of roughly 10 mGal with respect to the low anomaly values to the northwest. If this residual anomaly is the product of a variation in the depth to the roof of an extensive granitic basement alone, the slab formula predicts that the minimum topography of the roof of the granite required to produce the anomaly is 1.5 km.

The *correspondence* between the strike of the lineaments and the general tectonic fabric of the region suggests that local tectonic structures may have partially influenced the intrusion of the granite. However, it is difficult to be certain whether the NE–SW trending Great Glen shear field was active at the time of the intrusion of the late orogenic granites or if the shear occurred afterwards exploiting earlier weaknesses within the basement.

The relationship between the post-orogenic granites and the tectonic framework of the Grampian Highlands is less certain. Watson (1984) observed that the E–W elongated suite of granites that includes the Monadhliath, Cairngorm and Lochnagar complexes lies along the E–W axis of the Moine/Dalradian boundary sigmoid. The E–W trend might then reflect a conjugate shear set to the NE–SW Great Glen shear field. However, the intrusion of the eastern complexes may have been influenced by the location of the mafic intrusions of the NE Highlands which are located directly to the north of the complexes. The mafic intrusions known as the Younger gabbros predate the main period of post orogenic granite intrusion and may have provided an obstacle to the high level emplacement of the granites. The Inch massif has been dated at 489 ± 17 Ma by a Rb–Sr whole rock isochron (Pankhurst, 1970). This roughly corresponds to the main Dalradian orogenic climax in the Grampians at 490 Ma (Watson, 1984).

The Buchan block is effectively decoupled from the Dalradian of central Scotland by a set of major lineaments, or shear zones (Ashcroft et al., 1984). These shear zones are orientated roughly NNE–SSW, N–S and E–W and are often marked by steep gravity anomaly gradients between the block and the surrounding anomaly minima over granite intrusions. Shear zones of particular importance are the Portsoy–Morven lineament, which forms the western margin of the block, a complementary lineament traversing

from Fraserburgh to Old Meldrum, forming the eastern boundary of the block, and the E-W southern margin of the Inch massif which separates the block from the region of granitic intrusion to the south (figure 3.8). The Portsoy-Morven lineament has a similar NNE-SSW trend to the lineaments of central Scotland and may represent a continuation of the tectonic fabric further east. A major shearing event effected the lineaments around 481 ± 15 Ma (Ashcroft et al., 1984). The anomalous nature of the block may explain the formation of the Moine/Dalradian sigmoid, which wraps around the southwestern margin of the block.

The lineaments of northern and central Scotland and the western North Sea, the Highland Boundary fracture zone, the Great Glen fault and the NW-SE trending southwestern margin of the Halibut horst appear to form a geometrically complex set of crustal blocks separated by marked lineaments. Differential movements between the various blocks may have exerted a profound influence on the evolution of the region, especially the subsidence and basin formation beneath the Inner Moray Firth.

The offshore continuation of the Caledonide fault trends of central Scotland has exerted a significant control over the Mesozoic/Cainozoic development of the sedimentary basins within the North Sea region (Threlfall, 1981; Johnson and Dingwall, 1981).

3.8.2 Central England and Wales

In contrast to central Scotland, central England and Wales are characterized by three main structural trends: NE-SW, NW-SE and N-S. These trends are clearly shown in figure 3.9 which displays all of the major lineament traces revealed in the four shaded relief digital images. The NE-SW, NNE-SSW structures include the Cheshire basin, the Church Stretton disturbance and the Pontesford lineament. Towards the southwest these lineaments appear to swing in trend towards the west.

Eastern England and the central Pennines are characterized by a complex series of NW-SE trending structures. Of particular importance are the Leeds-Askern-Spital lineaments and the two lineaments in East Anglia. Similarly trending structures are common in the southwestern North Sea, notably the *Solepit* high. Towards the southeast a slight tendency for these lineaments to swing towards the east is observed. Further

Figure 3.8. Location of the major shear zones in northeastern Scotland

Ab = Aberdeen; C = Collieston; E = Ellon; Fr = Fraserburgh; H = Huntly; I = Inch;
O = Oldmeldrum; P = Portsoy; Ph = Peterhead; T = Turrif.

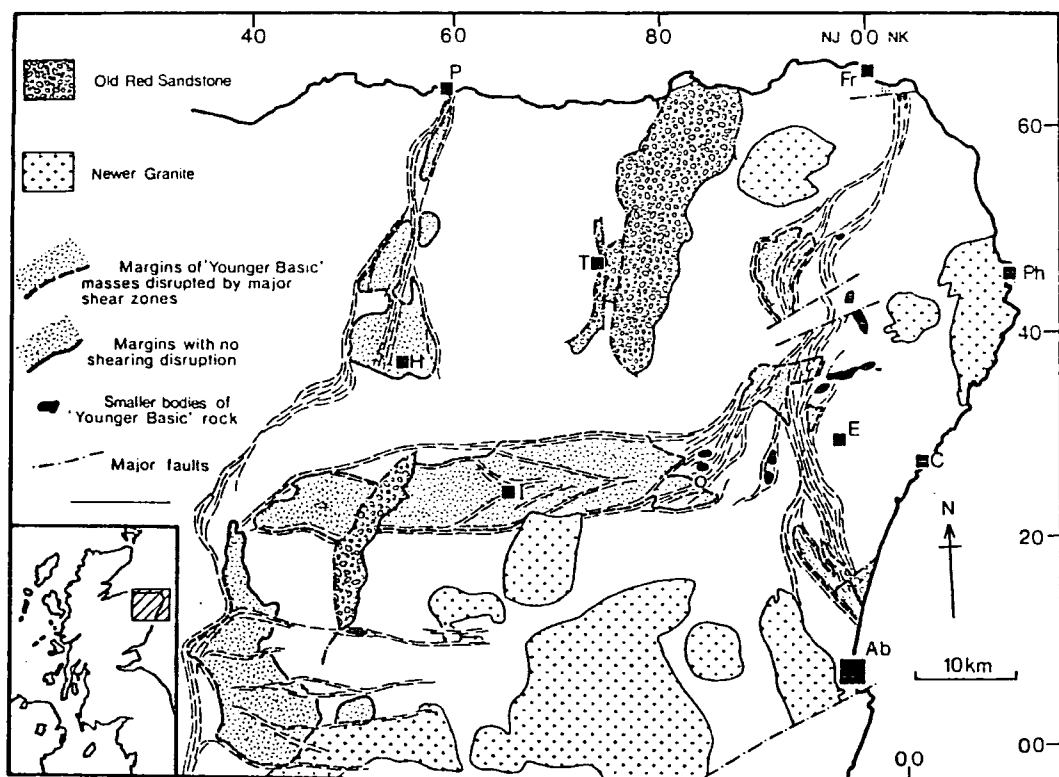
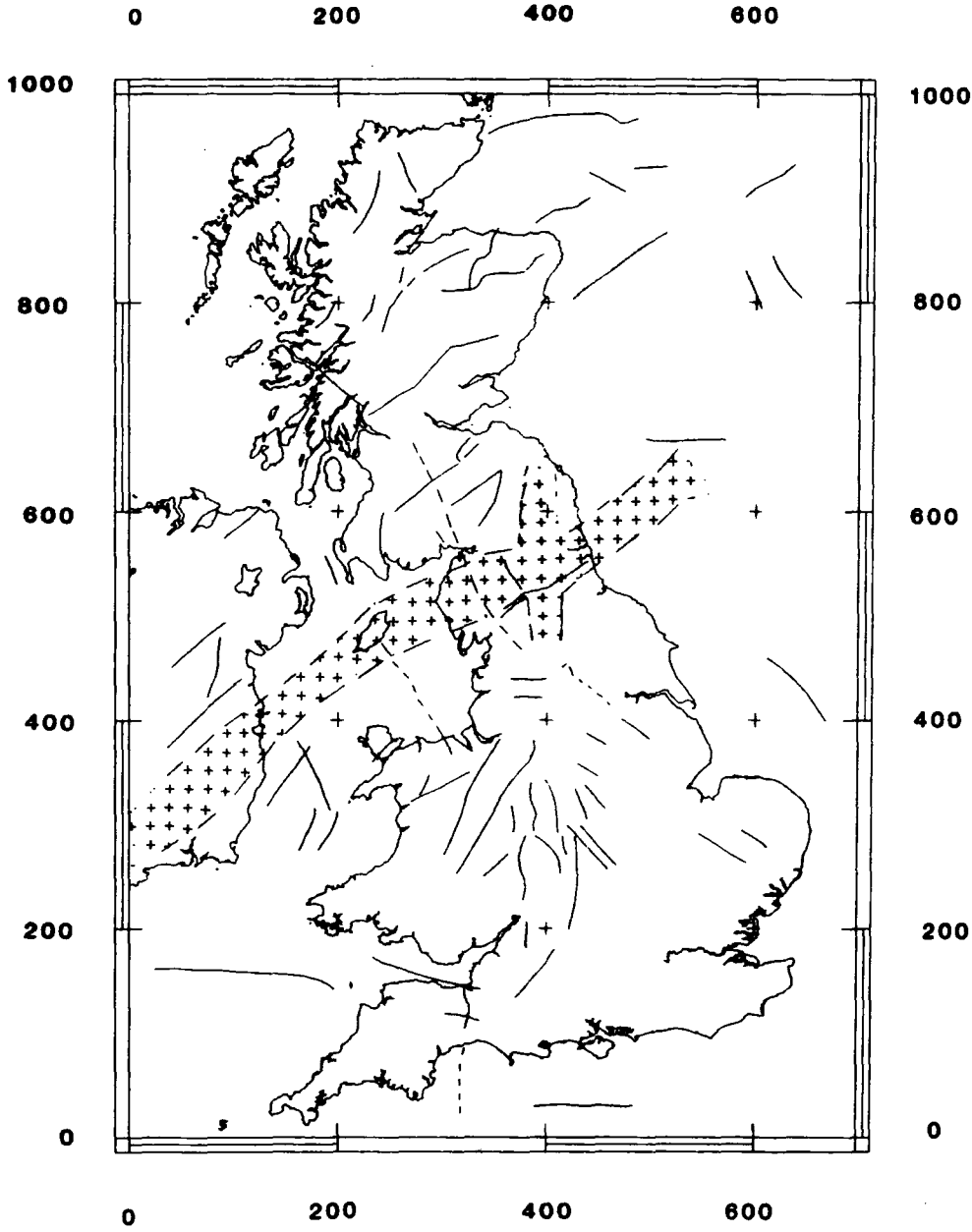


Diagram taken from Ashcroft et al. (1984)

Figure 3.9. Map of the major lineaments observed on the digital images of the Bouguer anomaly gravity of the UK and adjacent regions. The scale is approximately 1:7,000,000 and the border annotation denotes Ordnance survey grid coordinates in km.



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Location of the major chains of known granitic intrusive activity
in the central British Isles

east a major NW–SE tectonic lineament, the Tornquist line, marks the southwestern margin of the Fennoscandian–Russian platform (Pegrum, 1984). The Tornquist line, which extends from the Black Sea coast of Rumania to the line of the Oslo graben, has experienced a complex history of tectonic activity including dip slip and strike slip faulting. The influence of this lineament may extend into the central North Sea region.

In the central Pennines, around Oldham and Holmfirth, several faint E–W trending lineaments are imaged. Similarly E–W trending anomalies are observed in the aeromagnetic map. In particular an E–W elongated aeromagnetic anomaly high (approximate maximum $+110\gamma$) runs from Holmfirth to Manchester, where the anomaly trend swings N–S.

The broad pattern of lineaments corresponds to an inverted ‘V’ shape, with the two dominant Caledonian trends of central Britain forming the two arms. This form of the Caledonides was first observed by Turner (1949). The pattern also agrees well with the suggestion of Soper et al. (1987) that the Midland microcraton acted as a rigid indenter, during the accretion of the southern British terrane onto the newly formed Laurentia–Baltica margin at the end of the Caledonian orogeny. Soper et al. (1987) proposed this model after a study of the systematic variation in cleavage/fold transection angles in the paratectonic Caledonian slate belt of the English Lake District. This work suggested that the observed transection angles were the result of transpressive strains in the slate belt associated with the northward movement of the Midlands massif. The time of the collision with Laurentia and Baltica was considered to be of early Devonian age, climaxing in the Emsian. The compressive forces generated by the collision may have influenced the change from across strike shortening to sinistral shear activity in the orthotectonic Caledonides of Scotland.

Separate evidence supporting the indenter hypothesis was proposed by Pharaoh et al. (1987) who showed that concealed felsic volcanic rocks within the Lower Palaeozoic succession of eastern England are petrologically and geochemically dissimilar to felsic volcanics concealed within the Precambrian Charnian igneous suite of Leicestershire. The concealed felsic volcanics of the Lower Palaeozoic of eastern England are considered

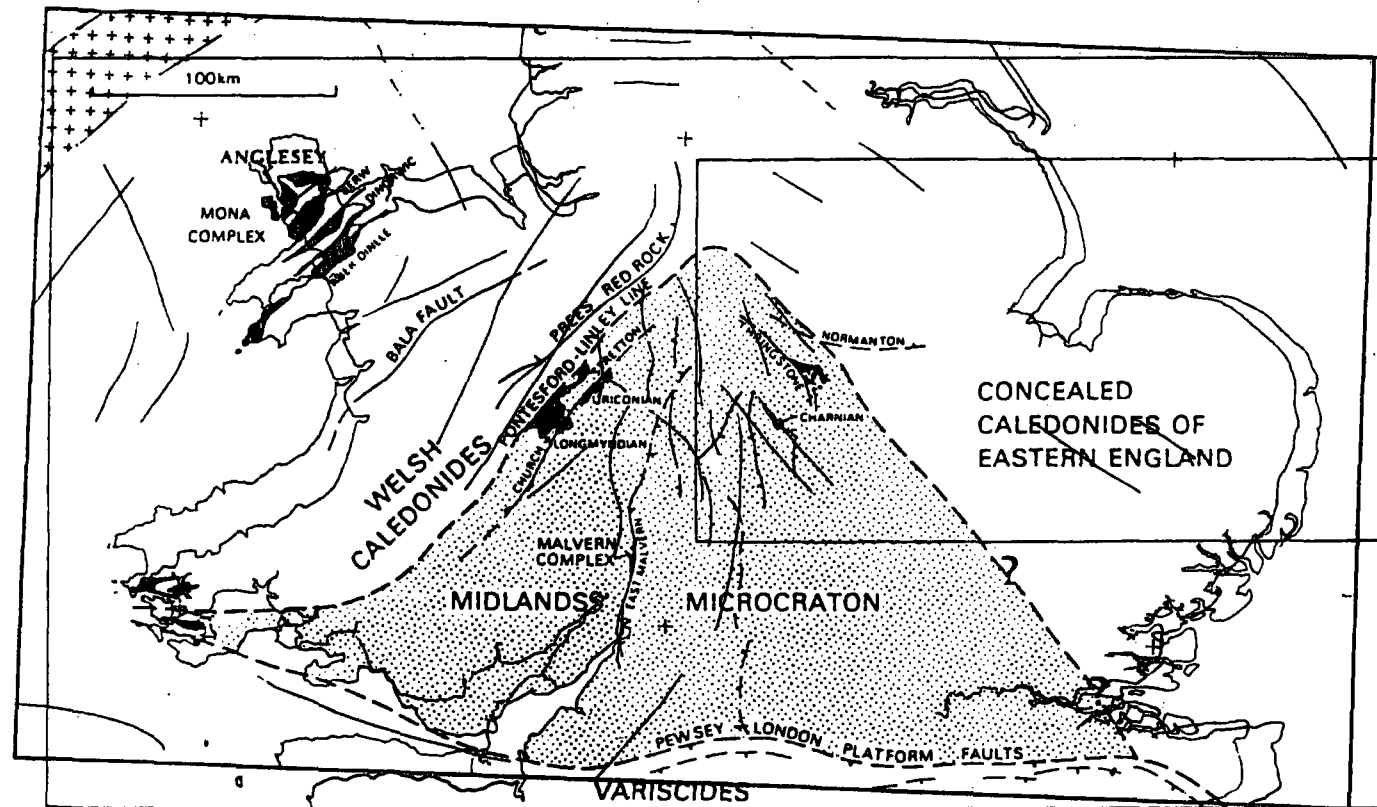
to be of late Ordovician age and probably form a stratigraphic unit or units within the Lower Palaeozoic sedimentary sequence. Pharaoh et al. (1987) concluded that much of eastern England is underlain by a concealed NW–SE trending Caledonian deformation belt, similar in form but not in orientation to that exposed in Wales.

The position of the eastern edge of the Midlands microcraton is still uncertain. Pharaoh et al. (1987) locate the edge as in figure 3.10 traversing from central England to the Thames estuary. If this location of the eastern edge of the microcraton is correct the overlay map of the imaged lineaments shows that the anomalous NW–SE trending structure comprising the Gainsborough gulf complex and the two lineaments in East Anglia lies within the proposed NW–SE trending foldbelt of the Caledonides. The tectonic evolution of this anomalous zone may then be the result of underlying weaknesses in the basement associated with the Caledonian orogeny. A similar situation occurs to the west of the microcraton where the NNE–SSW trending Church Stretton fault of Caledonian origin has influenced the development of the Permo–Triassic Cheshire basin.

The internal structure of the microcraton is fairly complex. The overlay lineament map of figure 3.10 shows that the lineaments of Charnian and Malvernian trend occur only within the proposed extent of the microcraton. The similar orientation of the Charnian trend and the eastern branch of the Caledonides may be merely coincidental but similar relationships between foldbelts of differing ages are observed elsewhere in the world. For example, the Acadian and Alleghenian deformation belts of North America. Therefore, the similarity between the Charnian trend and that of the NW–SE Caledonian foldbelt maybe a result of the cyclic opening and closure of the Iapetus ocean.

There is a further possible NE–SW trend in southwest Wales. Plate VI shows the dominant zone of Malvernian trends extending from the western boundary fault of the Warwickshire coalfield to the Malvern axis. As discussed earlier the Malvern axis has experienced a complex tectonic history with at least two main phases of compressional activity. The axis was reactivated as a tensional feature in Permo–Trias times. The

Figure 3.10. Comparison between the observed Bouguer anomaly lineaments and the proposed subsurface geometry of the Midlands microcraton 'indenter'



Base diagram taken from Pharaoh et al. (1987)

NNW–SSE offset of the major extensional features, the Stafford graben, the Worcester basin and the basin near Cheltenham, indicates a regional dextral transtension. This may be the result of a NW–SE orientated stress field as suggested by Chadwick (1985). This stress orientation can also explain the reactivation of Variscan structures in the Wessex basin (Chadwick, 1986).

3.9 Regional overview

The inter–relationships between the tectonic domains of the UK and the North Sea can be determined from plates VIII, IX, X and XI. These digital images are based on a 7×7 km grid of Bouguer anomaly estimates covering the region defined by the OSGB national grid coordinates 0.0, 805.0, 0.0, 994.0 km. The digital images were developed from the most recent data compilation displayed in figures 2.1, 2.2 and 2.3. The shaded relief effect was produced using a series of Prewitt edge masks, as described in section 3.2.

The imaged lineament patterns can be used to divide the region into a set of sub–domains, separated by major lineaments. There are six sub–domains defined as follows

- (1) The region northwest of the Highland Boundary fracture zone: this may be further subdivided into:
 - (1.1) the Caledonian foreland (n.b. the Outer Isles thrust is also imaged here);
 - (1.2) the region of low relief negative Bouguer anomalies over the southern northwest Highlands and the northern Grampian Highlands;
 - (1.3) the region of intensely negative Bouguer anomalies over the post orogenic granites;
 - (1.4) the Inner Moray Firth basin;
 - (1.5) the region of positive Bouguer anomalies over the northern North Sea and the anomalous Buchan block;
- (2) Southern Scotland and northern England, and Ireland: this section is dominated by distinct NE–SW orientated tectonic blocks, such as the Midland Valley, the

Plate VIII Bouguer anomaly gravity: northwestern edge mask filter

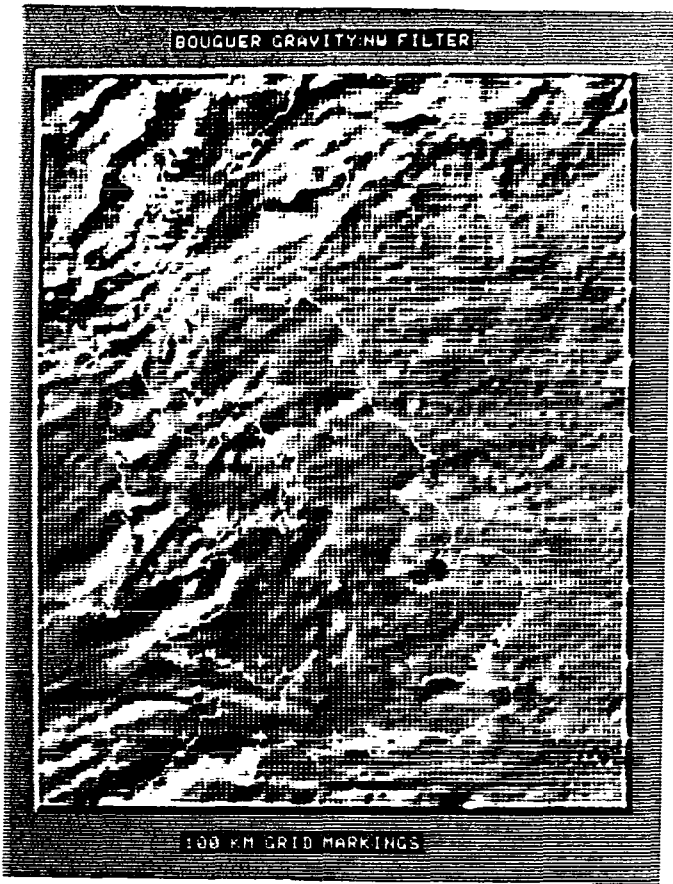


Plate IX Bouguer anomaly gravity: northeastern edge mask filter



Plate X

Bouguer anomaly gravity: northern edge mask filter

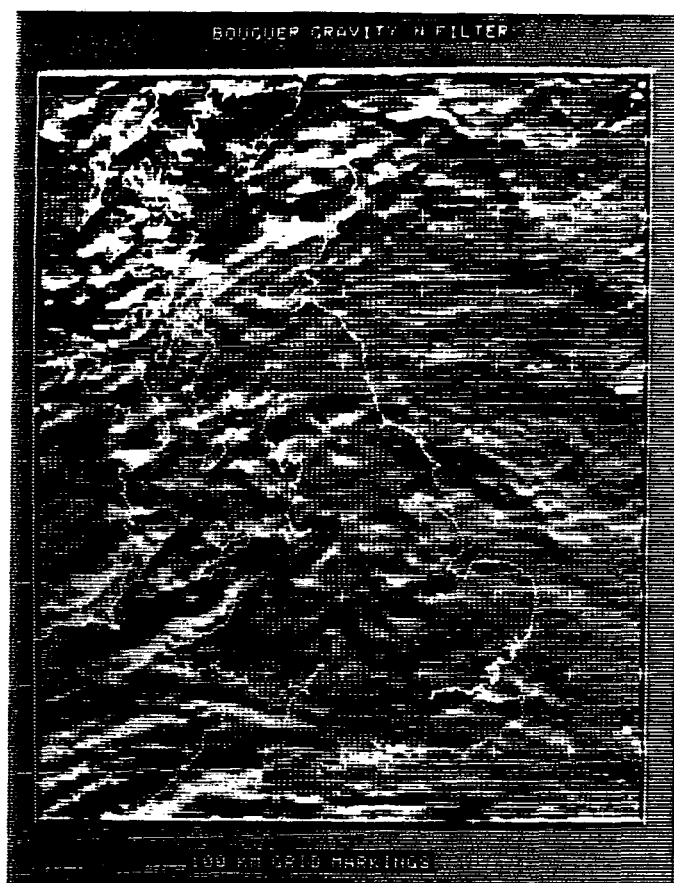


Plate XI

Bouguer gravity anomaly: western edge mask filter



Southern Uplands and the basement of the Irish midlands. The proposed line of the Iapetus suture lies within this domain. The southern boundary of this unit roughly coincides with the Leinster–Isle of Man–Lake District–Northern Pennine granite arc. It may be more realistic to consider the whole of this domain the boundary between the tectonic provinces of central and northern Scotland, and central England. The E–W lineaments imaged in the North Sea off southern Scotland and northern England indicate that the NE–SW tectonic fabric may swing into an E–W orientation offshore.

- (3) The southwestern North Sea and eastern England: this region displays a strong NW–SE tectonic trend associated with the NW–SE trending branch of the Caledonides and the Charnian trend of the eastern Midlands of England. Within the southern North Sea two major NW–SE trending structures are imaged, one of which coincides with the *Solepit* inversion axis (Glennie and Boegner, 1981).
- (4) the Midlands microcraton: this is characterized by its own distinct internal tectonic structure.
- (5) Wales and the southern Irish Sea: this region may be considered as a southerly continuation of domain two, but the trend of the Cheshire basin, and the swing in the cleavage of the Welsh Lower Palaeozoic succession (Soper et al., 1987) suggest a more complex evolution, probably a consequence of the close proximity of the microcraton indenter.
- (6) The Variscan foldbelt of south and southwestern England: this region is characterized by E–W trending structures, the result of reactivation of Variscan basement structures.

Further information may be deduced from the broad pattern of the major domains and their lineaments. The variation in trend of the major Caledonide features in southern Britain, the westward swing of the NE–SW lineaments and the eastward swing of the NW–SE structures noted earlier, may reflect a draping effect of the major lineaments around the microcraton indenter.

To the south, the microcraton is bounded by the Variscan foldbelt the strongest

feature of which is the Exmoor gravity gradient. Further south, Variscan features are poorly imaged until the English Channel structures are reached. Karner et al. (1987) suggested the lack of a clear signature for the Variscan foldbelt within the imaged Bouguer anomaly data indicated that the foldbelt is a thin skinned orogen in this region. However, the recent SWAT profile interpretations (BIRPS and ECORS, 1986) suggest that the Variscan Front is imaged as an extensional fault beneath the Celtic Sea which extends for a considerable depth into the crust. If the latter interpretation is correct then the preserved front does not appear to generate a significant lineament in the observed Bouguer anomalies. North of the Variscan front the compression associated with the Variscan orogeny tended to reactivate older basement features, such as the NE–SW fold axes in the Midland Valley (Anderson, 1978).

The continuation of the Exmoor gradient beneath the Wessex basin anomaly low is difficult to locate. The most probable continuation reappears slightly to the east of the Isle of Wight in the form of the Pays de Bray fault. This interpretation is consistent with the aeromagnetic data, because the Bristol Channel Fracture Zone–Pays de Bray fault line traverses slightly to the south of a major aeromagnetic high over southern England, which presumably represents a single unit of basement.

The Malvern axis, clearly defined by both gravity and aeromagnetic data, cannot be traced to the south of the ESE projected trace of the Exmoor gradient. Kellaway and Hancock (1983) speculated that roughly 100 km of Variscan sinistral shear may have occurred along the Bristol Channel fracture zone–Pays de Bray lineament, which would explain the disappearance of the Malvern axis trace. However, a more consistent interpretation is that the Malvern axis exists only within the microcraton and would not be expected to continue into the foldbelt domain.

The NW–SE trending anomaly lows over the Permo–Triassic basins of western Britain and the Irish Sea form a later sub-fabric superimposed upon the dominant Caledonide tectonic fabric. Ziegler (1982) suggested that these basins may form the northern continuation of a complex wrench–pull apart system, including the Pays de Bray fault, which compensated for the opening of the Western Approaches basin and

the Bristol Channel/Celtic Sea graben in Permo–Trias times. This pull apart system appears to have exploited a conjugate line of weakness to the main Caledonide fabric.

3.10 Conclusions

Many of the lineaments imaged in the Bouguer gravity data have exerted a significant control on the tectonic evolution of the UK region. In particular, many of the lineaments formed during the Caledonide orogeny appear to have been reactivated during later periods of tension or compression and have controlled the subsurface shape of later granitic intrusions and the formation of later sedimentary basins.

The major imaged tectonic fabrics of northern and central Britain agree well with recent proposed models for the Lower Palaeozoic evolution of the UK region. The Caledonian orogeny is now considered to comprise a ‘Y’ shaped configuration formed by the collision of three lithospheric plates (Soper and Hutton, 1984). The three foldbelts are the North Atlantic, the Appalachian and the north German–Polish Caledonides. The Caledonides of north Scotland, east Greenland and Scandinavia were formed by the E–W collision between the Laurentia and Baltica landmasses in the Ordovician to late Silurian (Soper and Hutton, 1984). The later deformation of the paratectonic slate belts of southern Scotland, northern England and eastern Ireland was produced by the early Devonian collision between the Midlands microcraton, part of a microcontinent of Gondwanaland origin known as Cadomia, with the Baltica–Laurentia landmass (Soper et al., 1987).

South of the Highland Boundary fracture zone the major imaged features include the NE–SW tectonic fabric of western Britain and Ireland and a NW–SE tectonic fabric in eastern England and the southern North Sea. The tentative region of E–W lineaments in the central North Sea, particularly the swing in orientation of the Southern Uplands fault, may mark the junction of the two fabrics. The fabrics are the product of two ancient zones of convergence: the Iapetus zone in the west and the Tornquist zone to the east. The microcraton indenter collided with the Laurentia–Baltica landmass within the embayment formed by the two zones of convergence. This later collision is

responsible for the slightly anomalous NNE–SSW orientation of the Church Stretton disturbance and probably also initiated the E–W structures observed within the central Pennines.

During the Lower Carboniferous, regional extension reactivated some of the basement features as extensional features forming regions of subsidence such as the Gainsborough gulf and the Northumberland and Stainmore troughs (Kent, 1966; Leeder, 1982). In contrast the compression generated by the Variscan orogeny reactivated some of the basement features north of the Variscan front as axes of inversion as well as forming a new set of basement lineaments within the foldbelt itself.

Following the Variscan orogeny a period of lithospheric extension occurred forming many new sedimentary basins. Often the margins of these basins exploited earlier lines of weakness. The wide range of orientations of these basins NE–SW, NNE–SSW, NW–SE and N–S indicates both a complicated series of basement weaknesses and a complex field of applied stresses. In the late Cretaceous thermal subsidence became dominant in the North Sea region and extensional activity decreased. A final round of inversion especially marked in the Wessex basin and the ~~Solent~~ Solent trough was produced by compression associated with the Alpine orogeny (Dewey, 1982; Glennie and Boegner, 1981).

CHAPTER 4

The application of digital image processing techniques to the Bouguer anomaly data for the Republic of Eire and Ulster

4.1 Introduction

Digital image processing techniques have been applied to the study of the lineaments in the Bouguer anomaly gravity field for the Republic of Eire and Ulster. The Bouguer anomaly data for Eire was kindly provided by Prof. T. Murphy of the Dublin Institute for Advanced Studies and was described in detail in Chapter 2. The Bouguer anomaly data for Ulster was provided by the Regional Geophysics Research Group (formerly the Applied Geophysics Unit) of the British Geological Survey. The lineaments of the Bouguer anomaly gravity field of Eire and Ulster show a greater uniformity of trend than the lineaments imaged for the Bouguer anomaly gravity field of Great Britain but some interesting features are revealed.

4.2 Digital image formation

The distribution of the gravity station point observations used to form the gravity data grid is shown in figures 2.1, 2.2 and 2.3. The data grid was based on the Irish national grid transverse mercator projection. The data grid was bounded by the Irish national grid coordinates 30.0, 370.0, 10.0, 470.0 km and the sampling interval was 4 km. The initial data grid was entered into the I²S image processing system as a byte matrix and then magnified by a factor of 3.0 in both dimensions using a bicubic spline interpolation. Plates XII and XIII show the resulting monochrome digital images that were formed by modifying the magnified data grid with Prewitt edge mask filters designed to enhance lineaments in the gravity field trending NW–SE and NE–SW respectively. A false colour digital image is not presented because the hues tend to

Monochrome digital image of the Bouguer anomaly gravity of the Republic of Eire and Ulster enhanced with a northeastern edge mask filter



Monochrome digital image of the Bouguer anomaly gravity of the Republic of
Eire and Ulster enhanced with a northwestern edge mask filter



obscure the fine details of the lineaments in central Eire. The amplitudes of the main Bouguer anomalies can be discerned from the contour map of the Bouguer anomaly gravity shown in figure 4.1. Digital images which enhance lineaments trending E–W and N–S are not shown because these show little information that is not displayed in Plates XII and XIII.

The marked cross hatching effect observed in the digital images is a product of filtering the digital image after image magnification. The region surrounding Eire and Ulster has been masked black because the data coverage in the eastern North Atlantic and the western Celtic Sea is incomplete and the values interpolated for these regions are not well defined.

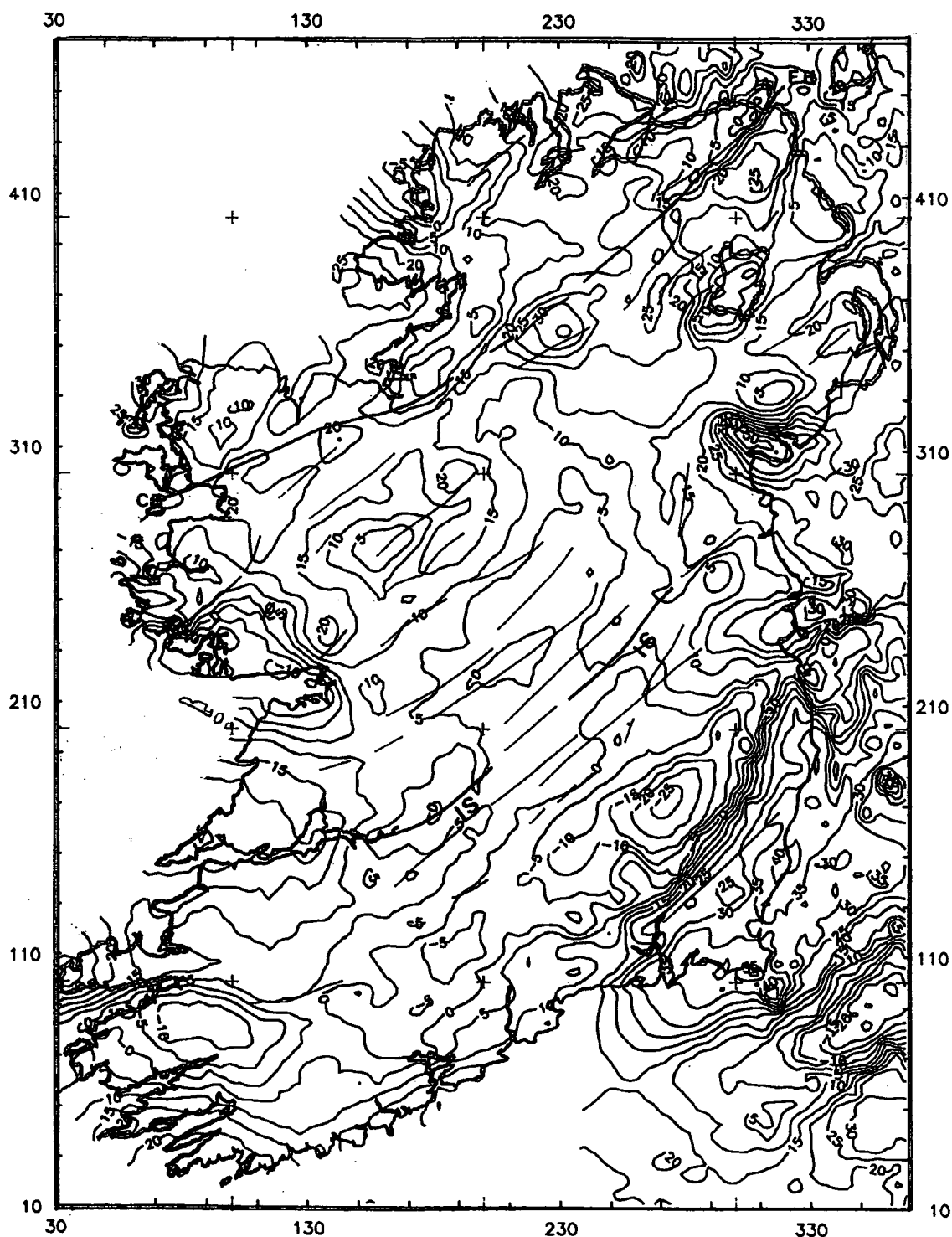
4.3 Image interpretation

The interpretation of the lineaments observed within the Bouguer anomaly data for Eire and Ulster is not intended to be as comprehensive as that presented for the UK region in Chapter 3 and only the major features of interest are discussed.

The most noticeable feature of the Bouguer anomaly digital images for Eire and Ulster is the dominant NE–SW orientation of the major lineaments. Plate XII, which shows the Bouguer anomaly data filtered to enhance lineaments trending NW–SE, displays very few lineaments. The lineaments imaged are described below. The northeastern margin of the Galway granite anomaly low is clearly marked (Plate XII, lineament a). A subtle Bouguer anomaly low bounded in places by steep anomaly gradients is imaged extending from Donegal Bay to Cavan (B). The northwestern section of this anomaly low overlies the northeastern part of the late Viséan–early Namurian Connaught coalfield outlier. The southeastern section of the anomaly trough overlies the Crossdoney granite. However, the gravity station density of coverage is poor for part of this region and the changes in the density of coverage may partially generate the lineaments observed in the digital image.

A series of faint NW–SE trending lineaments are observed in Munster (C). The origin of these lineaments is unknown. The main structural trends of this region are

Figure 4.1. Bouguer anomaly map of the Republic of Eire and Ulster. The contour interval is 5 mGal. The gridding interval is 4 km. The scale is approximately 1:2,500,000 and the border annotation denotes Irish grid coordinates in km.



The overlay map displays some of the Bouguer anomaly lineaments observed on the digital images of the Bouguer anomaly data and the approximate positions of the Fair Head-Clew Bay lineament (Max and Riddihough, 1975) and the proposed trace of the Iapetus suture (Phillips et al., 1976) marked FH-CB and IS respectively.

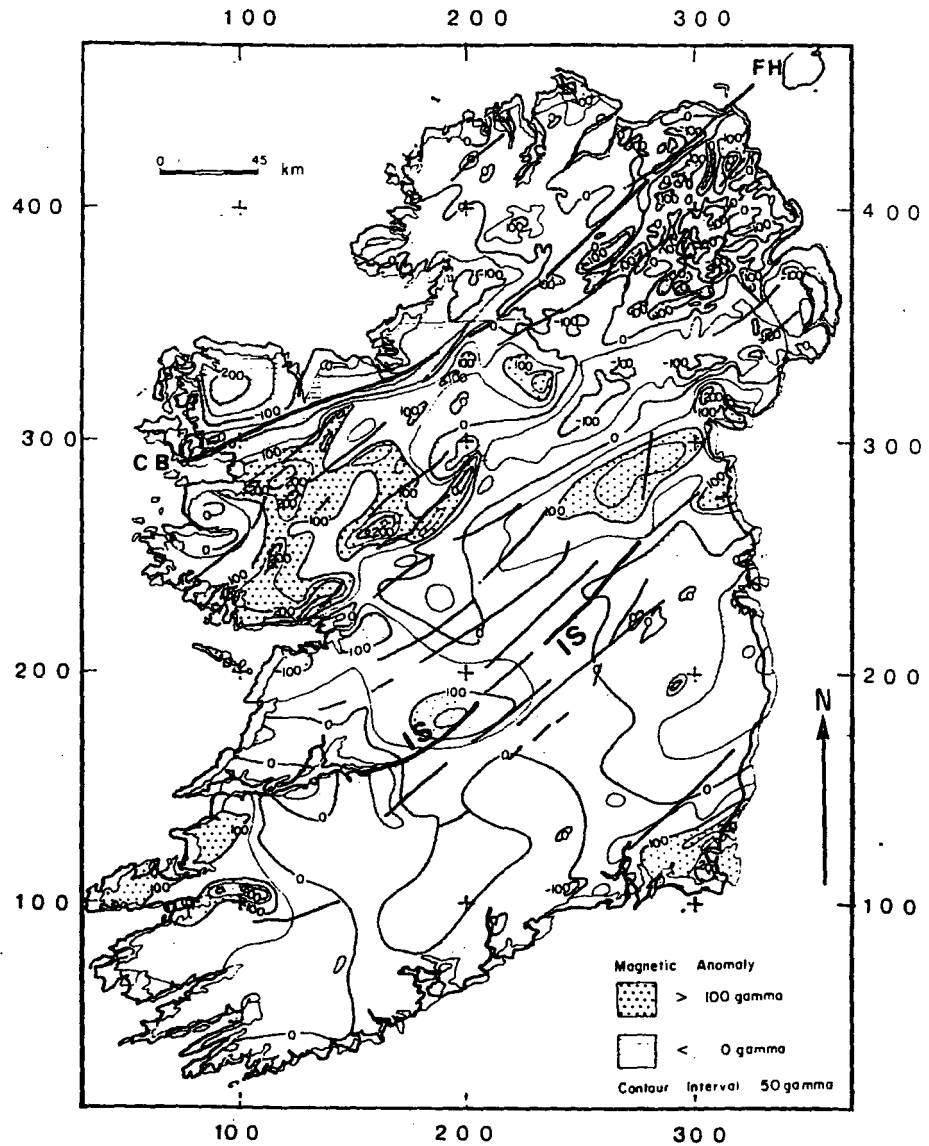
orientated E-W and ENE-WSW following the trace of the Variscan front. As observed in southwestern England and the Celtic Sea the Variscan front is poorly expressed within the Bouguer anomaly gravity field.

A similar series of lineaments is imaged in Ulster and Donegal (D). The origin of these lineaments is also uncertain. Magnetic anomaly maps for Eire and Ulster show a series of mainly negative NW-SE trending anomalies northeast of a line from Dublin to Sligo associated with Tertiary dykes (Murphy, 1981). However, these are unlikely to be large enough to produce the observed Bouguer anomaly lineaments.

Lineaments of NE-SW orientation are imaged throughout Eire and Ulster except for the southwestern region of Munster. A subject of considerable interest is the trace of the continuation of the major NE-SW trending faults observed in Scotland, namely the Highland Boundary fracture zone and the Southern Uplands fault. Max and Riddihough (1975) considered the Fair Head-Clew Bay lineament observed in aeromagnetic and land magnetic data (figure 4.2) to represent a deep seated structural line along the southwestern continuation of the trace of the Highland Boundary fracture zone in Scotland. The lineament separates a region of negative magnetic anomalies in the northwest from a region of positive anomalies to the southwest, which may mark a major change in the nature of the underlying basement. However, the Fair Head-Clew Bay lineament separates two characteristically different magnetic terrains within the orthotectonic zone of the Irish Caledonides, whereas the Highland Boundary fracture zone marks the southeasterly termination of the orthotectonic Caledonides of Scotland. This discrepancy was explained as the result of the Highland Boundary fracture zone in Scotland being a relatively late feature that may not coincide with the deeper structural line formed by the Fair Head-Clew Bay lineament in Ireland (Riddihough and Max, 1976). During the Caledonide orogeny the older, deeper structural lines may have behaved in a similar manner in Ireland and Scotland.

The trace of the Fair Head-Clew Bay lineament is discontinuous and considerably less clear within the Bouguer anomaly data. The intense NE-SW trending lineament imaged traversing southwest from Fair Head is probably the result of a Mesozoic sedi-

Figure 4.2. Magnetic anomaly map of the Republic of Eire and Ulster. The scale is approximately 1:3,500,000 and the border annotation denotes Irish grid coordinates in km. The overlay map displays some of the imaged Bouguer anomaly lineaments and the Fair Head-Clew Bay lineament (FH-CB) and the proposed trace of the Iapetus suture (IS).



The magnetic anomaly map is taken from Murphy (1981) after Riddihough

mentary basin beneath the Antrim plateau lavas (Plate XIII, lineament a). The Bouguer anomaly gradient at the edge of the basin is much greater on the southeastern margin than on the northwestern margin which suggests the southeastern margin is possibly fault bounded. The Fair Head–Clew Bay lineament observed on the magnetic anomaly map may run along the southeastern margin of the basin or slightly to the southeast within the metamorphic basement beneath the plateau lavas. Further south, the broad Bouguer anomaly low over Lough Neagh and central Antrim (B) may be caused by the onshore extension of the Ulster or Magee basin (Karner et al., 1987).

Traversing southwest from Antrim, the line of the Fair Head–Clew Bay lineament may be imaged along the northwestern margin of a marked NE–SW elongated Bouguer anomaly high of 16–18 mGal amplitude east of Donegal Bay (lineament c). The origin of the Bouguer anomaly high is again uncertain. The anomaly high lies westsouthwest of the Lower–Middle Ordovician Tyrone igneous complex which includes a component of dense basic intrusives and actually partially overlies the southwestern section of the Fintona block of Old Red Sandstone and the Lower Carboniferous succession northeast of the Connaught coalfield outlier. Density measurements show that neither the mean density of the Carboniferous limestone ($2681 \pm 33 \text{ kg m}^{-3}$) nor the sandstone ($2673 \pm 59 \text{ kg m}^{-3}$) is of particularly high density (Morris, 1973). Therefore, the origin of the Bouguer anomaly high is more likely to be a region of uplifted or anomalously dense basement. In particular, the anomaly high may reflect a westsouthwestward continuation of the igneous rocks of the Tyrone igneous complex.

Southwest of Sligo, the Fair Head–Clew Bay lineament as imaged in the magnetic anomaly data departs from the strike of the main lineaments of the gravity field. The magnetic lineament curves to the north over the north and central Ox Mountains and then strikes NE–SW before swinging E–W in the Clew Bay district. The main lineaments of the Bouguer anomaly gravity continue to strike NE–SW and terminate at the western margin of the Galway granite (lineaments d, e and f). The most extensive of these lineaments, lineament d, roughly follows the surface strike of the Killavil–Archdale Castle fault (Sevastopulo, 1981). This fault has experienced a complex history of tec-

tonic activity. In a study of the Lower Carboniferous rocks between the Curlew and Ox Mountains in Northwestern Ireland, Dixon (1972) suggested that the local stratigraphy indicated a left lateral displacement along the fault of as much as 16 km. However, the fault also appears to have a dip slip component that varies in amplitude along strike (see figure 10, Dixon, 1972). In the vicinity of Ballymote, the fault downthrows the Lower Bricklieve limestone to the northwest by some several hundreds of metres. To the northeast, the probable continuation of this fault marks the northwestern margin of the late Visian-early Namurian sandstones and shales of the Connaught coalfield outlier. Brandon and Hodson (1984) describe the fault as a high angled, compound, reverse fault of Caledonian trend with an effective downthrow to the southeast of between 36 and 116 m. Brandon and Hodson (1984) argue that there has been no lateral movement along the fault. However, both Dixon (1972) and, Brandon and Hodson (1984) consider that the fault was active at times during the Carboniferous. The complexity of the fault zone appears to be represented by the along strike variation in the intensity of the imaged Bouguer anomaly lineament. If, as in the Irish Midlands, the density of the sedimentary succession is roughly constant the Bouguer anomaly lineament may be mostly generated by the vertical displacement of the sedimentary cover-basement interface.

The region between the Fair Head-Clew Bay lineament and the Southern Uplands lineament, the continuation of the Southern Uplands fault in Scotland, is considered to comprise a segmented zone of relatively small magnetic and geological bodies of mixed crustal affinity (Max et al., 1983). These include Grampian massifs, Lower Palaeozoic sedimentary basins bounded by shear faults, relics of Lower Palaeozoic oceanic and related crust, and possibly older fragments of microcontinents. There is little clear evidence for this within the digital images of the Bouguer anomaly data, but the composite, discontinuous nature of the imaged gravity lineaments suggests a marked difference between the basement beneath central and northern Ireland and that beneath southern Scotland

The Southern Uplands lineament observed in the aeromagnetic and land magnetic

anomaly data suggests that the continuation of the Southern Uplands fault in Ireland traverses roughly NE–SW from Belfast Lough to the eastern limit of Galway Bay (Max et al., 1983). The Bouguer anomalies observed in the Irish Midlands southeast of the Southern Uplands lineament are of particular interest. A series of well defined roughly NE–SW trending lineaments are imaged which define the margins of a number of low amplitude anomaly troughs and highs. This anomaly trend has been investigated in detail by Brown and Williams (1985).

The geology of the Midland plain consists of four main components. A thin surface layer of bog and till overlies the Carboniferous limestone succession. The observed Bouguer anomaly highs correlate with inliers of red sandstones which may have cores of Silurian rocks. The inliers display a marked NE–SW trend which is the result of deformation during the Caledonian orogeny. The sedimentary succession continues beneath the Carboniferous limestones in the form of upper Devonian–lower Carboniferous red sandstones, Silurian siltstones and greywackes, and siltstones and shales of Ordovician age. The deepest known rocks are Ordovician volcanics and pyroclastics. These are probably underlain by a Precambrian basement of granulite facies gneisses. Although the upper crustal structure of the Irish Midlands was poorly constrained by the Irish Caledonian suture seismic profile (ICSSP), Jacob et al. (1985) observed a 6.0 km s^{-1} velocity refractor at a depth of about 4 km which may be tentatively associated with crystalline basement.

Brown and Williams (1985) considered the major density contrast to occur between the dense Ordovician pyroclastic rocks (2750 kg m^{-3}) and the overlying succession of less dense Ordovician to Carboniferous sediments (2650 kg m^{-3}). From this assumption the alternating anomaly highs and lows of a residual Bouguer anomaly map of the Midland plain were interpreted as the result of a series of blocks and troughs. The residual Bouguer anomaly map was produced by calculating the medium and long wavelength components of the Bouguer anomalies generated by the major granite complexes of the region and subtracting them from the simple Bouguer anomaly gravity field and the removal of the component of the simple Bouguer anomaly field with wavelengths greater

than 38 km. The block and trough structure was considered to have formed during the Carboniferous where basins infilled by relatively low density sediments formed in swiftly subsiding troughs separated by more stable, slowly subsiding blocks.

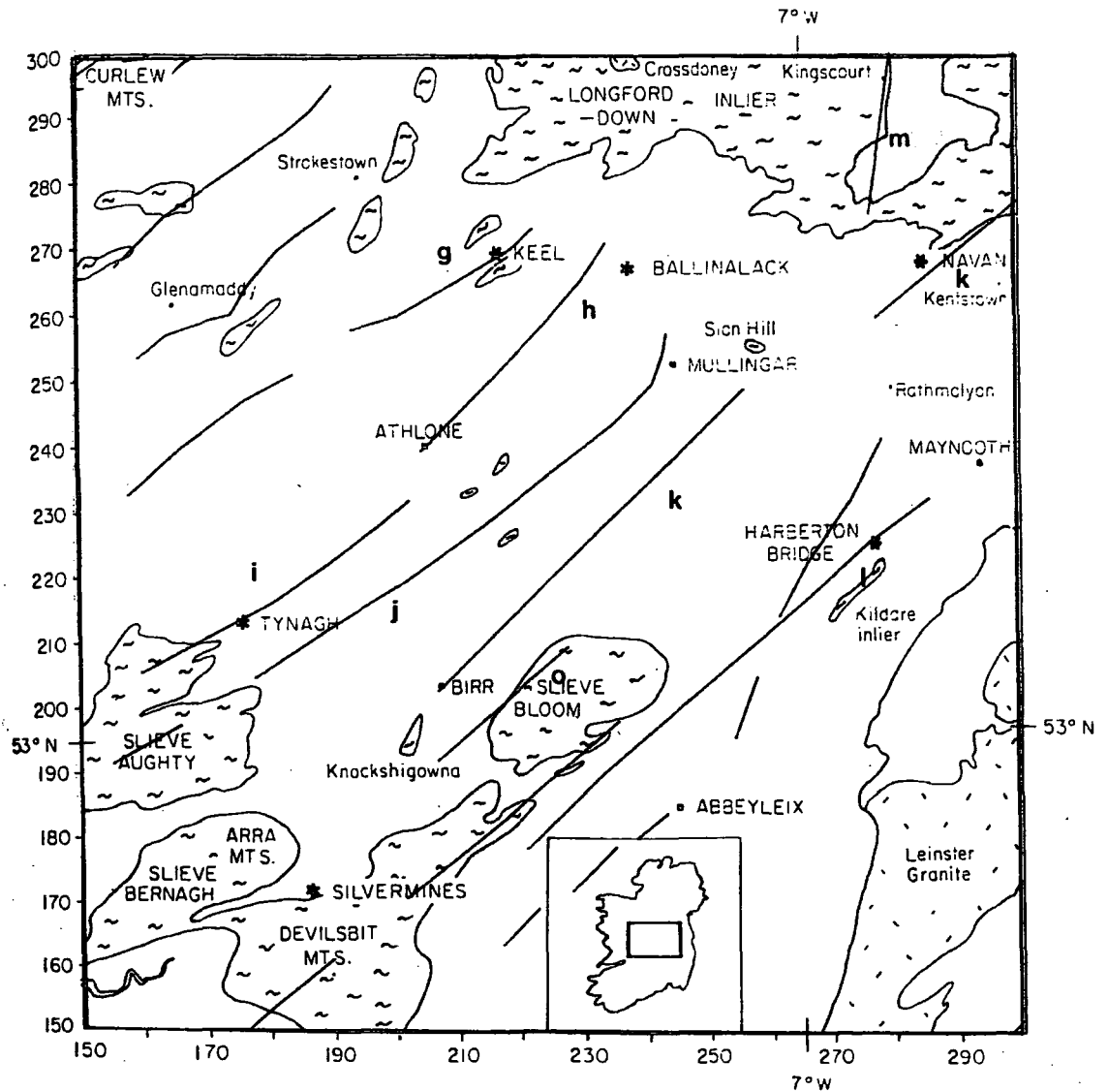
The margins of some of these blocks are clearly delimited by the imaged lineaments. The precise definition of the structure of these blocks is of considerable interest because the major Pb–Zn deposits of the Irish Midlands are located within Lower Carboniferous limestones at the margins of the blocks. The metal bearing fluids required to generate the ore deposits may have originated from the dewatering of the shales at the base of the sedimentary succession in the troughs and may have migrated to the present host rocks along the growth faults at the block margins (Brown and Williams, 1985). Figure 4.3 shows the correlation between the imaged lineaments in the Bouguer anomaly gravity field and the major ore deposits.

Brown and Williams (1985) identified five main blocks, namely the Strokestown block, the Longford–Keel block, the Ballinalack–Slieve Aughty block, the Sion Hill–Arra Mountains–Navan–Silvermines block and the Kildare block. On Plate XIII, the following components of the blocks are clearly imaged:

- (1) the southeast margin of the Longford–Keel block (g);
- (2) the northwest margin of the Ballinalack–Slieve Aughty block (h);
- (3) the southeast margin of the Ballinalack–Slieve Aughty block (i);
- (4) the northwest margin of the Sion Hill–Arra Mountains–Navan–Silvermines block (j);
- (5) the northwestern margin of the Kildare block (l).

Lineament k has a complex origin. The northeastern section of the lineament between the coast and Navan is formed by a pronounced ridge of positive Bouguer anomalies associated with the Llanvirn–Caradoc basic lavas of the Grangegeeth volcanic group (Phillips et al., 1976). This section of the lineament follows the surface trace of the Iapetus suture as proposed by Phillips et al. (1976). However, to the southwest the proposed trace of the suture swings further to the southsouthwest passing through the northwestern part of the Slieve Bloom inlier. The inferred suture trace then swings back to a

Figure 4.3. Correlation between the lineaments observed on the digital images of the Bouguer anomaly gravity and the location of the major Pb-Zn ore deposits of the Midlands plain of Ireland. The scale is approximately 1:1,150,000 and the border annotation denotes both Irish grid coordinates in km and latitude and longitude. The lineaments referred to in the text are labelled.



Background map taken from Brown and Williams (1985)

NE-SW, ENE-WSW orientation traversing between the Slieve Phelim-Silvermines-Devilsbit and Cratloe group of inliers to the south and the Arra Mountains-Slieve Bernagh inliers to the north. In Westmeath and Offaly, lineament k lies to the northwest of the suggested suture. The lineament is characterized by a NE-SW trend and a distinctly linear form. The lineament is probably associated with a slight, discontinuous gravity low which splits the Sion Hill-Arra Mountains-Silvermines-Navan block into two (Brown and Williams, 1985). The origin of this anomaly low is considered to be near surface karstification (Murphy, 1962) possibly formed preferentially along a Caledonian fault zone.

The relationship between the lineaments and the ore deposits requires further investigation. Brown and Williams (1985) described the relationship of the known ore deposits to the block margins. The Navan deposit occurs at the apex of a concave bend in the trough margin from a NE-SW trend to a roughly E-W strike. The Tynagh deposit is located on an E-W fault where the fault has a maximum throw. The Ballylinalack deposit occurs close to the termination of lineament h. These structures are considered to have improved the permeability of the trough-block margins allowing the metal bearing fluids to rise more effectively. The imaged lineaments indicate that other locations where conditions favourable for the development of ore deposits may occur are at the tightly curling northeastern termination of lineament j, near Mullingar, and at the intersection of lineament l with the NNE-SSW trending lineament which probably marks a major fault just to the southwest of the Harberton Bridge ore deposit.

The origin of the block and trough system is attributed to the reactivation of Caledonian lines of weakness by N-S tension generated by Hercynian plate margin processes (Brown and Williams, 1985). Syn-depositional faulting during the Carboniferous was probably initiated during the early Tournaisian.

The anomalous N-S trending lineament m within the Midland plain is produced by a Permo-Carboniferous sedimentary basin east of Kingscourt. The western margin of the basin is fault bounded. To the southeast, the Midland plain is bounded by the Leinster batholith. This produces a major Bouguer anomaly low with an amplitude

of nearly 30 mGal with respect to the regional Bouguer anomaly level in the Midland plain. The Bouguer anomalies show that the subsurface extent of the batholith greatly exceeds the observed surface outcrop. The batholith may extend to a western limit beneath the Devonian of the Killarney district (Murphy, 1981).

Lineament n is roughly positioned along the Wexford Boundary lineament. This lineament defines the northwestern margin of a region of high amplitude, positive Bouguer anomalies which marks the northwestern limit of rocks deformed during the Cadomian orogeny in Eire (Max et al., 1983).

4.4 Discussion

Although the imaged Bouguer anomaly data for Eire and Ulster displays only a single, dominant lineament orientation, the tectonic fabric is characterized by subtle variations in the trend and intensity of the lineaments. The strongest feature imaged is associated with the continuation of the Highland Boundary fracture zone. However, the trace is discontinuous and the different southwestwards continuations of the Fair Head–Clew Bay magnetic lineament and the trend of the main gravity lineaments provides a significant difficulty in the interpretation. As discussed in Chapter 3, magnetic anomaly data generally provides a better control on the nature of the basement than gravity data. The trend of the main gravity lineament follows the Killavil–Archdale Castle fault. This fault must have been active during or after the Carboniferous at least because in the vicinity of Ballymote the upper Carboniferous limestone formation is downthrown to the northwest by the fault. However, earlier activity along the fault zone cannot be discounted. The trend of the gravity lineaments indicates that the basement of the Clew Bay region, although south of the Fair Head–Clew Bay lineament may be separated from the main mass of the southwestern basement by a NE–SW striking zone of weakness. This zone of weakness may have influenced the intrusion of the Galway granite to generate the marked lineament at the northwestern margin of the Bouguer anomaly low over the granite. The granite is considered to be of Caledonian age (399 ± 1 Ma, Stillman, 1981) which suggests that the zone of weakness was active

before the Carboniferous.

The Bouguer anomaly gravity field of the Midland plain is dominated by the block and trough structure described by Brown and Williams (1985). There is a subtle variation in the form of the lineaments across the plain. The block margins in the northwest tend to be curvilinear. The Ballinalack–Slieve Aughty block in particular shows a distinct swing in orientation from NE–SW in the northeast to ENE–WSW in the southwest. Note also the variation of the lineaments along the block margins. In the northeast, the northwestern margin of the block forms the most distinct lineament, whereas in the southwest the southsouthwest margin is more clearly imaged. Further southeast, the lineament produced by the alignment of karst holes in Westmeath and Offaly which is presumed to lie along an earlier Caledonian line of weakness and the northwest margin of the Kildare block display a much more linear form. This change in the structural style of the basement may have been influenced by the Lower Palaeozoic Longford–Down massif which forms the northeast termination of the northwestern blocks. However, lineament k abuts against the most southeasterly extension of the massif. The change in the nature of the lineaments cannot be assigned to the change in basement at the Iapetus suture either because most of lineament k lies to the northwest of the suture.

Whatever the cause of this subtle variation, the reactivation of these presumably Caledonian structures by tension during the Hercynian would have produced a complex stress system within the basement of the Midland plain. It would be of interest to attempt to predict the regions affected by tensional and compressional stresses and to compare their distribution with that of the Pb–Zn ore deposits.

The proposed line of the Iapetus suture (Phillips et al., 1976) is poorly imaged except between the east coast and Navan. The faint lineament o that runs through the northwestern section of the Slieve Bloom inlier may represent the suture further to the southwest but this lineament is of limited extent. The Leinster batholith forms a stable block on the southeastern margin of the Midland plain. This block marks the southeastwards termination of the basement block and trough structure of the Midlands

and may have influenced the extent of the deformation.

4.5 Conclusions

The digital images of the Bouguer gravity anomaly field define clearly the internal structural framework of Eire and Ulster. In general terms, the Irish block forms the southwestern continuation of the Iapetus zone of convergence observed in western Britain and the Irish Sea in the images of the Bouguer anomaly data for the UK region. However, the nature of the tectonic framework changes along the strike of the convergence zone. The major boundary faults observed in Scotland are not as clear in Ireland. The trace of the Highland Boundary fracture zone is discontinuous and the Southern Uplands lineament of Max et al. (1983) is not apparent in the Bouguer anomaly data. A subtle variation in the form of the imaged lineaments is observed traversing NW–SE across the centre of the former zone of convergence. The cause of this is unknown but the variation may provide an additional constraint on the evolution of the Caledonide orogeny.

As in south and southwestern England, there is no clear signature in the Bouguer anomaly data for the second orogenic front that crosses the UK and Eire; the Variscan front. The most important feature of Hercynian plate margin processes observed in Eire is the reactivation of the earlier Caledonian lines of weakness to form the block and trough structure of the Midland plain. Therefore, as observed for the UK, basement weaknesses generated during early orogenic periods have exerted a marked control of the subsequent tectonic evolution of the region.

CHAPTER 5

The nature of the isostatic compensation of the topography of the United Kingdom region

5.1 Introduction

The association of negative Bouguer anomalies over large scale topographic features such as mountain ranges led to the concept of isostasy. Isostasy is the process by which the elevation of the Earth's surface is supported by density variations at depth. The observed gravity anomalies are generated by lateral density variations.

The earliest hypotheses of the mechanisms by which isostatic equilibrium could be attained were proposed by Pratt (1855) and Airy (1855). Both mechanisms considered local isostasy where any surface load is compensated solely by density variations lying directly beneath the load. Pratt suggested that the crust comprises a series of vertical columns with a common base level known as the depth of compensation. The density of each column is inversely proportional to its height. Airy proposed that mountain chains are compensated by underlying low density roots of crustal material which displace the denser mantle beneath.

The gross *structure* of the crust appears to match that predicted by Airy's hypothesis. Mountain chains are supported by a thickened crust whilst oceanic regions are underlain by a thin crust. However, many regions show departures from the simple Airy model and some regions such as mid-ocean ridges display a form of isostasy more characteristic of Pratt isostasy.

More complex forms of isostasy have been proposed which are related to the theory of lithospheric flexure. The outermost layers of the Earth comprise a rigid, strong lithosphere overlying a weak asthenosphere (Barrel, 1914). Regional compensation occurs when topographic loads are supported by the regional deformation of the lithosphere

(Vening Meinesz, 1941). This form of compensation is commonly observed in oceanic regions. Typical surface loads are seamounts and seamount chains (Walcott, 1970b; Watts, 1978).

The application of cross spectral techniques to the analysis of isostasy was first proposed by Dorman and Lewis (1970). The gravitational attraction of the compensating masses is non-linear because the attraction cannot be exactly determined by a two dimensional convolution between the surface topography and a linear filter known as an isostatic response function. However, the non-linear terms are fairly small (Dorman and Lewis, 1970) and in certain conditions examination of the linear response function, which predicts a best fit in the least squares sense to the observed Bouguer anomalies when convolved with the topography, can yield useful information on the nature of the compensation. The linear response function is obtained by normalizing the fourier transform of the observed Bouguer gravity by the transform of the topography. The observed response function can be compared with linear approximations of response functions representing the various isostatic models. Listings of the most important computer programmes used in the study of isostasy are presented in Appendix C.

5.2 Theoretical models of the response functions for Airy and regional compensation

In this section I derive theoretical response functions for Airy and regional compensation. A simple two layer model of the continental lithosphere is assumed. The lithosphere comprises the Earth's crust of density ρ_0 and part of the the upper mantle of density ρ_m . The Moho discontinuity forms an important density contrast within the lithosphere . Surface topographic loads deform the lithosphere perturbing the depth of the Moho density contrast to produce the compensating masses. The theoretical response function derivation following assumes that all of the observed Bouguer anomalies result from the perturbation of the Moho density contrast.

The derivation assumes a planar Earth. Although the compensation is a phenomenon of global proportions and should be modelled using a spherical Earth, pro-

viding that only a small region is investigated this approximation should be acceptable (see Dorman and Lewis, 1970).

The theoretical response function is calculated in two stages. The deformation of the lithosphere by topographic loads is determined and then the gravitational effect of the perturbation of the Moho is evaluated. This approach is a modification of the methods applied by Banks et al. (1977) and Karner (1982). Consider an initial surface topography $h_I(\mathbf{r})$ which deflects the lithosphere by $w_T(\mathbf{r})$. $\mathbf{r}$ is the projection of the position vector onto the xy plane. The final surface topography after the deflection of the lithosphere $h_T(\mathbf{r})$ is equivalent to $h_I(\mathbf{r}) + w_T(\mathbf{r})$. The deflection of the lithosphere $w_T(\mathbf{r})$ is evaluated by modelling the lithosphere as a thin elastic plate overlying an inviscid fluid substratum. The thin plate model may only be applied if a number of assumptions are made. These have been concisely summarized by Karner (1982):

- (1) vertical stresses are negligible;
- (2) planar cross sections that are normal to the neutral surface of the thin plate remain planar;
- (3) the bending moment is determined only by the second derivative of $w_T(\mathbf{r})$;
- (4) deflections are small so that stretching along the neutral surface does not occur;
- (5) the initial, preloading stress of the system is hydrostatic.

Using the thin plate equation the equilibrium deflection is defined by (Jeffreys, 1970)

$$D \cdot \nabla^4 w_T(\mathbf{r}) = p(\mathbf{r}) \quad 5.1$$

where $p(\mathbf{r})$ is the net upward force applied per unit area. This is the sum of the initial topographic loads and the buoyancy forces generated by the displacement of the mantle by the crust so that

$$p(\mathbf{r}) = -\rho_0 g h_I(\mathbf{r}) - \rho_m g w_T(\mathbf{r}) \quad 5.2$$

where g is the gravitational acceleration. D is the flexural rigidity of the elastic plate. This specifies the strength of the plate. The greater the flexural rigidity of the plate the larger the applied force required to deform the plate. The flexural rigidity is related

to the elastic thickness T_e by the expression

$$D = \frac{ET_e^3}{12(1 - \sigma^2)} \quad 5.3$$

where E is the Young's modulus of the elastic plate and σ is Poisson's ratio. E is taken to be $1 \times 10^{11} \text{ N m}^{-2}$ and Poisson's ratio is usually assigned a value of 0.25.

The flexure equation is simplified in the wavenumber domain. This is accomplished by determining the two-dimensional fourier transform of the thin plate equation and the earlier relationships. The fourier transform is defined as

$$W_T(\mathbf{k}) = \int_S w_T(\mathbf{r}) e^{-i\mathbf{k} \cdot \mathbf{r}} dS. \quad 5.4$$

The fourier transform is denoted by a capital letter. $\mathbf{k}$ is the two dimensional wavevector where

$$|\mathbf{k}| = k = (k_x^2 + k_y^2)^{\frac{1}{2}} \quad 5.5$$

$$k_x = \frac{2\pi}{\lambda_x} \quad k_y = \frac{2\pi}{\lambda_y}$$

In the wavenumber domain the expressions become

$$k^4 DW_T(\mathbf{k}) = P(\mathbf{k}) \quad 5.6$$

$$P(\mathbf{k}) = -\rho_0 g H_I(\mathbf{k}) - \rho_m g W_T(\mathbf{k}) \quad 5.7$$

$$H_T(\mathbf{k}) = H_I(\mathbf{k}) + W_T(\mathbf{k}) \quad 5.8$$

Substituting (5.7) and (5.8) into (5.6) and rearranging gives the expression for the deflection of the lithosphere

$$W_T(\mathbf{k}) = -\rho_0 H_T(\mathbf{k}) / (\rho_m - \rho_0) \xi \quad 5.9$$

where

$$\xi = 1 + \frac{Dk^4}{(\rho_m - \rho_0)g}.$$

The gravity anomalies observed at the Earth's surface generated by the topography on the Moho $w_T(\mathbf{r})$ can also be determined in the wavenumber domain. The gravity

anomaly produced by the topography $h(\mathbf{r})$ about a mean depth z of the density contrast $\Delta\rho$ between two layers is given by (Parker, 1972).

$$\Delta G(\mathbf{k}) = 2\pi G \Delta\rho e^{-kz} \sum_{n=1}^{\infty} \frac{k^{n-1}}{n!} F(h^n(\mathbf{r})) \quad 5.10$$

where G is the gravitational constant ($6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$), F denotes the fourier transform operator and z is positive downwards. As the summation increment n increases $n!$ becomes the dominant term. The series is uniformly and absolutely convergent in any bounded domain of the wavenumber space. The rate of convergence is inversely proportional to $\max|h(\mathbf{r})|/z$ (Parker, 1972). A linear approximation of the gravity anomaly produced by the Moho topography is obtained from the first term of the summation

$$\Delta G(\mathbf{k}) = 2\pi G(\rho_m - \rho_0)e^{-kz_m} W_T(\mathbf{k}) \quad 5.11$$

where z_m is the mean depth to the Moho. For continental regions this truncation is generally acceptable. Higher order terms would have to be included if the gravity effect of the ocean-continent transition was required.

The theoretical response function can now be determined by normalizing the wavenumber representation of the gravitational effect of the compensation by the fourier transform of the observed topography

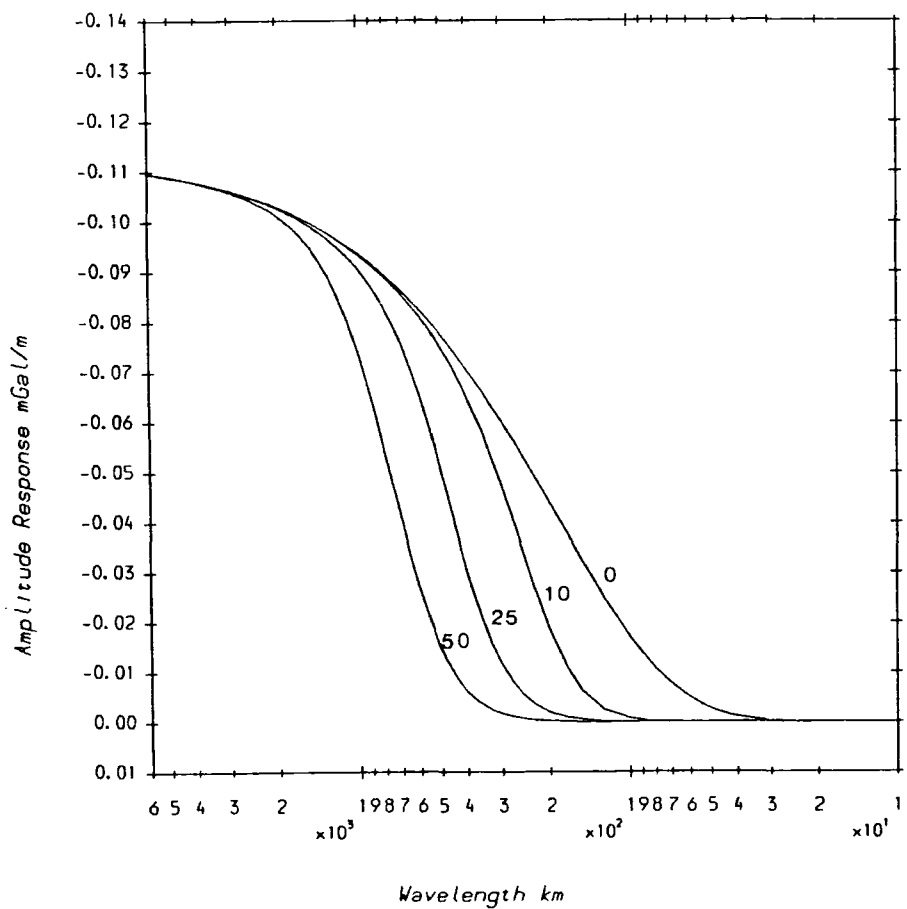
$$Q(k) = \frac{\Delta G(\mathbf{k})}{H_T(\mathbf{k})} = -2\pi G \rho_0 e^{-kz_m} / \xi \quad 5.12$$

A series of theoretical response functions for various values of T_e derived from this formula are shown in figure 5.1. At short wavelengths the response is zero. This does not necessarily mean that the topography is uncompensated. The low response results from the attenuation of the short wavelength gravity signal by upward continuation and from the negligible deformation of the lithosphere for finite elastic thicknesses. At long wavelengths ($\lambda > 2000 \text{ km}$) the apparent strength of the lithosphere is insignificant. Topographic loads of such wavelengths are assumed to be supported by simple Airy isostasy. The amplitude of the response function is then controlled by the slab formula. The roll over of the response between these asymptotic values is controlled by the elastic



Figure 5.1. Theoretical amplitude response for surface loading for various values of the elastic thickness of the continental lithosphere

The annotation on the amplitude response curves denotes the elastic thickness of the lithosphere in km for each curve. The additional amplitude response parameters are $\rho_0 = 2700 \text{ kg m}^{-3}$, $\Delta\rho = 650 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.



thickness of the lithosphere. As the elastic thickness of the lithosphere increases, the wavelength of the loads at which the lithosphere begins to be deformed increases and the roll over of the response function is shifted towards the longer wavelengths. When $T_e = 0$ the topography is supported by Airy isostasy. For Airy isostasy the roll over region of the response function is controlled solely by the upward continuation factor and the roll over region occurs at the shortest wavelengths for any of the theoretical curves.

The nature of the compensation of the UK can be investigated by comparing the observed response function with these theoretical models.

5.3 The determination of the observed isostatic response function for the UK

Gridded representations of the topography and Bouguer gravity of the UK were generated using the gravity and topography database. The grid parameters required careful consideration for the study to be successful. The size of the grid was a compromise. A large grid was required to define the long wavelength response ($\lambda \geq 1000$ km) but as far as possible the averaging of the response over a number of different tectonic provinces was avoided.

The data grids analysed covered the region bounded by the OSGB national grid coordinates 0.0, 700.0, 0.0, 1000.0 km. This region covers the entire UK and eastern Ireland but does not include much of the tectonically distinct North Sea province. A 10 km gridding interval was utilized. This sampling interval is adequate because features with wavelengths of less than 20 km are not significant in the observed response. The problem of aliasing was reduced by averaging the data within each 10 km grid square. The topography and Bouguer grids used for the initial part of this study are shown in figures 5.2 and 5.3.

The theoretical models of the response function assume a constant density contrast at the surface (e.g. $\rho_{rock} - \rho_{air}$). Therefore, because the UK region encompasses both land and shallow marine regions, the observed topography has been modified slightly

Figure 5.2. Contour map of the topography of the UK and adjacent regions. The contour interval is 100 m. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

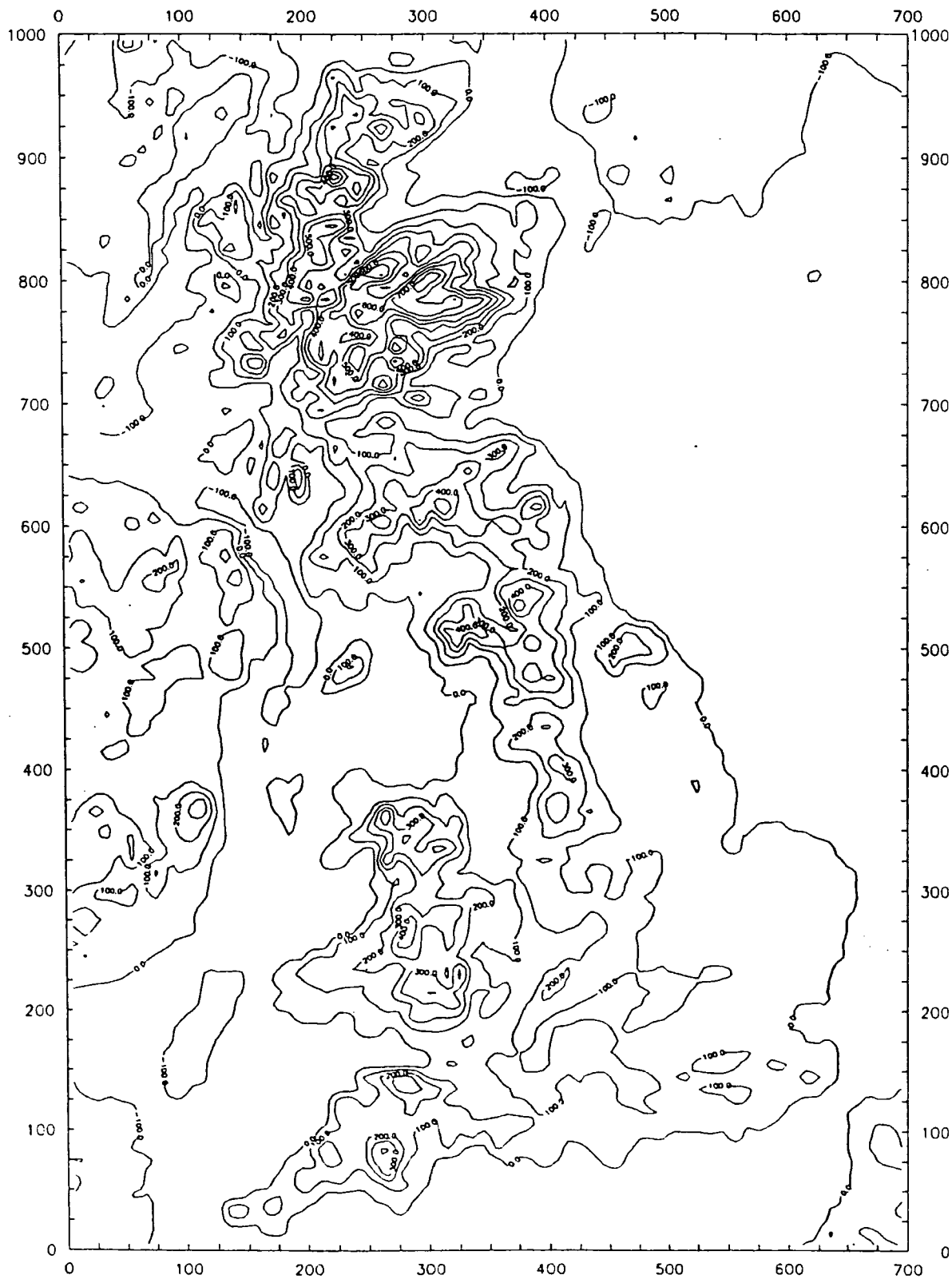
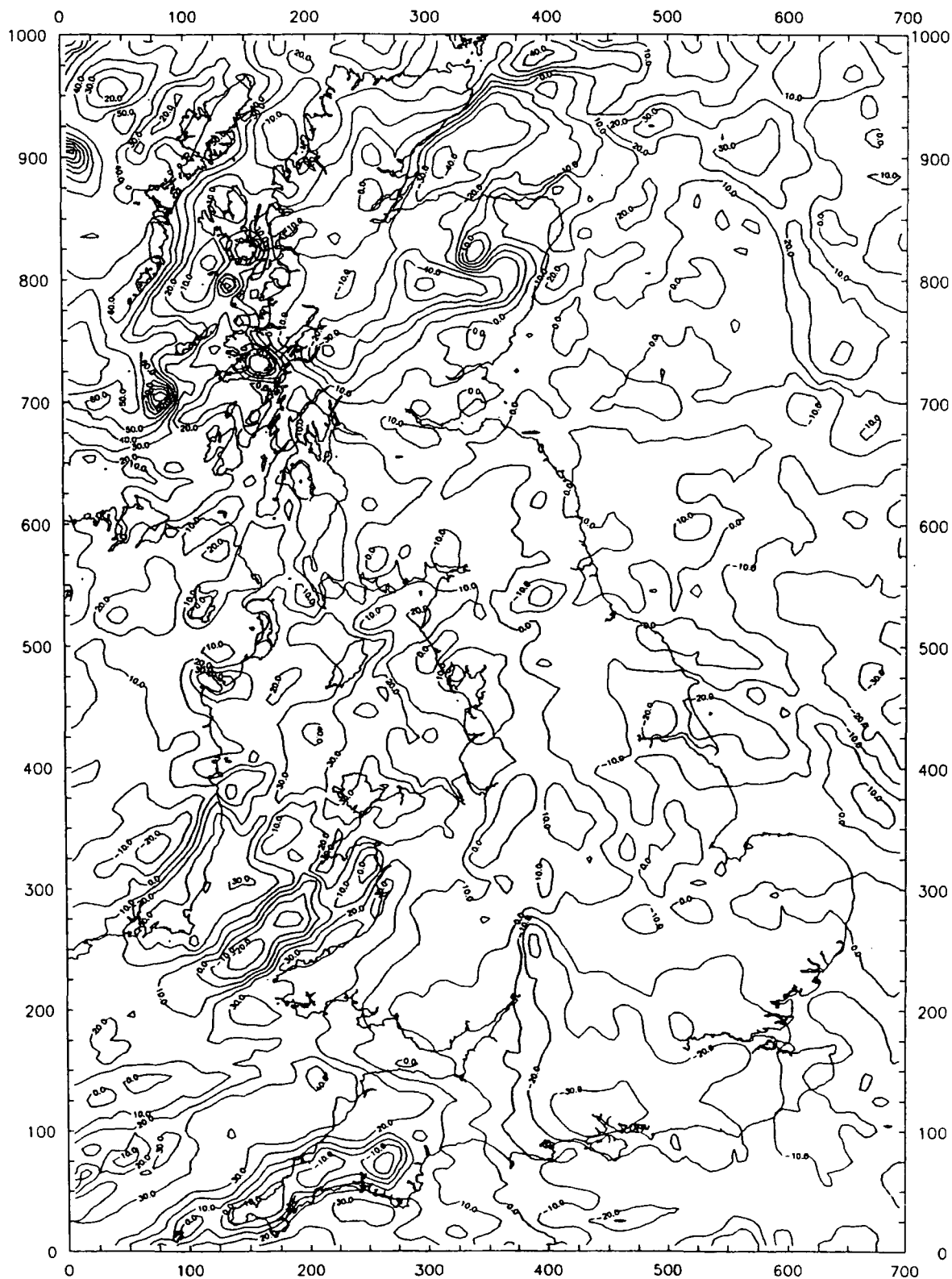


Figure 5.3. Contour map of the Bouguer anomaly gravity of the UK and adjacent regions. The contour interval is 10 mGal. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.



before determining the observed response. In marine regions the load of the water of density 1030 kg m^{-3} was replaced by an equivalent load of rock of density 2700 kg m^{-3} , and the topography was modified accordingly.

The discrete fourier transforms of the topography and Bouguer gravity data were determined using the fast fourier transform (Cooley and Tukey, 1965). In the wavenumber domain the isostatic response function $Q(k)$ is defined by

$$B(\mathbf{k}) = Q(k) \cdot H(\mathbf{k}) \quad 5.13$$

where $B(\mathbf{k})$ is the fourier transform of the Bouguer gravity and $H(\mathbf{k})$ is the fourier transform of the topography. The response function is considered to be isotropic (Dorman and Lewis, 1970). To reduce bias by noise the response function is estimated from (McKenzie and Bowin, 1976)

$$\hat{Q}(\bar{k}) = \frac{\langle B(\mathbf{k})H(\mathbf{k})^* \rangle}{\langle H(\mathbf{k})H(\mathbf{k})^* \rangle} \quad 5.14$$

The asterisk denotes the complex conjugate. The angle brackets represent averaging around annuli centred on the origin in the wavenumber domain. $\bar{k}$ is the average wavenumber for each waveband. The averaging enhances the isotropic response at the expense of the random noise in the Bouguer gravity which is not expected to display azimuthal coherence (McNutt, 1979). The noise is the product of density contrasts uncorrelated with topography. The annuli are logarithmically spaced. This provides more information on the response in the diagnostic low wavenumber region ($k \leq 2.09 \times 10^{-2} \text{ km}^{-1}$).

The observed response $\hat{Q}(\bar{k})$ is treated as a complex number and is expressed by its amplitude and phase. If the real and imaginary parts of $\hat{Q}(\bar{k})$ are denoted by $\hat{Q}_R(\bar{k})$ and $\hat{Q}_I(\bar{k})$ then

$$|\hat{Q}(\bar{k})| = (\hat{Q}_R^2(\bar{k}) + \hat{Q}_I^2(\bar{k}))^{\frac{1}{2}} \quad 5.15$$

$$\text{phase } \hat{Q}(\bar{k}) = \tan^{-1} \left(\frac{-\hat{Q}_I(\bar{k})}{\hat{Q}_R(\bar{k})} \right) \quad 5.16$$

The variance of $\hat{Q}(\bar{k})$ is given by (Dixon et al., 1983)

$$\sigma_n^2(\bar{k}) = \frac{1}{n} \left(\frac{\sum_{i=1}^n B^2(k_i)}{\sum_{i=1}^n H^2(k_i)} - |\hat{Q}(\bar{k})|^2 \right) \quad 5.17$$

where n is the number of wavenumber terms in the waveband and i denotes the individual estimates within the waveband.

The coherence is a measure of the fraction of the power in the gravity spectrum that is linearly related to topography. The coherence is calculated from the cross spectra between the two signals

$$C(\bar{k}) = \langle B(\mathbf{k})H(\mathbf{k})^* \rangle \quad 5.18$$

and their respective power spectra

$$E_0(\bar{k}) = \langle H(\mathbf{k})H(\mathbf{k})^* \rangle \quad 5.19$$

$$E_1(\bar{k}) = \langle B(\mathbf{k})B(\mathbf{k})^* \rangle \quad 5.20$$

The coherence is defined as

$$\gamma_0^2(\bar{k}) = C^2(\bar{k})/E_0(\bar{k})E_1(\bar{k}) \quad 5.21$$

In the presence of noise positive bias is removed by using the expression

$$\gamma^2(\bar{k}) = (n\gamma_0^2(\bar{k}) - 1)/(n - 1) \quad 5.22$$

(Munk and Cartwright, 1966). n is the number of wavenumber components in each waveband. The standard errors of the coherence estimates are determined from

$$\Delta\gamma^2(\bar{k}) = (1 - \gamma_0^2(\bar{k}))/((2\gamma_0^2(\bar{k})/n)^{\frac{1}{2}}) \quad 5.23$$

(Bechtel et al., 1987).

5.4 Periodicity and the discrete fourier transform

The discrete fourier transforms of topography and gravity arrays of dimensions $m \times n$ actually represent the transforms of infinite periodic repetitions of the arrays. This periodicity is a consequence of the discrete representation of the spectra in the wavenumber domain. The periods of repetition are $m\Delta x$ and $n\Delta y$ respectively, where Δx and Δy are the sampling intervals. Discontinuities at the edges of the arrays can

generate artificial high wavenumber noise in the spectra if the array edges are not smoothed in some manner before the discrete fourier transform is calculated.

Three methods of smoothing the arrays can be applied (McNutt, 1983):

- (1) linearly ramping the eastern and southern borders of the topography array into equilibrium with the western and northern borders respectively. The length of these ramps should be no more than about 5% of the total dimensions of the array. The Bouguer gravity over the border ramps is first predicted using an assumed response function and then by using iterative estimates of the observed response;
- (2) east-west mirror imaging of the two data arrays accompanied by topographic ramping and Bouguer gravity prediction along the southern border;
- (3) tapering the array edges to zero using a cosine taper. The length of the cosine taper is usually specified to be 10%, or less, of the total array dimensions.

McNutt (1983) concluded that the cosine taper is the least desirable method because it forces a perfect correlation between gravity and topography for wavelengths of similar magnitude to the length of the taper. However, although the ramping and mirroring techniques remove the first order discontinuities at the array edges, higher order discontinuities such as changes in gradient remain. Mirror imaging the array also contaminates the long wavelength response.

A further complication arises from cyclic convolution. The multiplication of the wavenumber domain coefficients of the topography and Bouguer gravity required to calculate the observed response function should be equivalent to convolution in the space domain. However, because the discrete transforms represent periodically repeating arrays of topography and gravity in the space domain, the product of multiplication in the wavenumber domain is not equivalent to the convolution of the finite arrays. The convolution calculated by the multiplication of the wavenumber coefficients of the repeating arrays is known as cyclic convolution (Meskó, 1984). To obtain a convolution proportional to the true convolution of the finite arrays, the arrays must be padded out with zeros to twice their original dimensions before calculating the discrete transforms.

To test the different methods of array modification, the gravitational attraction of

the compensation of the topography of the UK was calculated assuming Airy isostasy. Observed response functions were then determined from the topography and the estimated Bouguer anomalies generated by the theoretical compensation using each of the main array modification techniques. The observed response functions were then compared with the expected theoretical response.

The Airy isostasy model assumes a mean crustal thickness of 30 km. The density of the crust ρ_0 is taken to be 2700 kg m^{-3} and that of the upper mantle 3400 kg m^{-3} . The deviation of the Airy root $r(x)$ from the mean crustal depth was calculated from

$$r(x) = -\rho_0 h(x) / (\rho_m - \rho_0) \quad 5.24$$

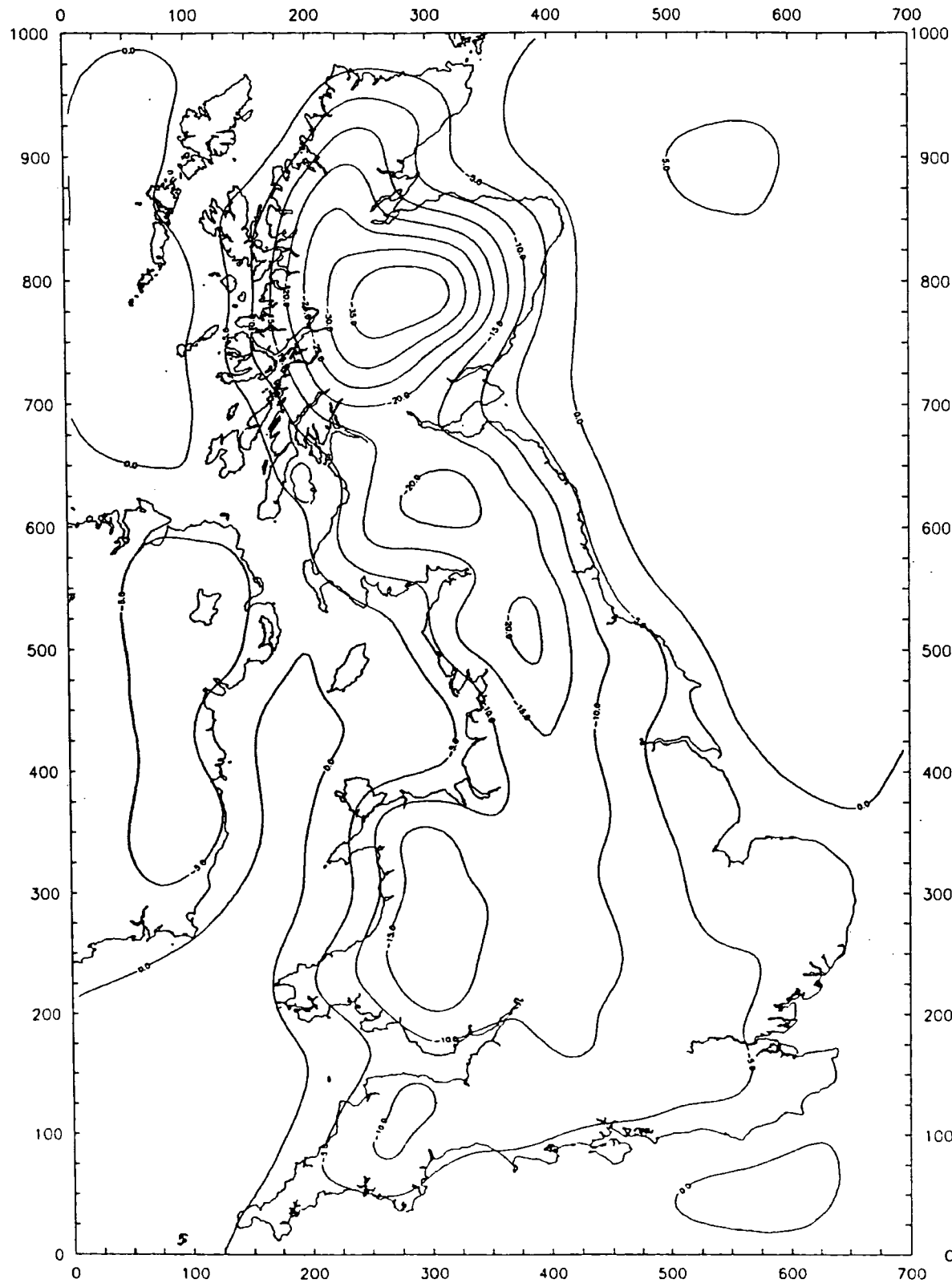
on land and

$$r(x) = -(\rho_0 - \rho_{water})h(x) / (\rho_m - \rho_0) \quad 5.25$$

at sea, where $h(x)$ is the surface topography, ρ_{water} is the density of sea water (1030 kg m^{-3}) and the z axis is taken to be positive downwards. The gravity anomalies generated by the root topography were determined in the wavenumber domain using the first term of the Parker's series expression (equation (5.10)) which is sufficiently accurate as the depth fluctuations of the Moho are much less than the depth of the Moho. Before the discrete fourier transform of the Airy root was calculated, the array edges were smoothed using a cosine taper of width 80 km and the array was padded out with zeroes. The calculated gravitational attraction is shown in figure 5.4. The Airy model data grids were then analysed using the three methods of array modification. The effect of detrending the arrays before tapering was also considered. The results of these tests are shown in figure 5.5.

The observed response for the zero padded arrays comprises 13 sampling levels. The ramped and mirror imaged arrays were sampled at only 11 levels because there were relatively fewer individual wavenumber estimates of the response. The zero padding does not produce an actual improvement in resolution because the uncertainty of the estimated response increases (see Bracewell, 1978). The number of sampling levels applied is a compromise between resolution and the instability of the estimates (Ussami, 1986).

Figure 5.4. Contour map of the gravity anomalies produced by the theoretical local Airy compensation of the topography of the UK region. The depth of compensation is 30 km. The contour interval is 10 mGal. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.



5.

km.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.

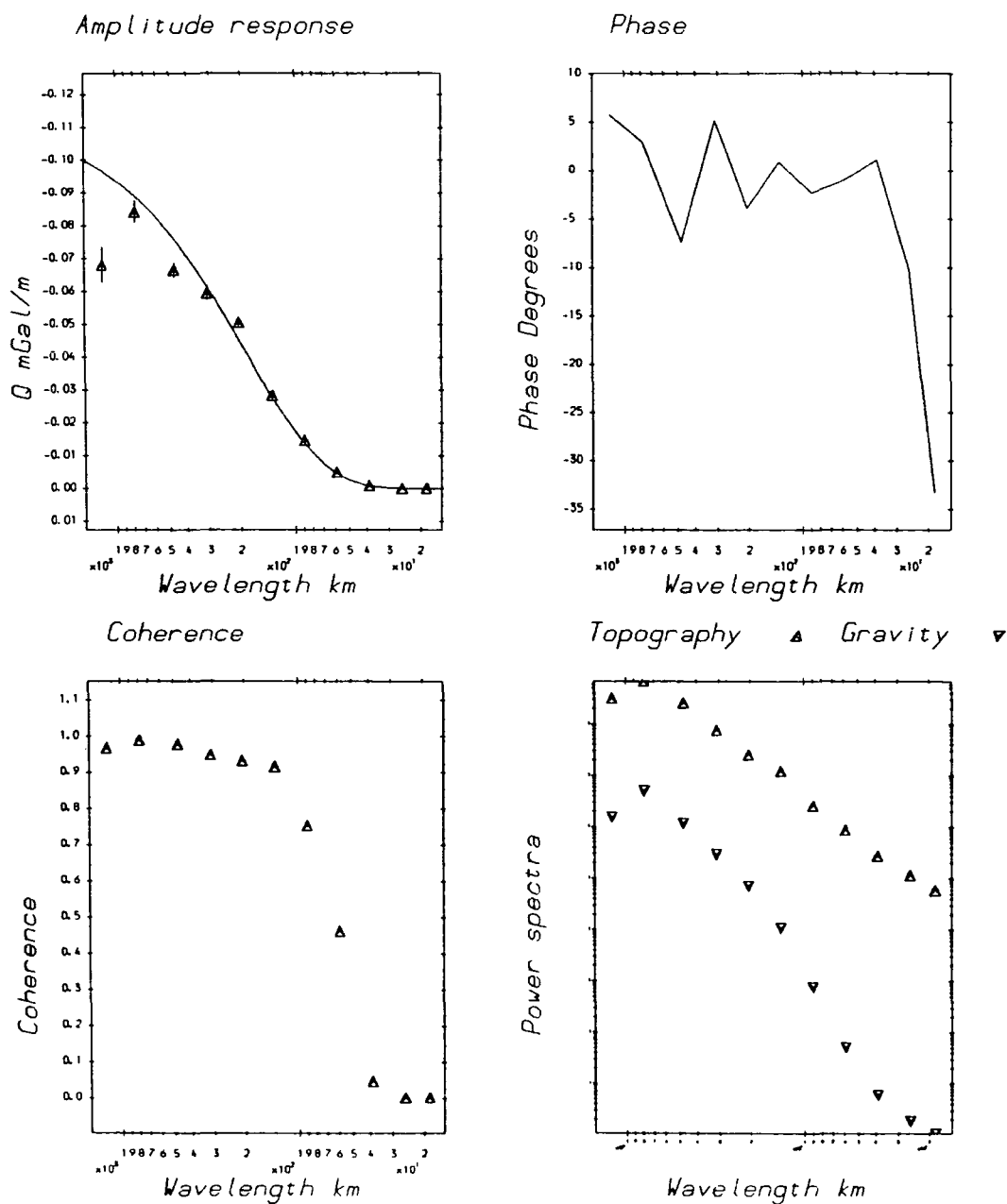


Figure 5.5c. The isostatic response function, coherence and power spectra determined from the theoretical Airy isostasy topography and gravity grids after the removal of a least squares best fit plane from the topography and gravity grids. 13 waveband averages have been determined for each component.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.

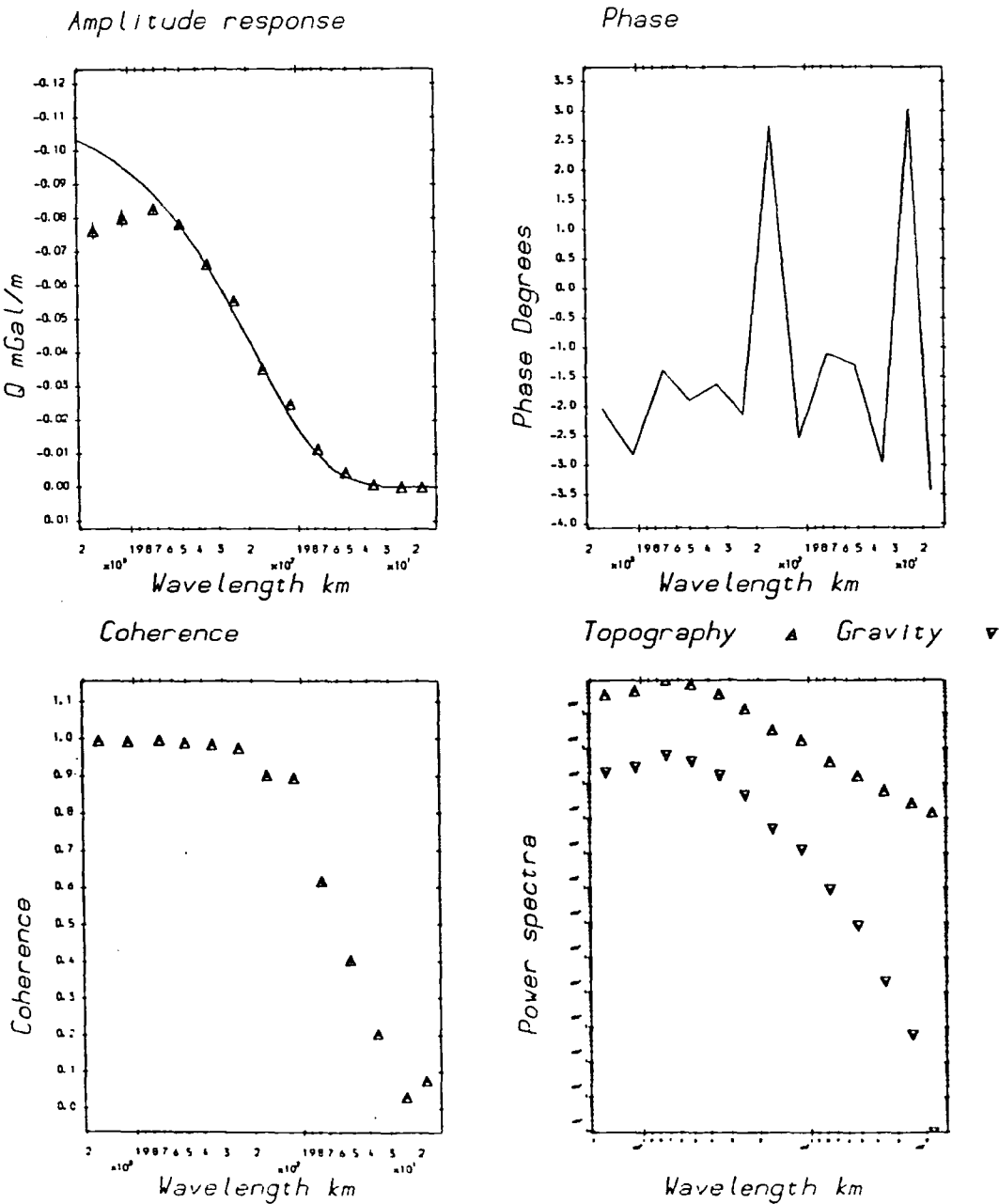
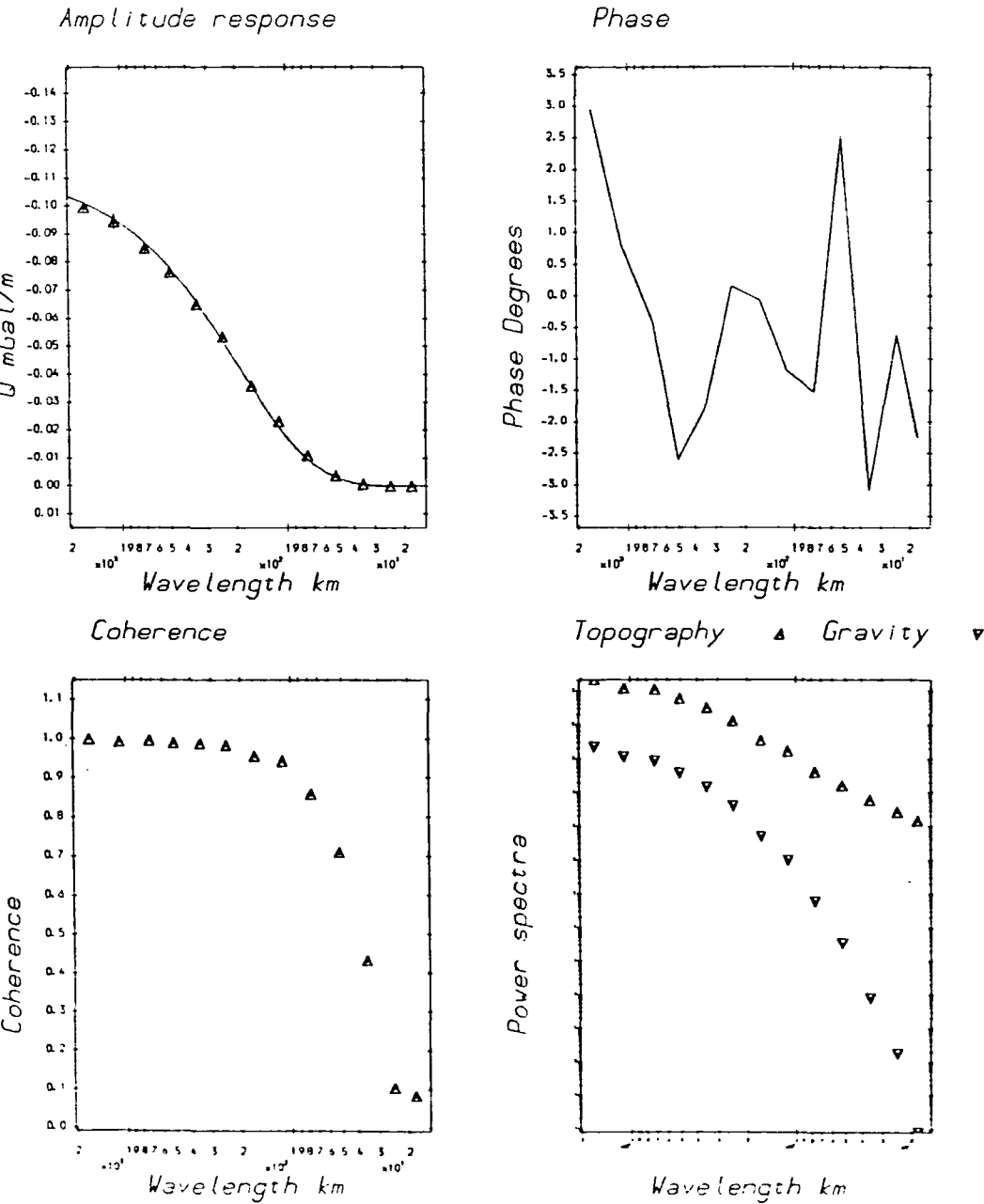


Figure 5.5d. The isostatic response function, coherence and power spectra determined from the theoretical Airy isostasy topography and gravity grids after the application of a cosine taper to the edges of the topography and gravity grids. 13 waveband averages have been determined for each component.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.



The estimates of the long wavelength response obtained using the ramped and mirrored arrays are poor. The observed response at long wavelengths underestimates the theoretical response. Similarly the long wavelength estimates of the response are corrupted by detrending the arrays. It is also important to note that linear trends within the data may have physical meaning and trend removal may generate a misleading response (Diamant, 1985). The amplitude response recovered using the cosine taper is acceptable. The width of the applied taper was kept short at 50 km so that any corruption of the observed response occurs at short wavelengths. Thus the important long wavelength response is accurately defined. The results are still acceptable for even the longest wavelength estimates which because of the zero padding refer to wavelengths greater than the original dimensions of the data grids.

The results of the array modification tests indicated that the cosine taper method should be utilised in the studies of the observed data. The Airy isostasy model also enables the accuracy of the observed phase of the response and coherence to be evaluated. The full results for the cosine taper test are discussed below.

The observed phase of the Airy model is very close to zero indicating that the response is real as predicted by the theoretical model. For Airy isostasy the coherence between the gravity and topography signals should equal 1.0. The observed coherence is close to 1.0 for wavelengths greater than 100 km. The decay in the coherence at wavelengths shorter than 100 km may arise from the difficulty of calculating the coherence when the gravity signal is much weaker than the topography signal.

5.5 Preliminary interpretation of the observed isostatic response function

5.5.1 Description of the observed response and coherence

The observed isostatic response function and coherence for the UK region are shown in figure 5.6. The results are tabulated in table 5.1. The theoretical response for Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$ is also shown. The observed standard deviation of the response increases as the wavelength of observation increases. This partly reflects the reduction in the number of individual wavenumber

Figure 5.6. The isostatic response function, coherence and power spectra determined from the topography and Bouguer gravity of the UK and adjacent regions. 13 waveband averages have been determined for each component.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.

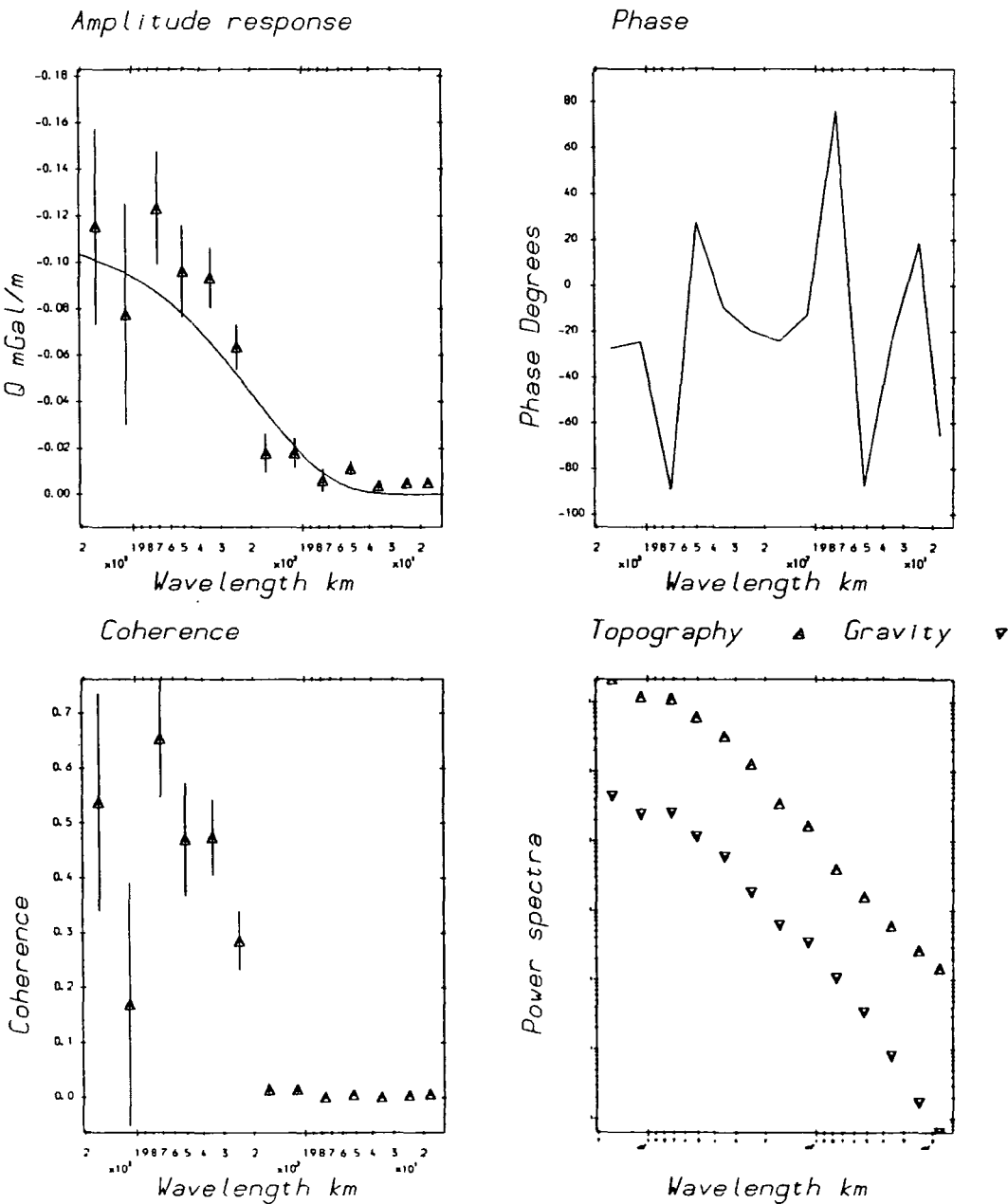


Table 5.1

Results for initial response function
analysis of the United Kingdom region

λ	$\hat{Q}_{amp}$	$\hat{Q}_{phase}$	σ_n	n	γ^2	$\Delta\gamma^2$
1647	-0.11549	-27.28	0.0420	4	0.5385	0.1979
1093	-0.07774	-24.59	0.0476	6	0.1698	0.2217
713	-0.12325	-89.03	0.0242	12	0.6546	0.1069
505	-0.09613	27.25	0.0199	24	0.4698	0.1029
347	-0.09347	-9.58	0.0131	54	0.4750	0.0690
242	-0.06373	-19.81	0.0098	102	0.2859	0.0536
164	-0.01792	-24.27	0.0082	254	0.0146	0.0118
112	-0.01802	-13.20	0.0062	518	0.0140	0.0077
76	-0.00621	76.05	0.0049	1112	0.0006	0.0016
52	-0.01141	-87.81	0.0029	2390	0.0058	0.0023
36	-0.00395	-24.91	0.0016	5120	0.0010	0.0007
24	-0.00517	18.49	0.0008	10934	0.0042	0.0009
18	-0.00529	-65.60	0.0007	7806	0.0065	0.0013

λ is the wavelength of the estimate in km; $\hat{Q}_{amp}$ and $\hat{Q}_{phase}$ are the amplitude and phase of the response in mGal m⁻¹; σ_n is the standard deviation of the response; n is the number of wavenumber terms averaged for each estimate; γ^2 is the coherence; $\Delta\gamma^2$ is the standard error of the coherence.

estimates within each waveband as $\bar{k}$ decreases which causes an increase in the variance of the estimate $\hat{Q}(\bar{k})$ (Ussami, 1986).

At short wavelengths, $\lambda < 200$ km, the amplitude response is low, but non-zero. The anomalously high estimate at $\lambda = 50$ km is probably a result of the 50 km width of the applied cosine taper. Between $\lambda = 200$ km and 700 km the amplitude response is overcompensated. The observed amplitude response is greater than that predicted for Airy isostasy. Between $\lambda = 100$ km and 500 km the response is roughly real with the associated phase values lying between $\pm 30^\circ$. However, for the $\lambda = 713$ km estimate the phase is approximately -90° . This is an unexpected result for such a long wavelength and is not predicted by flexure. The amplitude response estimates for $\lambda > 1000$ km are associated with large errors. The observed phase for these estimates lies between -20° and -30° .

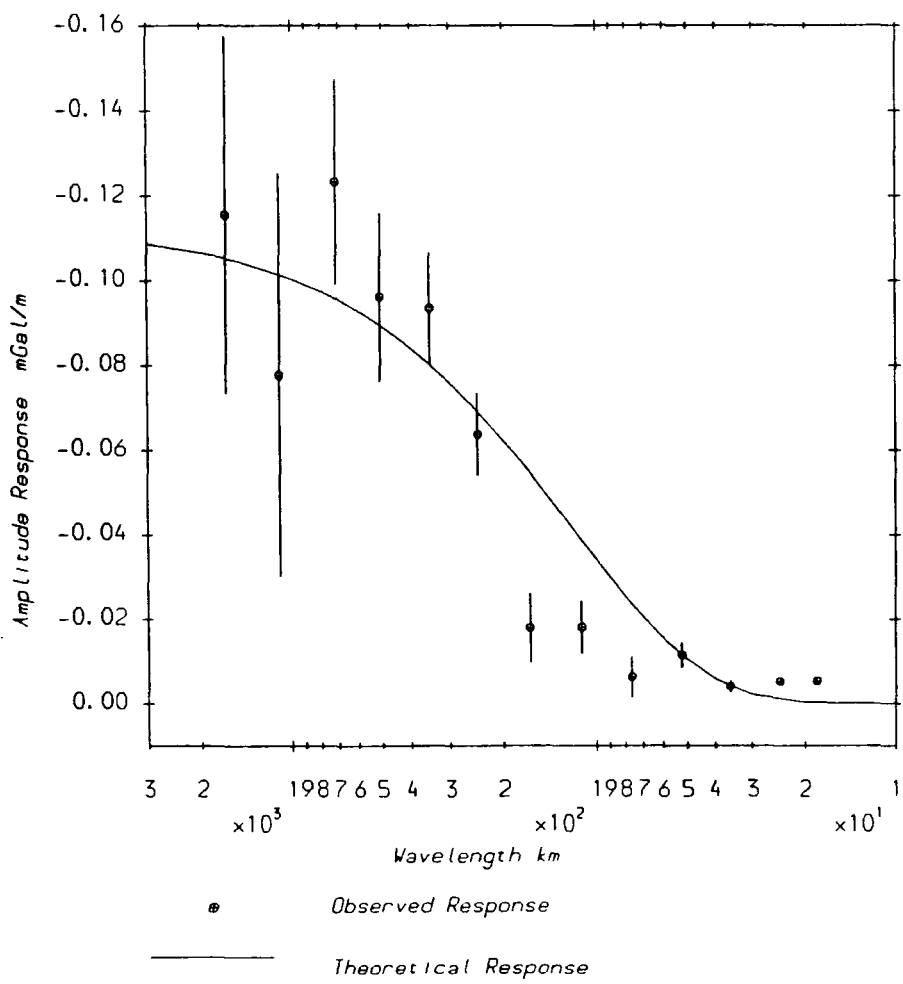
The observed coherence is low for $\lambda < 200$ km. Between $\lambda = 200$ km and 700 km the coherence rises steadily but it drops dramatically for the 1093 km wavelength estimate. The coherence increases again for the longest wavelength estimate.

5.5.2 Comparison of observed and theoretical response functions

The observed response shows a marked deviation from the theoretical response functions (figure 5.6). The roll over region of the theoretical response shifts towards the longer wavelengths as the elastic thickness of the lithosphere increases. Therefore, if the observed response is modelled with the theoretical response the best fitting model will require local Airy isostasy and a shallow depth of compensation (< 30 km) to explain the apparent overcompensation. Using the l_1 norm as a measure of misfit, the best fit to the observed data is obtained for a depth of compensation of 19 km (figure 5.7). However, the fit between the observed and theoretical amplitude response is poor for wavelengths between 60 and 200 km and the observed coherence markedly differs from that obtained for local Airy isostasy in the earlier test examples.

Similar results have been obtained using cross spectral techniques for the USA and Australia (Banks et al., 1977; McNutt and Parker, 1978). The isostatic response for the USA was best explained by a lithospheric elastic thickness of only 5–10 km. An even

Figure 5.7. l_1 norm best fit between the observed amplitude response for the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical amplitude response for surface loading. The theoretical amplitude response function parameters are $T_e = 0$ km, $\rho_0 = 2700$ kg m⁻³ and $z_m = 19$ km.



thinner elastic thickness of 1 km, which was less than the depth to the compensating density contrasts, was required for Australia. The values for the elastic thickness of the lithosphere estimated using cross spectral techniques are significantly lower than those determined from the analysis of individual applied loads. Estimates of the elastic thickness of the continental lithosphere at the Himalayas (80–100 km), the Alps (25–50 km) and the Appalachians (80–120 km) were obtained by Karner and Watts (1983). The Boothia uplift (Walcott, 1970a) and the Mid-continent gravity high of the USA (Cohen and Meyer, 1966) appear to be regionally compensated by a continental lithosphere with an elastic thickness of approximately 30 km (McNutt, 1980).

5.5.3 The importance of subsurface loading of the continental lithosphere

The apparent low elastic thicknesses obtained from the response function analyses of continental regions can be explained as the consequence of three possible sources of error in the initial assumptions of the interpretations:

- (1) the lithosphere maybe loaded by density contrasts within and possibly beneath the lithosphere as well as by surface topography;
- (2) the extensive continental regions required for the analysis may mean that an average response for a number of different tectonic provinces is determined;
- (3) the determination of $\hat{Q}(\bar{k})$ maybe biased towards regions of significant topographic amplitude thus ignoring the stable continental interiors.

These points were considered in detail by Forsyth (1985). The initial derivation of the theoretical response considered a surface topography of density ρ_0 loading a laterally homogeneous lithosphere. However, thermal perturbations in the lithosphere, intrusive activity, crustal underplating, sedimentary basins, variations in the mean density of the upper and lower crusts and so on generate density contrasts that act on the lithosphere from within (Forsyth, 1985). Forsyth (1985) determined the theoretical response for subsurface loading when the loading is modelled as topography on the Moho to be

$$Q'(k) = -2\pi\rho_0 G e^{-kz_m} \phi \quad 5.26$$

where

$$\phi = 1 + \frac{Dk^4}{\rho_0 g}$$

and z_m is the mean depth to the Moho. If the initial, pre-flexure topography of the Moho is $W_I(\mathbf{k})$ and the deflection produces a topography $H_B(\mathbf{k})$ at the surface and a final topography $W_B(\mathbf{k})$ on the Moho then from the thin plate equation

$$W_I(\mathbf{k}) = W_B(\mathbf{k}) - H_B(\mathbf{k}) \quad 5.27$$

$$W_B(\mathbf{k}) = -\rho_0 H_B(\mathbf{k}) \phi / \Delta \rho \quad 5.28$$

The theoretical response $Q'(k)$ for a number of different elastic thicknesses is shown in figure 5.8. At short and long wavelengths the response is similar to that of surface loading. At intermediate wavelengths the stiffness of the lithosphere suppresses the formation of topography and the amplitude of the response becomes much greater than that for surface loading.

The theoretical response for subsurface loading bears little relation to the observed response function but if the subsurface response for a number of different tectonic provinces is averaged or if both surface and subsurface loading occur the method of determining the observed response function may generate misleading results if interpreted in terms of a uniform lithosphere loaded solely by topography (Forsyth, 1985).

5.5.4 Comparison of the influence of surface and subsurface loading on the observed response

From the definition of the response function (5.13) the estimator $\hat{Q}(k)$ may be written as

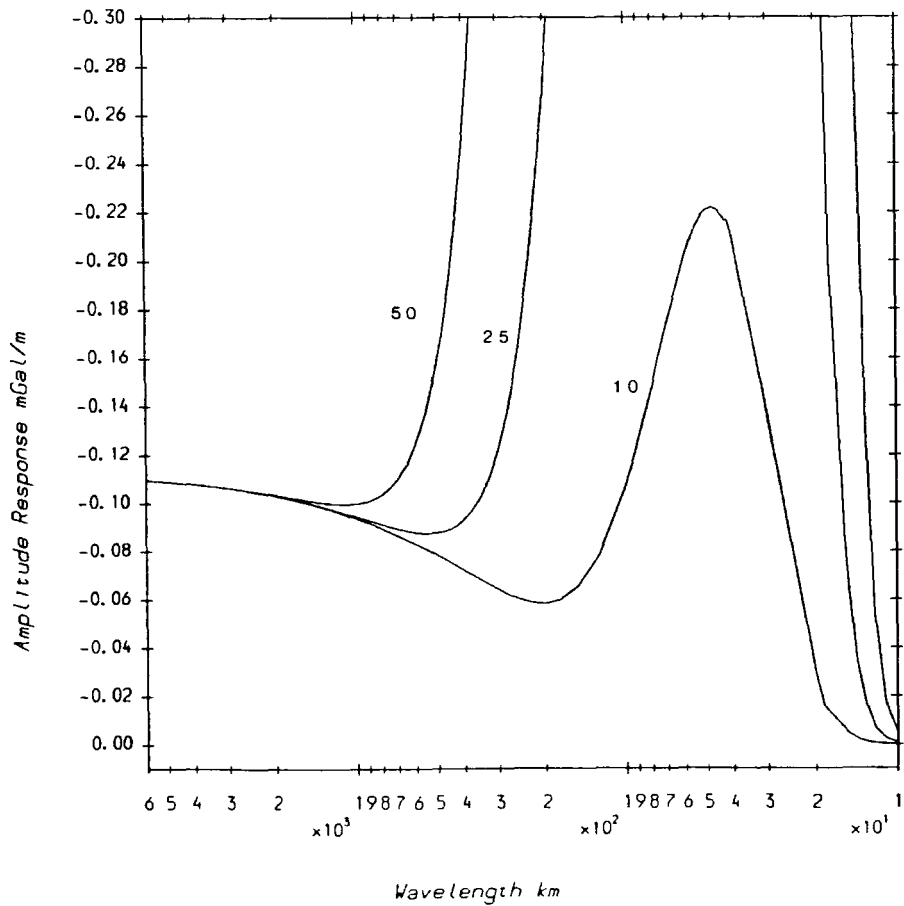
$$\hat{Q}(k) = \frac{\langle Q(k) \cdot H(\mathbf{k}) \cdot H(\mathbf{k})^* \rangle}{\langle H(\mathbf{k}) \cdot H(\mathbf{k})^* \rangle} \quad 5.29$$

Therefore, the observed value of $\hat{Q}(k)$ is weighted by the square of the amplitude of the topography. The averaged response over a number of different tectonic provinces will be biased towards those regions characterized by the greatest topography (Forsyth, 1985). If both surface and subsurface loading occur in a given region these weighting factors will control the relative importance of the two forms of loading on the observed response.

The combined effect of the two forms of loading on a region of uniform elastic thickness has been calculated by Forsyth (1985). Although the theoretical responses

Figure 5.8. Theoretical amplitude response for subsurface loading at the Moho for various values of the elastic thickness of the continental lithosphere.

The amplitude response curve annotation denotes the elastic thickness of the continental lithosphere in km. The additional amplitude response function parameters are $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.



are both real, the observed response may be complex if the two signals are out of phase (Stephenson and Beaumont, 1980). Labelling the real and imaginary parts of the fourier transforms of the topography with the subscripts R and I respectively, the fourier transform of the Bouguer gravity is given by

$$B(\mathbf{k}) = Q({}_RH_T + i{}_IH_T) + Q'({}_RH_B + i{}_IH_B) \quad 5.30$$

and that of the topography

$$H(\mathbf{k}) = {}_RH_T + {}_RH_B + i({}_IH_T + {}_IH_B) \quad 5.31$$

Note that for convenience the wavenumber argument has been left out of the complex topography. The value of $\hat{Q}(k)$ may be determined from

$$\begin{aligned} \langle B \cdot H^* \rangle = & \langle Q({}_RH_T^2 + {}_IH_T^2) + Q'({}_RH_B^2 + {}_IH_B^2) + (Q + Q') \cdot ({}_RH_{BR}H_T + {}_IH_{BI}H_T) \\ & + i(Q' - Q)({}_IH_{BR}H_T - {}_IH_{TR}H_B) \rangle \end{aligned} \quad 5.32$$

and

$$\langle H \cdot H^* \rangle = \langle {}_RH_B^2 + 2{}_RH_{BR}H_T + {}_RH_T^2 + {}_IH_B^2 + 2{}_IH_{BI}H_T + {}_IH_T^2 \rangle \quad 5.33$$

If we assume that the initial surface and subsurface loads are statistically independent the ensemble averaging required to calculate $\hat{Q}(k)$ should eliminate cross terms such as ${}_IH_{BI}H_T$ and $\hat{Q}(k)$ should be real. The expected admittance is then given by

$$\hat{Q}(k) = -2\pi G\rho_0 e^{-kz_m} \frac{\{\phi H_B^2 + H_T^2/\xi\}}{\{H_B^2 + H_T^2\}} \quad 5.34$$

where $H_T^2 = {}_RH_T^2 + {}_IH_T^2$. The assumption of statistical independence is significant. If the initial loads are not statistically independent the observed response may be complex. This appears to be the case for most of the UK response, except for the intermediate wavelengths.

The amplitudes of the initial surface and subsurface loads may be expressed by the ratio of bottom to surface loading f

$$|H_B| = f\rho_0|H_T|/\xi\Delta\rho \quad 5.35$$

If $f = 1$ and the plate is strong $H_T > H_B$. Therefore, the response will be biased towards the surface loading. When the plate is weak the two responses are identical.

Substituting equation (5.35) into (5.34) gives the following expression for $\hat{Q}(k)$ as a function of k and f

$$\hat{Q}(k) = -2\pi G \rho_0 e^{-kz_m} \frac{\{\phi(f\rho_0/\xi\Delta\rho)^2 + 1/\xi\}}{\{(f\rho_0/\xi\Delta\rho)^2 + 1\}} \quad 5.36$$

The theoretical values of $\hat{Q}(k)$ for several values of f are plotted in figure 5.9. When f is small (< 1) the response is similar to that of a weaker plate loaded by subsurface loading alone (Forsyth, 1985).

The observed response may also be approximated as the result of the subsurface loading of a number of distinct tectonic provinces (Forsyth, 1985). Consider a population of provinces all of equal area with elastic thicknesses distributed uniformly from zero to $T_{e_{max}}$. If the applied subsurface load is of constant amplitude in each province, the response for a given wavenumber will be biased towards those provinces that bend most easily at that wavenumber.

This effect may be modelled quantitatively (Forsyth, 1985). Initially we assume that the initial subsurface load is constant, independent of T_e and ϕ , and that the phases are random. If the initial subsurface load is modelled as the topography $W_I(\mathbf{k})$ on the Moho for each province the resulting surface topography is given by

$$H_B(\mathbf{k}) = -W_I(\mathbf{k})\Delta\rho g/\rho_m \left(\frac{Dk^4}{\rho_m g} + 1 \right) \quad 5.37$$

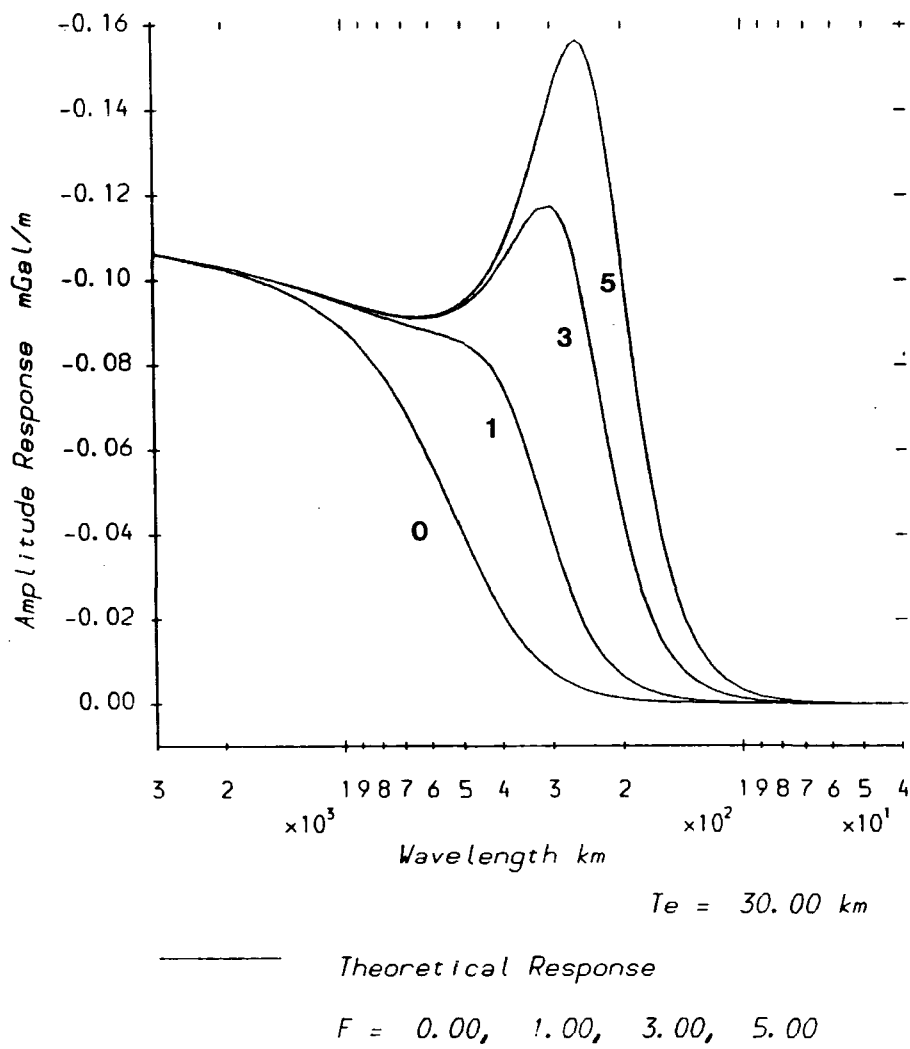
The subsurface response $Q'(k)$ is given by (5.26). The expected response for the whole region may be then determined from

$$\hat{Q}(k) = \frac{\int_0^{T_{e_{max}}} Q'(k) H_B^2(k) dT_e}{\int_0^{T_{e_{max}}} H_B^2(k) dT_e} \quad 5.38$$

where $T_{e_{max}}$ is set at 100 km. The integral is determined by numerical integration. Using $\rho_0 = 2700 \text{ kg m}^{-3}$ and $\rho_m = 3350 \text{ kg m}^{-3}$ a best fitting (by eye) curve was given for $z_m = 40 \text{ km}$ (figure 5.10). If these assumptions are correct the depth of loading for the UK is slightly shallower than that for the USA where the best fit was obtained for $z_m = 45 \text{ km}$ (Forsyth, 1985).

Before the true elastic thickness of the lithosphere can be estimated the relative importance of subsurface loading in the region must be determined. The response

Figure 5.9. Theoretical amplitude response for mixed surface and subsurface loading for various values of the loading ratio f . The amplitude response curve annotation denotes the value of f . The additional amplitude response function parameters are $T_e = 30$ km, $\rho_0 = 2700$ kg m⁻³, $\Delta\rho = 650$ kg m⁻³ and $z_m = 30$ km.



calculated from (5.14) is biased towards the topography of surface loads. The response function given by

$$\hat{Q}^{-1}(k) = \frac{\langle H(\mathbf{k}) \cdot B(\mathbf{k})^* \rangle}{\langle B(\mathbf{k}) \cdot B(\mathbf{k})^* \rangle} \quad 5.39$$

which predicts the best fit in a least squares sense to the topography from the Bouguer gravity is similarly biased to the square of the Bouguer gravity amplitude. If there is no contribution from loads within the plate then $\hat{Q}(k) \approx 1/\hat{Q}^{-1}(k)$ (Forsyth, 1981). If subsurface loading is important or the flexural rigidity varies the change in the weighting factors should cause $\hat{Q}(k) \neq 1/\hat{Q}^{-1}(k)$ (Forsyth, 1985).

$\hat{Q}(k)$ and $1/\hat{Q}^{-1}(k)$ have been determined for both the Airy isostasy test example and the real topography and Bouguer gravity grids of the UK. The results are displayed in table 5.2 and figures 5.11 and 5.12. For this test we assume that only surface loading is present and that the observed response should be real. The imaginary terms are considered to be associated with noise.

The results for the Airy isostasy example are very similar confirming the assumption that $\hat{Q}(k) \approx 1/\hat{Q}^{-1}(k)$ when only surface loading is operative. The results for the observed topography and Bouguer gravity show significant deviations between $\hat{Q}(k)$ and $1/\hat{Q}^{-1}(k)$. For wavelengths less than 200 km the values of $1/\hat{Q}^{-1}(k)$ become very unstable. This instability occurs because the filter $\hat{Q}^{-1}(k)$ is trying to predict the topography from the Bouguer gravity which may be considered to be a filtered representation of the topography (McNutt, 1983). At longer wavelengths the two responses appear to be similar but this is mainly a consequence of the large range of values of $\hat{Q}^{-1}(k)$. Note that even with this large range several of the discrete values of $1/\hat{Q}^{-1}(k)$ have had to be omitted. The deviation between $\hat{Q}(k)$ and $1/\hat{Q}^{-1}(k)$ indicates that the isostatic model comprising surface loading alone is inconsistent with the data. This result is not surprising because a number of the topographic features of the UK appear to be associated with the loading generated by underlying density contrasts. In particular, much of the high topography of the Grampian Highlands, the English Lake District, the northern Pennines, Dartmoor and Bodmin moor may be supported by the buoyancy of granitic material within the upper crust (Bott et al., 1958; Bott, 1967; Bott, 1974;

Table 5.2

Comparison of $\hat{Q}_{real}$ and $1/\hat{Q}_{real}^{-1}$
for the United Kingdom region

λ	$\hat{Q}_{real}$	$1/\hat{Q}_{real}^{-1}$
1647	0.10265	0.198
1093	0.07069	0.277
713	0.00209	10.625
505	-0.08547	-0.220
347	-0.09216	-0.196
242	-0.05996	-0.231
164	0.01634	1.064
112	-0.01754	-1.161
76	-0.00150	-17.508
52	0.00044	47.749
36	0.00358	3.640
24	0.00490	1.273
18	0.00219	1.926

λ is the wavelength of the estimate in km; $\hat{Q}_{real}$ is the real part of the response in mGal m^{-1} ; $1/\hat{Q}_{real}^{-1}$ is the inverse of the real part of $\hat{Q}^{-1}$ in mGal m^{-1} .

Figure 5.11. Comparison between $\hat{Q}_{real}(k)$ and $1/\hat{Q}_{real}^{-1}(k)$ determined from the theoretical Airy isostasy topography and gravity grids.

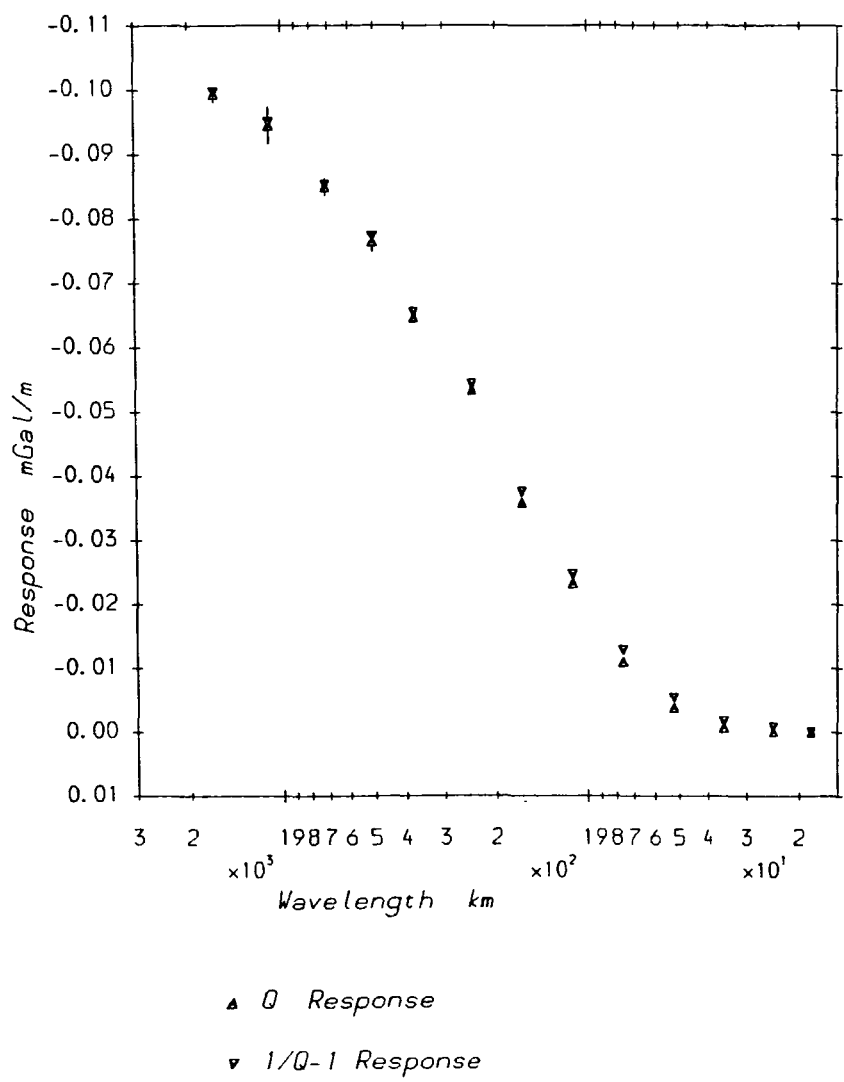
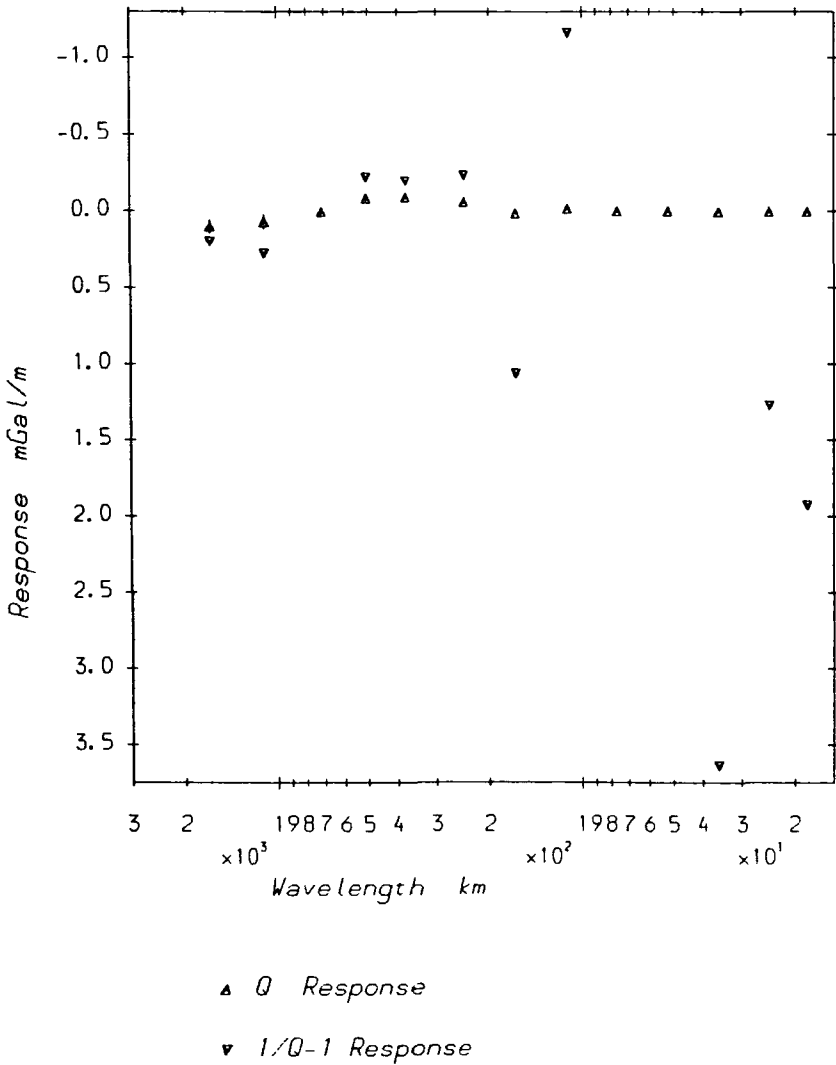


Figure 5.12. Comparison between $\hat{Q}_{real}(k)$ and $1/\hat{Q}_{real}^{-1}(k)$ determined from the topography and Bouguer anomaly gravity of the UK and adjacent regions.



Hipkin and Hussain, 1983).

The real components of $\hat{Q}(k)$ are interesting and reveal some important points which were not shown by the plot of the amplitude response. Theoretically, a negative correlation between the topography and Bouguer anomalies is expected. However, the three longest wavelength response estimates show a positive correlation. Between wavelengths of 500 and 70 km the correlation is negative as predicted except for the 164 km wavelength estimate. For wavelengths below 70 km the correlation is positive but the phase is very variable. The cause of the positive correlation at short wavelengths may be that the Bouguer correction density is too low (McNutt, 1983). The intermediate region ($200 < \lambda < 700$ km) roughly corresponds to the response predicted for flexure but the long wavelength response is clearly anomalous. The odd response estimate for the 713 km wavelength probably reflects a transition between the two forms of response.

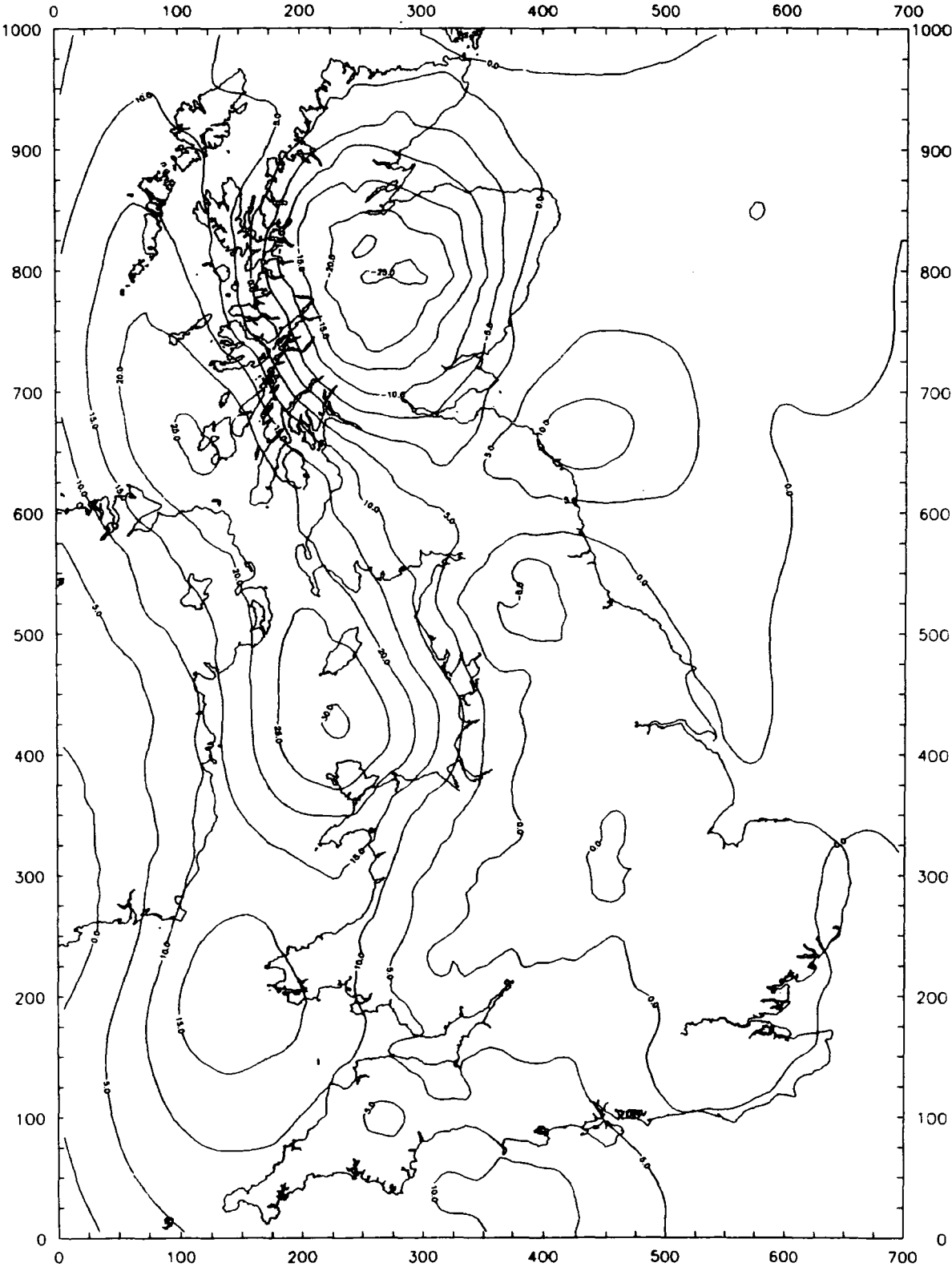
The interpretation of the long wavelength response ($\lambda > 700$ km) will be discussed later but it is important to note that the results of flexural models of the response function should only be compared with the observed response at intermediate wavelengths ($70 < \lambda < 700$ km).

5.6 Isostatic anomalies

The bias in the observed response towards surface loading causes the gravity field predicted by the convolution of the observed response with the topography mainly to represent the gravity anomalies produced by the compensation of the surface topography. Throughout this study the gravity anomalies determined by the filtering of the topography will be known as the predicted gravity. If the predicted gravity is subtracted from the Bouguer gravity to form an isostatic anomaly map, the resulting isostatic anomalies are mainly the result of subsurface loads.

The predicted gravity for the UK region is shown in figure 5.13. There is a clear correlation between some of the major features of the predicted gravity and the original topography. The region of highest topography, the Grampian Highlands of Scotland, is marked by a broad low of amplitude -25 mGal. The dimensions of this low are roughly

Figure 5.13. Contour map of the 'predicted gravity' of the UK and adjacent regions determined by filtering the topography with the observed isostatic response function. The contour interval is 10 mGal. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.



225 km E-W and 290 km N-S giving the low a wavelength in the region of 450–580 km. A belt of high predicted gravity values approximately 300 km wide traverses roughly N-S along the Irish Sea into the southern Hebrides. Over central Ireland the values fall to the west. The predicted gravity for the shallow North Sea province is characterized mainly by low amplitudes which reflects the low topographic amplitude of the region. Northern and central England are marked by negative values, especially over the high topography of the Pennines.

The isostatic anomaly map derived from the subtraction of the predicted gravity from the Bouguer gravity is shown in figure 5.14. The majority of the observed isostatic anomalies may be classified into three main sources of origin:

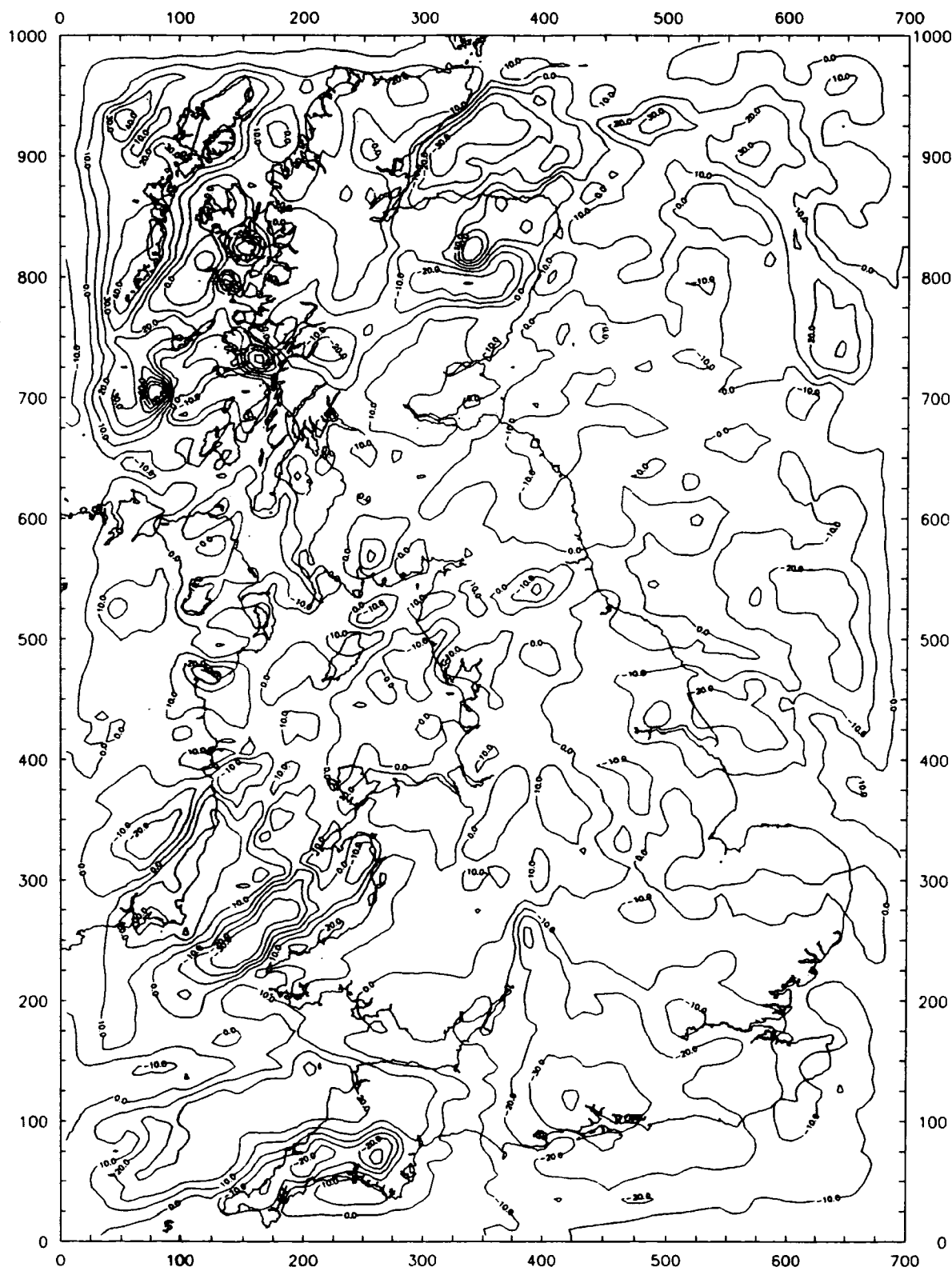
- (1) sedimentary basins;
- (2) granitic intrusions;
- (3) mafic igneous complexes.

The appearance of significant isostatic anomalies over sedimentary basins such as the Wessex basin, the southern North Sea basin, the Inner Moray Firth basin and so on is not surprising because the basins are not associated with significant topographical features making a correlation between gravity and topography unlikely. Thus the sedimentary basins are not easily amenable to study by cross spectral techniques and are most likely a significant source of incoherent energy in the gravity spectrum.

In contrast, the granites of the UK are generally associated with both high topography and significant Bouguer anomalies (Bott et al., 1958; Bott, 1967; Bott, 1974; Hipkin and Hussain, 1983). It would not be unreasonable to expect the granites to influence the observed response. However, the presence of significant isostatic anomalies over many of the granite complexes indicates that if this is the case the statistical procedure used to determine the response obscures the relationship. This problem is discussed in more detail later where the specific response for the Cornubian batholith massif is analysed and the effect of the granite complexes on the overall response for the UK is investigated.

The high amplitude isostatic anomalies observed over the Tertiary igneous com-

Figure 5.14. Isostatic anomaly map of the UK and adjacent regions produced by subtracting the 'predicted gravity' from the observed Bouguer anomaly gravity. The contour interval is 10 mGal. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.



plexes of the Hebrides, northwestern Highlands, northeastern Ireland and the younger gabbros of the northeastern Highlands are to be expected. The intrusions are relatively rare throughout the UK and the response function obtained for the relevant wavelengths of these features will represent an average of the observed response for the whole UK. The response function cannot be the required transfer function to predict the large, positive Bouguer anomalies over the complexes from their associated positive topography.

5.7 Isostasy and the intrusive granite complexes

The association of high topography and negative Bouguer anomalies over the major intrusive granite complexes suggests that some form of isostatic compensation is present. Bott et al. (1958) and Bott (1974) applied Gauss' theorem to the negative Bouguer anomalies over the granites of the Cornubian massif and the Lake District respectively and determined that the causative mass deficiencies were of the same order of magnitude as the mass of the high topography overlying the granites. This indicated that the upthrust produced by the underlying mass deficiencies was sufficient to support the excess topography but did not prove that the actual uplift was of isostatic origin. The uplift of the granite blocks was presumably facilitated by faulting within the upper crust but a regional tensional stress regime may have been required before uplift could occur (Bott et al., 1958). Hipkin and Hussain (1983) concluded that the isostatic compensation of the major topographic masses of northern Britain was brought about by density variations within the upper 16 km of the crust. In particular, the buoyancy effect of the granites in the Grampian Highlands suggests that this may support the higher elevation.

The influence of the granite complexes on the regional response function was investigated by determining the observed response function for the Cornubian batholith region of southwest England. The Cornubian batholith was chosen because it produces a large Bouguer gravity anomaly with amplitudes of the order of 45–55 mGal over Dartmoor and is associated with marked topographical highs particularly over Dart-

moor and Bodmin Moor. Topography and Bouguer gravity grids were formed for the region bounded by the OSGB grid coordinates 100.0, 300.0, 0.0, 120.0 km. The sampling interval was 4 km. Contour plots of the two grids are shown in figures 5.15 and 5.16.

The Bouguer anomaly low over the massif is the major feature of the Bouguer anomaly map, but significant high Bouguer anomaly values are observed offshore to the northwest and over the Plymouth Bay region. The main topographical features are associated with the granites. Therefore, the observed response $\hat{Q}(k)$ calculated from (5.14) will be biased towards the regions of high topography and the isostatic relationship of the granites. At wavelengths of similar magnitude to the dimensions of the grid the observed response will represent the regional variation over the grid and the influence of the granites may be less important. The accuracy with which the response function represents the relationship between topography and Bouguer gravity over the granites can be examined through a comparison of the observed Bouguer anomalies and the predicted gravity anomalies determined by convolving the response function with the topography.

The observed response is displayed in figure 5.17. The amplitude response rises rapidly at short wavelengths but decreases for wavelengths greater than 80 km. The low amplitudes of the longer wavelength estimates may represent a more regional form of compensation. The longest wavelength estimate of the 10 averaging levels has been omitted because only one wavenumber estimate was averaged and thus the determined response and coherence have little meaning.

For wavelengths less than 80 km the phase is low indicating a real response. The coherence also generally increases steadily up to wavelengths of 80 km magnitude.

The predicted gravity (figure 5.18) shows that the response function effectively describes the relationship between topography and Bouguer gravity. The predicted gravity closely matches the form of the main anomaly minima although the amplitudes are not always predicted accurately. There is a systematic variation between the observed Bouguer anomaly values and the predicted gravity. The predicted gravity min-

Figure 5.15. Contour map of the topography in the vicinity of the Cornubian batholith, SW England. The contour interval is 50 m. The gridding interval is 4 km. The scale is approximately 1:1,500,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

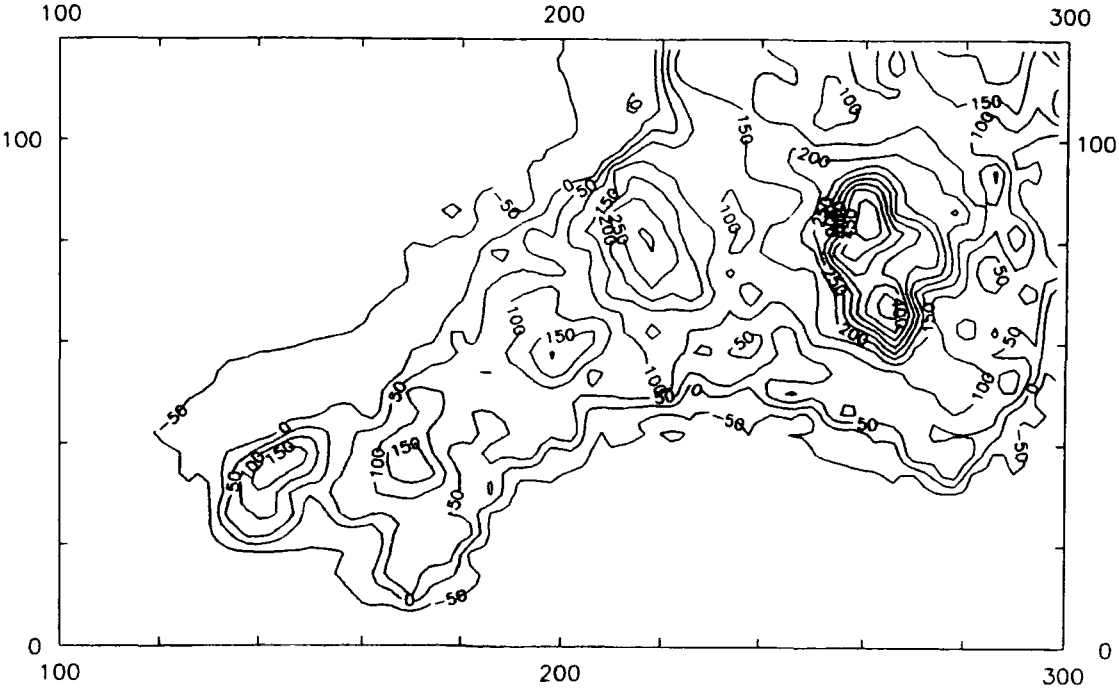


Figure 5.16. Contour map of the Bouguer anomaly gravity in the vicinity of the Cornubian batholith, SW England. The contour interval is 5 mGal. The gridding interval is 4 km. The scale is approximately 1:1,500,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

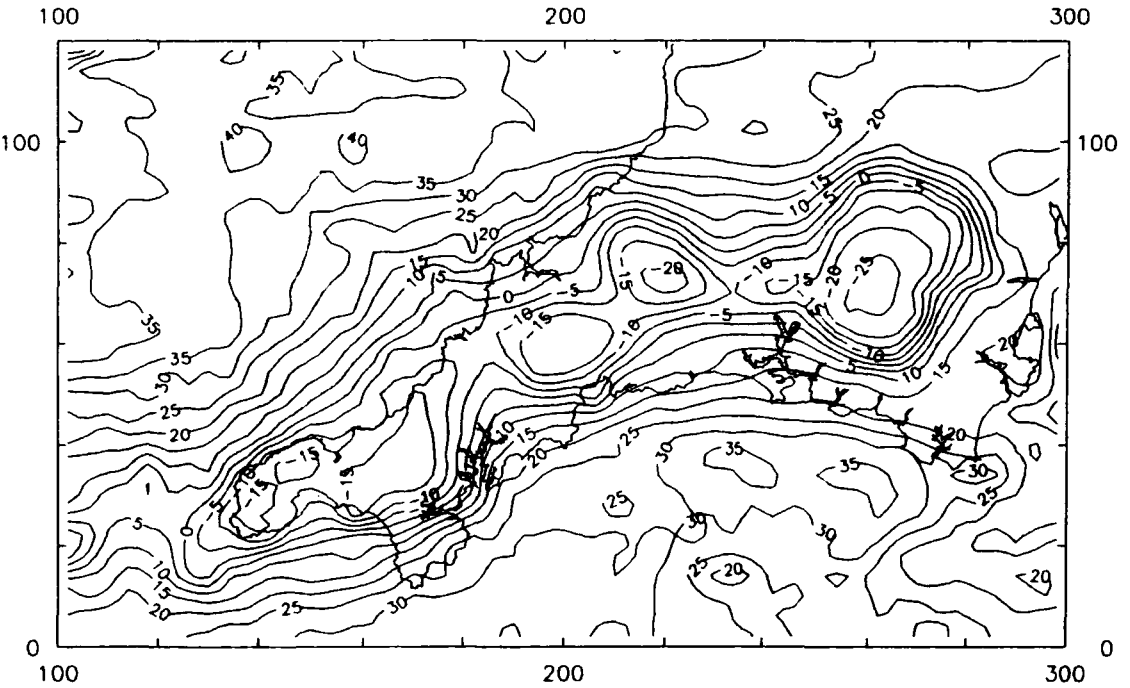


Figure 5.17. The isostatic response function, coherence and power spectra determined from the topography and Bouguer anomaly gravity in the vicinity of the Cornubian batholith.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.

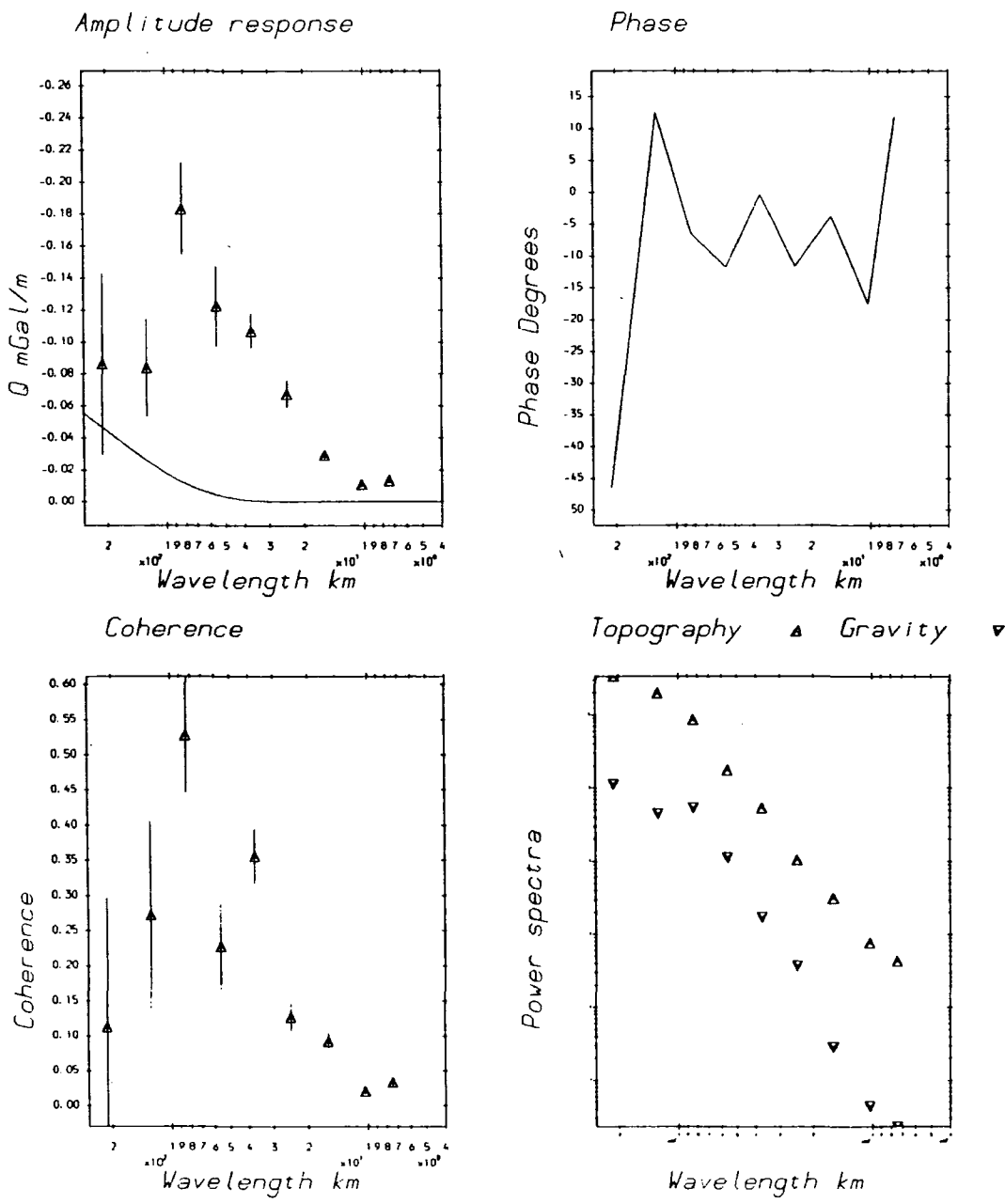
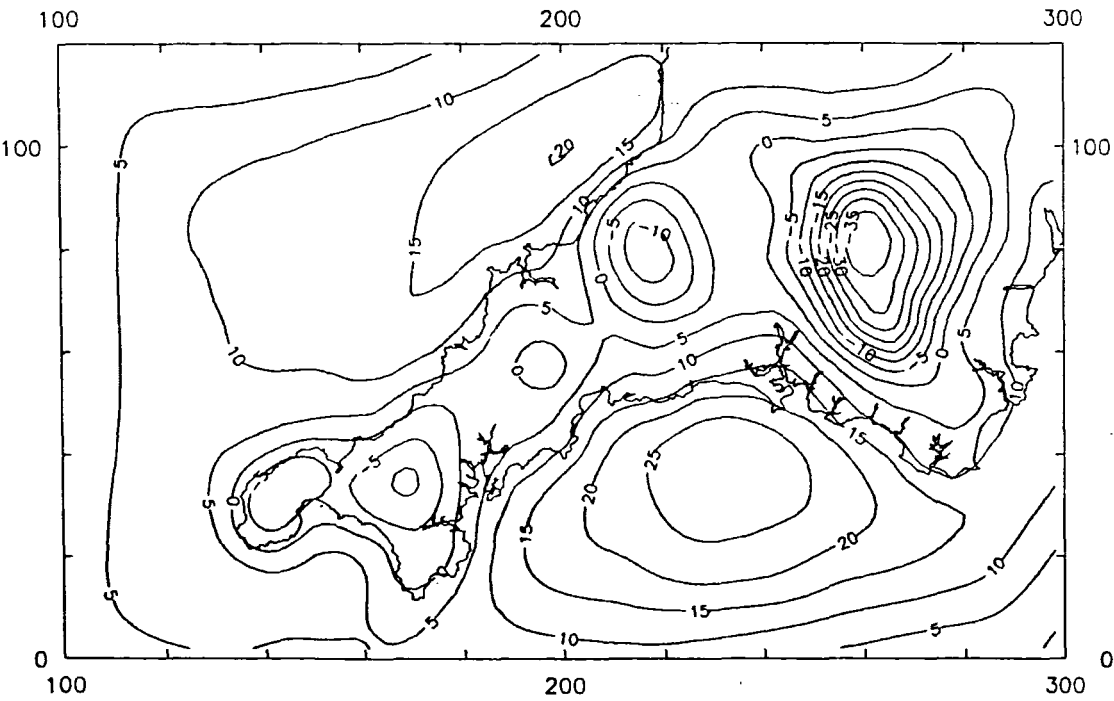


Figure 5.18. Contour map of the 'predicted gravity' determined by filtering the topography with the observed response function in the vicinity of the Cornubian batholith. The contour interval is 5 mGal. The gridding interval is 4 km. The scale is approximately 1:1,500,00 and the border annotation denotes Ordnance Survey coordinates in km.



over Dartmoor is greater in amplitude than the corresponding Bouguer anomaly low, whereas for the other granite complexes the local Bouguer anomaly minima are of greater amplitude than the filtered topography lows. The response function represents the average relationship between topography and gravity. For the Dartmoor granite the topography must be greater than the average for the observed Bouguer gravity. This indicates that the Dartmoor topography may be undercompensated. The other complexes appear to be overcompensated. The predicted gravity anomalies are some 10–15 mGal less negative than the observed anomalies.

The amplitude response for $\lambda < 80$ km has been modelled using the theoretical response $Q(k)$ in equation (5.12) assuming local Airy isostasy with $T_e = 0$. The observed response cannot be modelled directly because the maximum expected theoretical amplitude response given by $-2\pi G\rho_0$ is significantly lower than the observed results. The earlier results suggest a significant component of over compensation. If the granite batholith is represented by a surface topography $g(x)$ above a given depth within the crust and has a density ρ_g and supports a topography excess $h(x)$ assuming isostatic equilibrium

$$\rho_0 h(x) = (\rho_0 - \rho_g)g(x) \quad 5.40$$

If we add an overcompensation factor C_f to represent the isostatic disequilibrium then

$$\rho_0 h(x) = (\rho_0 - \rho_g)g(x)/C_f \quad 5.41$$

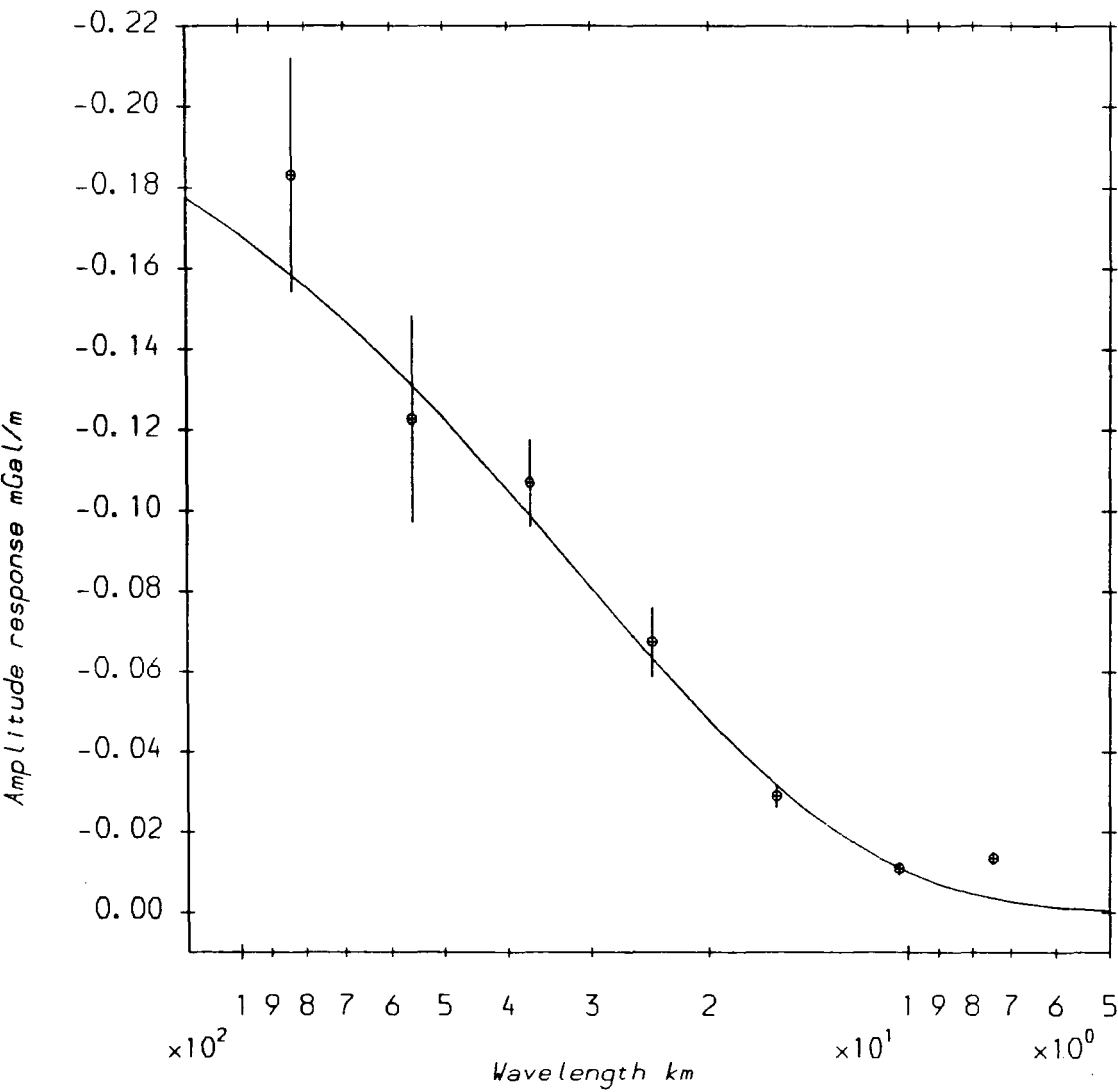
and $Q(k)$ is approximated by

$$Q(k) = -2\pi G\rho_0 e^{-kz_l}/\xi C_f \quad 5.42$$

where z_l is the depth of loading. The application of this equation is less valid than for the continental lithosphere model because the non-linear terms of the full series representation for the Bouguer anomaly generated by the granite–basement interface $g(x)$ will be more important. However, investigations have shown that the error is almost negligible and the formula should be adequate for a rough approximation.

Modelling the observed amplitude response using equation (5.42) a good fit was obtained for $\rho_0 = 2750 \text{ kg m}^{-3}$, $z_l = 5 \text{ km}$ and $C_f = 0.5$ (figure 5.19). The massif as a

Figure 5.19. Comparison between the observed and theoretical amplitude responses for the topography and Bouguer anomaly gravity in the vicinity of the Cornubian batholith.



$P_{\text{crust}} = 2750.0 \text{ kg/m}^3$ Compensation factor = 0.50
Depth = 5000.0 m Elastic thickness = 0.0 km

whole appears to be overcompensated. Bott et al. (1958) considered that the apparent overcompensation may be a consequence of a more regional uplift generated by the granites which would be more difficult to detect. The compensation occurs at very shallow depths and appears to be confined to the upper crust. The best fit depth of 5 km underestimates the known depth of the base of the granites (Bott et al., 1970) but gives the expected depth for an equivalent layer.

In conclusion, the granite complexes as represented by the Cornubian batholith are best described as achieving a form of local compensation within the upper crust. The significance of this is that the observed response function and coherence for the UK cannot be completely explained by the loading of an elastic plate lithosphere model. Compensation may be achieved through more than one mechanism. The form of compensation may be partly dependent on wavelength. Relatively small features formed by the granites may be compensated locally but longer wavelength loads and some other short wavelength loads require flexural support. In some cases the different isostatic mechanisms may possibly be considered individually but when the wavelengths at which the different forms of isostatic compensation are operative overlap the interpretation obtained for any of the individual mechanisms alone may be in error.

5.8 Removal of the influence of the granitic complexes of the UK from the observed response function

The 10×10 km topography and Bouguer gravity grids for the UK were modified to remove the isostatic effects of the major granitic complexes. The granitic complexes considered were the Cornubian massif, the Leinster granite, the Wensleydale granite, the Weardale granite, the Lake District batholith, the Cheviot granite, the Loch Etive granite and the East Highland granite complex which includes the Monadhliath, Cairngorm and Lochnagar complexes and the Aberdeenshire granites. The granitic intrusions of the Southern Uplands were not taken into account because of a lack of available information and the uncertainty in their lateral extent.

The negative Bouguer anomalies and high topography associated with the granitic

complexes were removed using the following procedure. The subsurface extent of the granite complexes was ascertained from previous literature. This information was then used to identify the 10×10 km grid squares which were underlain by granite. The location of the Cornubian batholith was estimated from Bott et al. (1958) and Lee (1986). The positions of the Lake District and north Pennine granites were ascertained from Bott (1967) and Bott (1974). The rough position of the Cheviot granite was taken from Spratling (1974) and the observed Bouguer anomaly minimum. The subsurface extent of the Scottish complexes was estimated from Lee (1986). The location of the Leinster granite was derived from surface outcrop and Bouguer anomaly data alone. Owing to the coarse resolution of the 10×10 km grid the required accuracy of the location of the subsurface extent of the granites was not great. The subsurface extent of each of the granite complexes studied is shown in figure 5.20.

Each complex was considered individually. The topography of each 10×10 km² grid square considered to be underlain by granite for a given complex was compared with a weighted average of the topography of the region immediately surrounding the complex. The weighted average was calculated in a similar manner to the weighted average interpolation technique discussed in Chapter 2 except that the topography of the grid squares considered to be underlain by granite was excluded from the calculations. If the low density granites support an excess component of topography the height of the individual grid elements over the complexes should exceed those of the weighted averages. For each grid square where this was true the vertical extent of the column of low density granite required to support the excess topography was calculated using Archimedes' Principle. This calculation required an estimate of the density of the granite intrusion and the surrounding country rocks for each complex. Also for each complex the vertical columns of granite required to support the excess topography were assigned a common base depth. The assumed densities and depths to the base of each of the main complexes are shown in table 5.3. The majority of this information was derived from the previous literature already cited but additional information on the Scottish complexes was taken from Dimitropolous (1981) and Hipkin and Hussain

Figure 5.20. Estimated subsurface extent of the major intrusive granitic complexes of the UK and adjacent regions discussed in Section 5.8. The scale is approximately 1:6,250,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

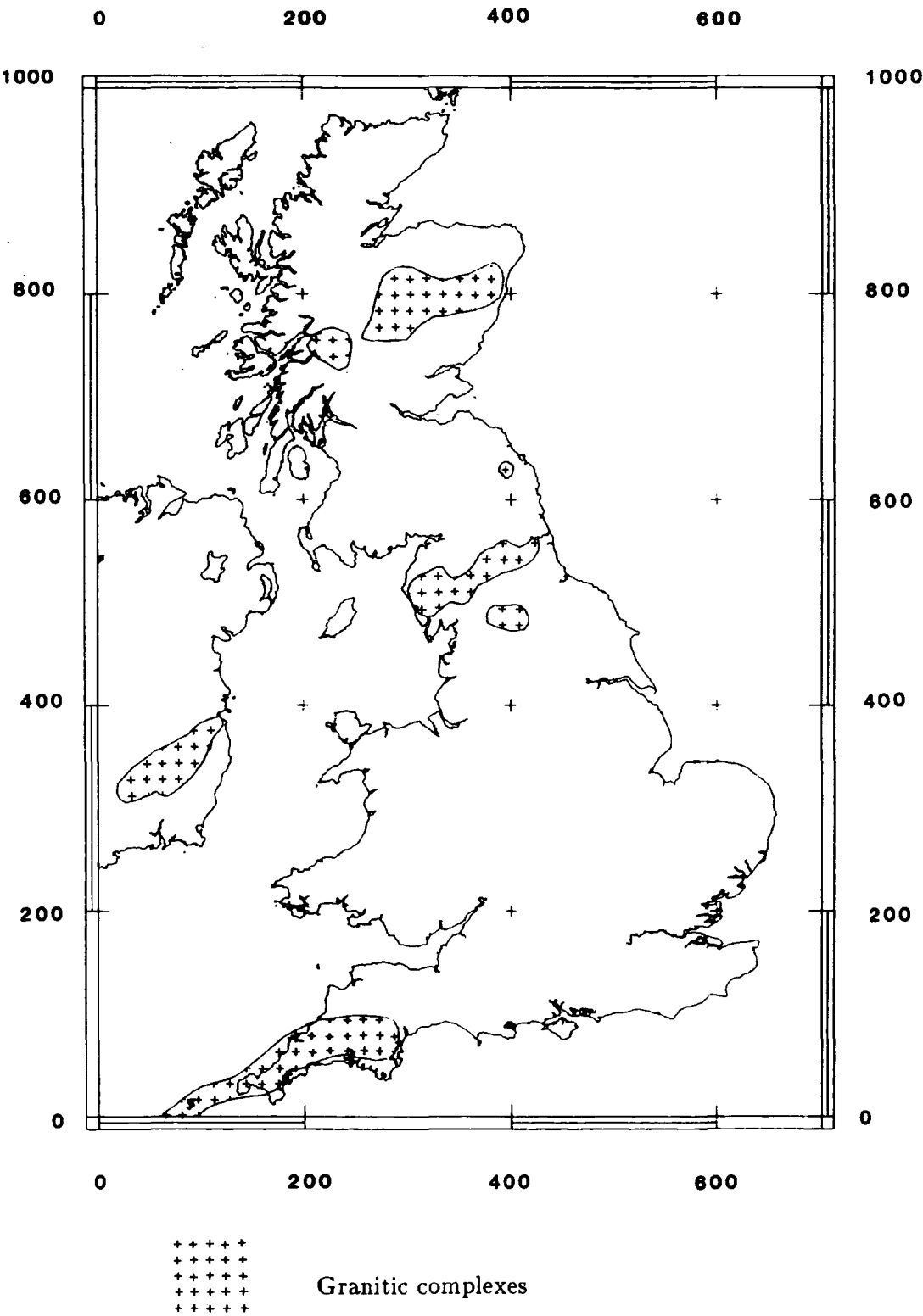


Table 5.3

Assumed parameters for granitic
complexes of the United Kingdom and Eire

Granite complex	Density of country rocks (kg m^{-3})	Density of granite (kg m^{-3})	Depth to base (km)
Cornubian batholith	2750	2600	10.0
Leinster granite	2740	2620	7.0
LD/Wr/Wn/Ch	2750	2640	9.0
Loch Etive/EHb	2740	2640	13.0

LD/Wr/Wn/Ch–Lake District, Weardale, Wensleydale and Cheviot granite complexes;
EHb–East Highland batholith complex.

(1983), and details of the Leinster granite were taken from Cassidy and Locke (1982).

The Bouguer anomaly produced by each granite complex was calculated from the component vertical columns using the formula for a right vertical prism (Goodacre, 1973). These anomalies were then subtracted from the observed Bouguer anomaly grid for the UK. Finally, the individual grid element heights over the complexes were replaced by the corresponding weighted averages of the surrounding topography.

Contour maps of the modified topography and Bouguer gravity are shown in figures 5.21. and 5.22. The modifications have not completely removed the Bouguer anomalies produced by the granite complexes; but they have been significantly reduced. The amplitude of the Dartmoor anomaly has decreased by roughly 20 mGal. However, the Bouguer anomaly associated with the Leinster granite has changed little which indicates that the batholith does not support a marked excess of topography. The high topography of the Grampian Highlands and the Lake District has been significantly reduced.

The reduction in topography is of particular importance because this will reduce any bias in the response function $\hat{Q}(k)$ towards the isostatic response for the granite complexes. The low amplitude of the Bouguer anomalies determined for the granites is probably the result of the regional uplift of the topography surrounding the granites. This will cause the estimates of the excess 'granite supported' topography to be underestimates.

5.9 The observed response for the modified data

The observed response for the modified topography and Bouguer gravity grids is shown in figure 5.23. The results are tabulated in table 5.4. The long wavelength ($\lambda > 700$ km) amplitude response values are slightly greater than those for the unmodified grids. The intermediate wavelength ($700 > \lambda > 200$ km) estimates are similar to the earlier response. The estimate for $\lambda = 164$ km has increased significantly. Therefore, the transition between compensated and uncompensated topography appears to be more gradual after the removal of the influence of the granites.

Figure 5.21. Topography of the UK and adjacent regions after the removal of the excess topography supported by the major granite intrusive complexes. The contour interval is 100 m. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

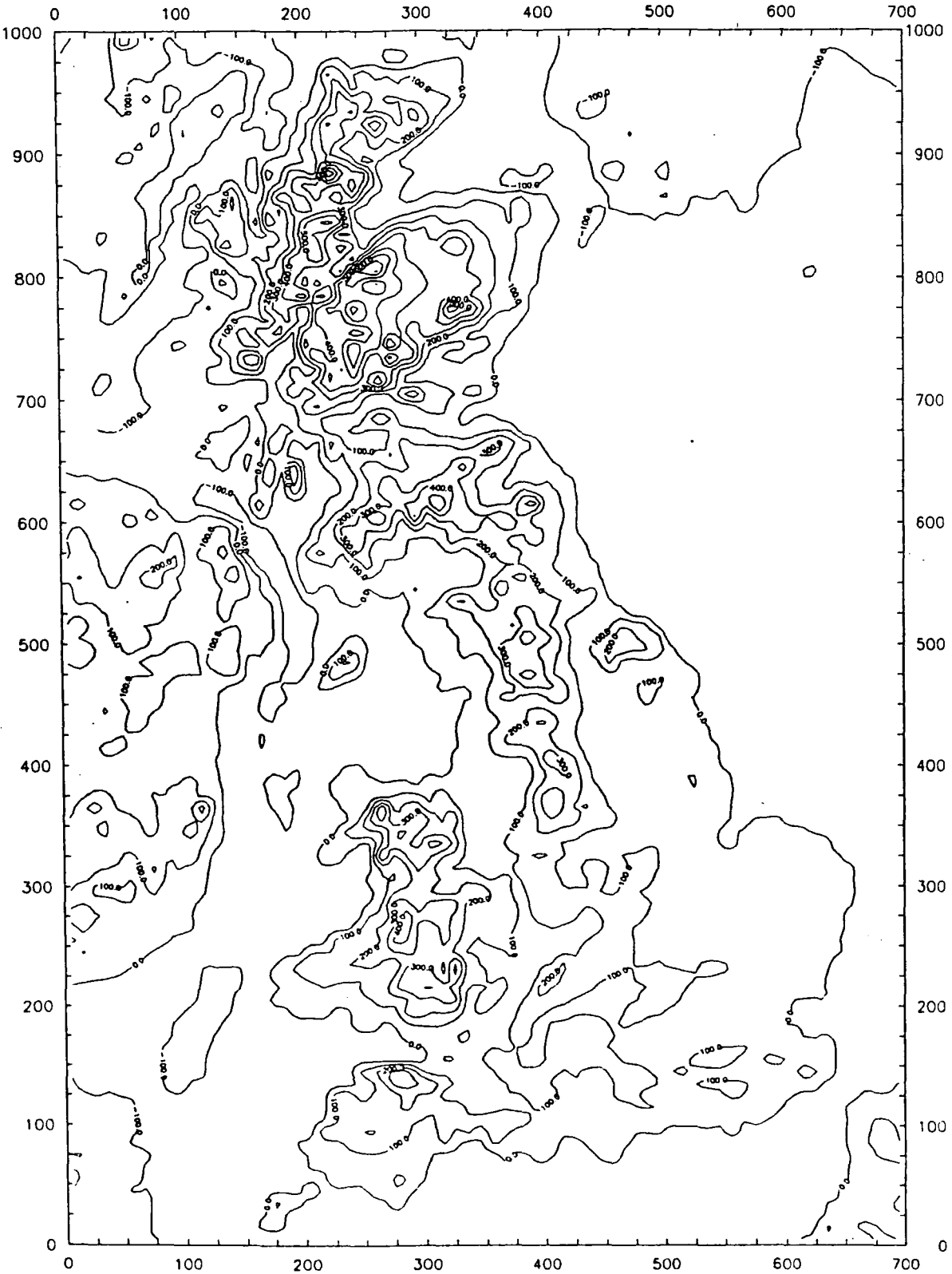


Figure 5.22. Bouguer anomaly gravity of the UK and adjacent regions after the removal of the local isostatic influence of the major granitic complexes. The contour interval is 10 mGal. The gridding interval is 10 km. The scale is approximately 1:5,000,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

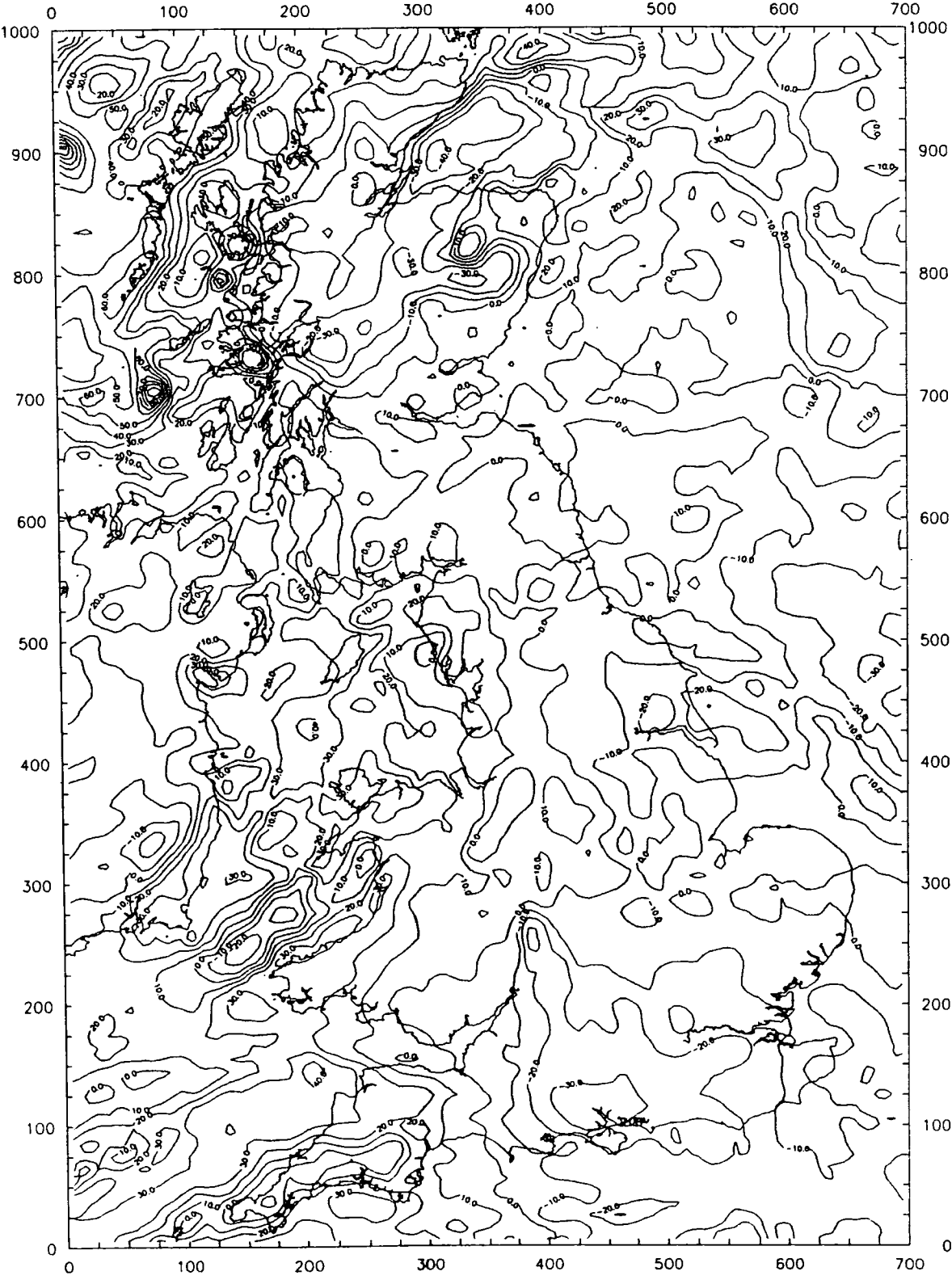


Figure 5.23. The isostatic response function, coherence and power spectra determined from the modified topography and Bouguer anomaly gravity of the UK and adjacent regions. 13 waveband estimates have been determined for each component.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.

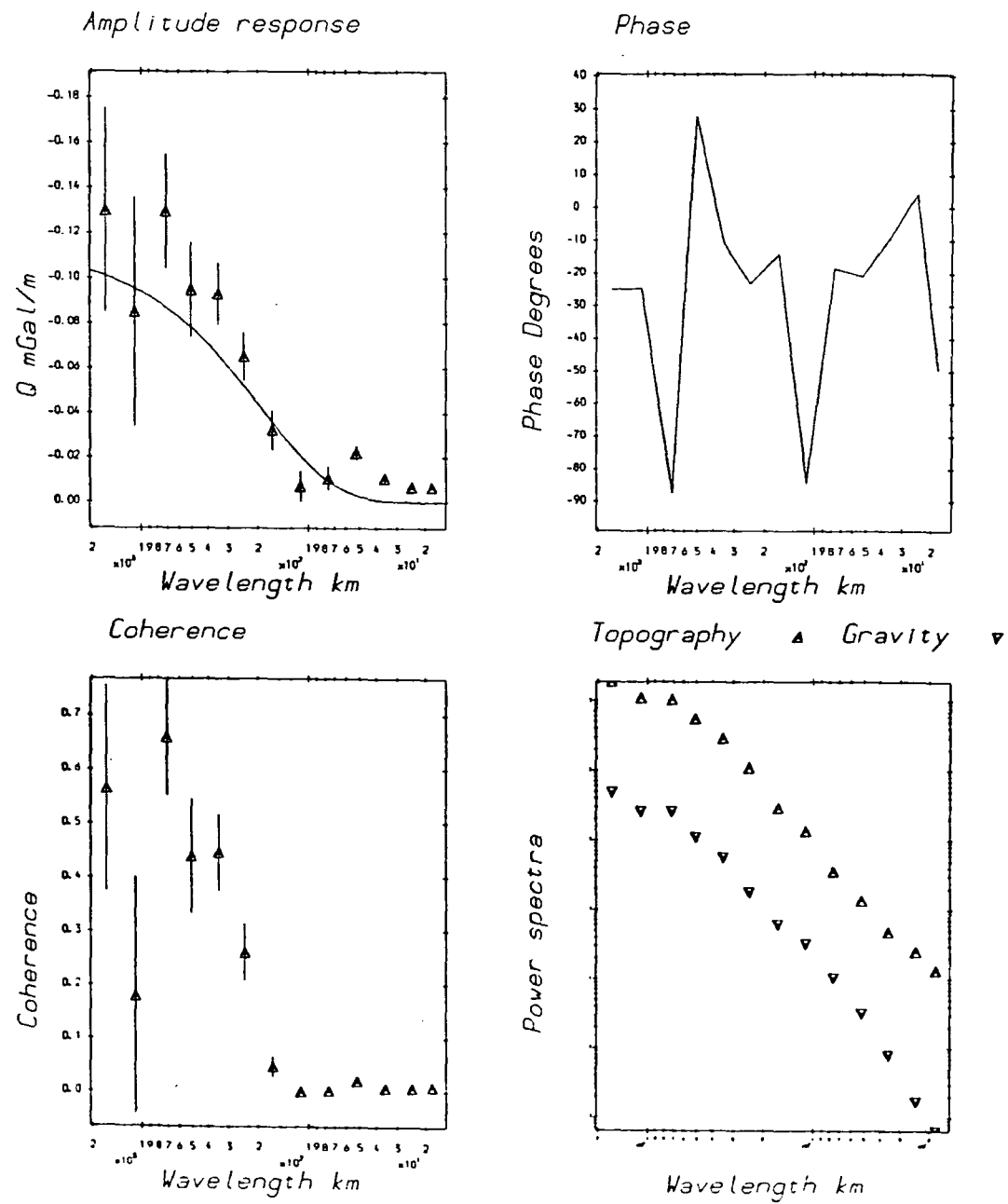


Table 5.4

Results for the response function analysis of the
modified topography and Bouguer gravity

λ	$\hat{Q}_{amp}$	$\hat{Q}_{phase}$	σ_n	n	γ^2	$\Delta\gamma^2$
1647	-0.12997	-25.11	0.0453	4	0.5641	0.1896
1093	-0.08491	-24.84	0.0509	6	0.1802	0.2220
713	-0.12959	-87.47	0.0252	12	0.6590	0.1058
505	-0.09484	27.96	0.0208	24	0.4401	0.1054
347	-0.09311	-10.53	0.0138	54	0.4464	0.0707
242	-0.06522	-23.24	0.0107	102	0.2612	0.0531
164	-0.03250	-14.06	0.0087	254	0.0478	0.0191
112	-0.00716	-84.56	0.0066	518	0.0003	0.0029
76	-0.01086	-18.51	0.0051	1112	0.0032	0.0027
52	-0.02219	-21.03	0.0031	2390	0.0208	0.0041
36	-0.01082	-9.32	0.0018	5120	0.0070	0.0017
24	-0.00702	4.18	0.0008	10934	0.0074	0.0012
18	-0.00696	-49.44	0.0008	7806	0.0102	0.0016

λ is the wavelength of the estimate in km; $\hat{Q}_{amp}$ and $\hat{Q}_{phase}$ are the amplitude and phase of the response in mGal m⁻¹; σ_n is the standard deviation of the response; n is the number of wavenumber terms averaged for each annuli; γ^2 is the coherence; $\Delta\gamma^2$ is the standard error of the coherence.

The phase of the response has changed but most of the intermediate and short wavelength estimates still lie within the $\pm 30^\circ$ range. Investigation of the real and imaginary parts of the response shows that the real part of the 164 km estimate records a positive correlation between topography and gravity. The coherence also changes slightly. At long wavelengths ($\lambda > 700$ km) the coherence estimates have increased slightly, whereas for the shorter wavelength estimates the coherence has decreased. This decrease in coherence is to be expected if there is a strong coherence between topography and gravity over the granites.

The influence of the granite complexes on the observed response function and coherence of the UK region introduces a further error into the interpretation of the cross spectral relationships in terms of lithospheric flexure alone. The statistical approach used in calculating the observed response for the UK makes the influence of the granite complexes difficult to predict quantitatively. This should also be true for other density contrasts which are related to topography in a manner different from the dominant mechanism of isostasy. The results of the Cornubian batholith study suggest that short wavelength topographic features may not be compensated by lithospheric flexure but may be compensated by other mechanisms which may result through brittle tectonic movements in the upper crust. The shallow depth of the compensation of the granites has important consequences for the interpretation of the UK response. If the compensation occurs within the upper crust it is clearly erroneous to model the response assuming a single density contrast at the Moho alone.

Therefore, before interpreting the observed response it is desirable to reduce these effects as much as possible. Unfortunately this is not easy in the case of the sedimentary basins. The relationship between topography and gravity in the vicinity of the sedimentary basins is often complex and may only be described by sophisticated thermo-mechanical models of the lithosphere (McKenzie, 1978; Watts et al., 1982; Wernicke, 1985). For some of these models an estimate of T_e is required before the topographic and gravimetric effects of the basin can be determined. As we wish to determine T_e independently of any such assumptions the effects of the basins cannot

be removed directly.

An alternative approach is to develop a more complex isostatic model which can account for some of the effects of the basins. The observed response and coherence may then be used to estimate T_e .

5.10 Estimating the elastic thickness of the lithosphere for the UK region

A more realistic approach to interpreting the observed response and coherence was proposed by Forsyth (1985). This method considers the influence of surface and subsurface loading on both the amplitude response and the coherence. In particular, the behaviour of the coherence is studied in detail. The method is briefly discussed for a two layer lithosphere model so that the principles behind a more complex three layer model applied later will be more clearly understood.

The surface and subsurface loading are assumed to be statistically independent. The subsurface loading is modelled by topography on the Moho. The low amplitude of the observed coherence often indicates that a strong correlation between surface and subsurface loads does not occur. Erosion may be responsible for randomising the two sets of loads (Forsyth, 1985).

The coherence can be predicted as a function of the elastic thickness of the lithosphere. When the lithosphere is infinitely strong the applied loads do not deform the lithosphere. Therefore, there should be no correlation between the surface topography and the Bouguer anomalies which result from the subsurface loading. The coherence will be 0.0. If the lithosphere is infinitely weak as for local Airy isostasy the surface topography will depress the lithosphere and Bouguer anomalies will result from the perturbation of the Moho density contrast. Similarly subsurface loads will deflect the lithosphere forming surface topography. The effects of the surface and subsurface loading become indistinguishable and the coherence is 1.0.

For a plate of finite elastic thickness the coherence should increase from 0.0 at short wavelengths to 1.0 at long wavelengths. The wavelength of the transition from incoherence to coherence may be used to estimate the elastic thickness of the lithosphere.

Assuming that the Bouguer anomalies are produced by topography on the Moho alone, the topography $W(\mathbf{k})$ can be determined by the downward continuation of the Bouguer anomalies if the mean depth of the Moho and the density contrast $\Delta\rho$ are known. If the lithosphere has a finite elastic thickness the initial loads $H_I(\mathbf{k})$ and $W_I(\mathbf{k})$ may be determined from the observed topography $H(\mathbf{k})$ and the Moho topography $W(\mathbf{k})$ (Forsyth, 1985)

$$H_I(\mathbf{k}) = \left(H(\mathbf{k}) + W(\mathbf{k}) \frac{\Delta\rho}{\rho_0\phi} \right) \left(\frac{\rho_0 + \Delta\rho\xi}{\Delta\rho} \right) \left(\frac{\phi}{\phi\xi - 1} \right) \quad 5.43$$

$$W_I(\mathbf{k}) = \left(W(\mathbf{k}) + H(\mathbf{k}) \frac{\rho_0}{\Delta\rho\xi} \right) \left(\frac{\Delta\rho + \rho_0\phi}{\rho_0} \right) \left(\frac{\xi}{\phi\xi - 1} \right) \quad 5.44$$

The components of the present relief on the surface and Moho interfaces $H_T(\mathbf{k})$, $H_B(\mathbf{k})$, $W_T(\mathbf{k})$ and $W_B(\mathbf{k})$ may be determined from the initial loads. The initial loads can be examined to determine if the assumption of statistical independence is warranted. The ratio of the amplitudes of the initial subsurface and surface loading is expressed by

$$f = \frac{\Delta\rho|W_I(\mathbf{k})|}{\rho_0|H_I(\mathbf{k})|} \quad 5.45$$

Assuming statistical independence the theoretical coherence is given by (Forsyth, 1985)

$$\gamma^2(\bar{k}) = \frac{\langle H_T(\mathbf{k})W_T(\mathbf{k}) + H_B(\mathbf{k})W_B(\mathbf{k}) \rangle^2}{\langle H_T(\mathbf{k})^2 + H_B(\mathbf{k})^2 \rangle \langle W_T(\mathbf{k})^2 + W_B(\mathbf{k})^2 \rangle} \quad 5.46$$

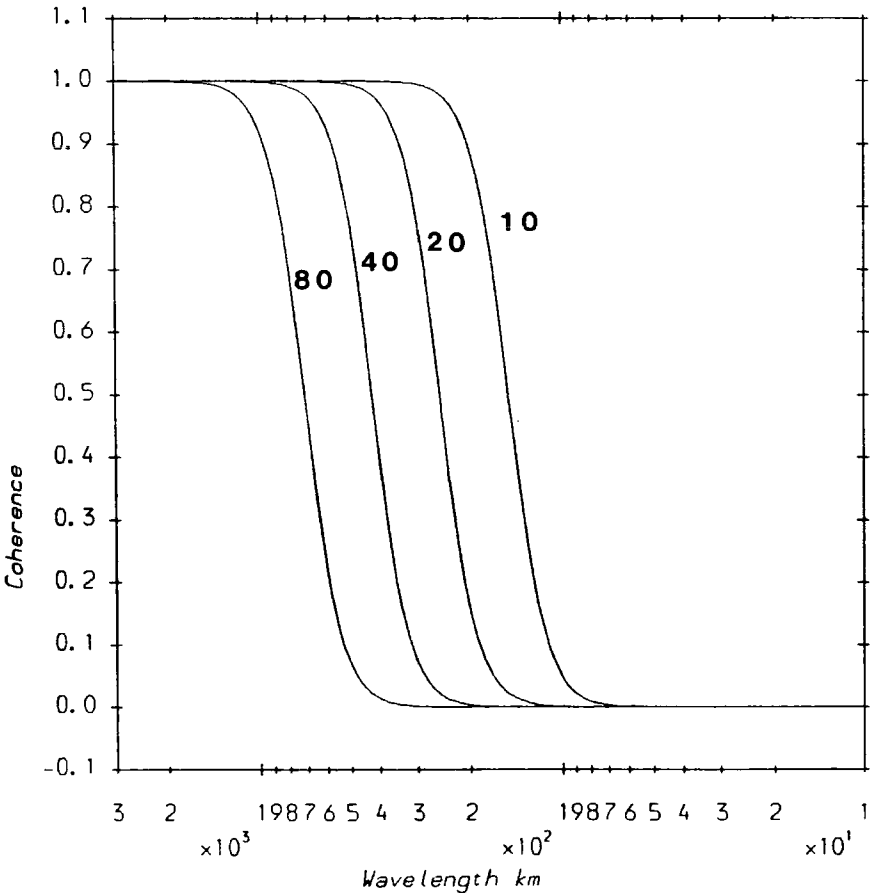
Additionally, the theoretical coherence $\gamma^2(k)$ for a given value of the ratio f may be determined by substituting equation (5.45) into (5.46). This gives the expression

$$\gamma^2(k) = \frac{(\rho_0/\Delta\rho\xi + f^2\rho_0^3\phi/\xi^2\Delta\rho^3)^2}{(1 + f^2\rho_0^2/\xi^2\Delta\rho^2)(\rho_0^2/\Delta\rho^2\xi^2 + f^2\rho_0^4\phi^2/\xi^2\Delta\rho^4)} \quad 5.47$$

The theoretical coherence for a number of values of T_e assuming that $f = 1.0$ for all wavenumbers is shown in figure 5.24. The transition between incoherence and coherence is clearly dependent on T_e .

The elastic thickness of the lithosphere can be determined by comparing the observed coherence with the theoretical model. If the initial loads are not determined f is assumed to be independent of wavenumber and is initially assigned a value of 1.0. The coherence is not as sensitive to changes in f as to changes in the elastic thickness.

Figure 5.24. Theoretical coherence between topography and Bouguer anomaly gravity for various values of the elastic thickness of the continental lithosphere and a subsurface-surface loading ratio of 1.0.



The coherence curve annotation denotes the elastic thickness of the continental lithosphere for each curve in km. The additional parameters in the coherence formula are $\rho_0 = 2700 \text{ kg m}^{-3}$ and $\Delta\rho = 650 \text{ kg m}^{-3}$.

Therefore, assuming $f = 1.0$ the theoretical and observed coherences may be matched to estimate T_e . The observed response function can then be modelled using the known value of T_e to obtain a better estimate of f (equation (5.36)). The new value of f is then used in the estimation of T_e . The process is then repeated until a stable estimate is obtained.

The main uncertainty in f arises from the uncertainty in the depth of the subsurface loading and the depth of the compensation. Before the estimation of T_e is made these depths have to be constrained. The depth of the subsurface loading has sometimes been obtained from the slope of the free air or Bouguer gravity power spectra (Karner and Watts, 1983). Alternatively, a priori knowledge such as the depth of the Moho has been used.

5.11 Determination of the depth of subsurface loading and compensation

5.11.1 Gravity data

The ambiguous nature of the sources of Bouguer anomalies makes the estimation of the depth of loading from gravity data alone difficult. However, several attempts have been made using the gradient of the observed power spectrum of the free air or Bouguer anomalies (Karner and Watts, 1983; Hipkin and Hussain, 1983; Bechtel et al., 1987). These methods have been investigated to determine if the techniques give reliable results and, if so, to use them to obtain the depths of loading for the UK region.

The approach of Karner and Watts (1983) is considered first. The power spectrum of the gravity anomaly produced by the topography $h(x)$ about a depth z of a density contrast $\Delta\rho$ is given by

$$|\Delta G(\mathbf{k})|^2 = (2\pi G \Delta\rho)^2 e^{-2kz} |H(\mathbf{k})|^2 \quad 5.48$$

If the actual gravity anomalies result from masses over a range of depths $z \pm \Delta z$ the ensemble average of the power spectrum is given by

$$\langle |\Delta G(\mathbf{k})|^2 \rangle = (2\pi G)^2 \langle \Delta\rho^2 \rangle \langle e^{-2kz} \rangle \langle |H(\mathbf{k})|^2 \rangle \quad 5.49$$

if $\Delta\rho$, z and $H(\mathbf{k})$ are linearly independent. The term $\langle e^{-2kz} \rangle$ may be expressed as $e^{-2k\bar{z}} \sinh(2k\Delta z)/k$ where $\bar{z}$ is the mean depth. Taking the logarithm to base 10 of each side of the equation gives

$$\log(|\Delta G(\mathbf{k})|^2) = -2k\bar{z} \log e + \log \sinh(2k\Delta z)/k + \text{constants} \quad 5.50$$

The exponential term is considered to be the dominant term in the power spectrum expression, therefore, a plot of $\log(|\Delta G(\mathbf{k})|^2)$ against k should have a slope of $-2\bar{z} \log e$. If the main density contrasts are clustered about a number of discrete depths the plot should comprise a number of linear segments.

An assumption of this approach is that $\log(|H(\mathbf{k})|^2)$ is independent of k . Bechtel et al. (1987) considered a single density contrast only but assumed that the topographic term was not a constant. For many surfaces the power spectrum of the topography can be expressed to a first approximation as

$$|H(\mathbf{k})|^2 = \frac{C}{k^\alpha} \quad 2 < \alpha < 3 \quad C = \text{Constant} \quad 5.51$$

(Sayles and Thomas, 1978; Brown, 1987). The expected power spectrum is given by

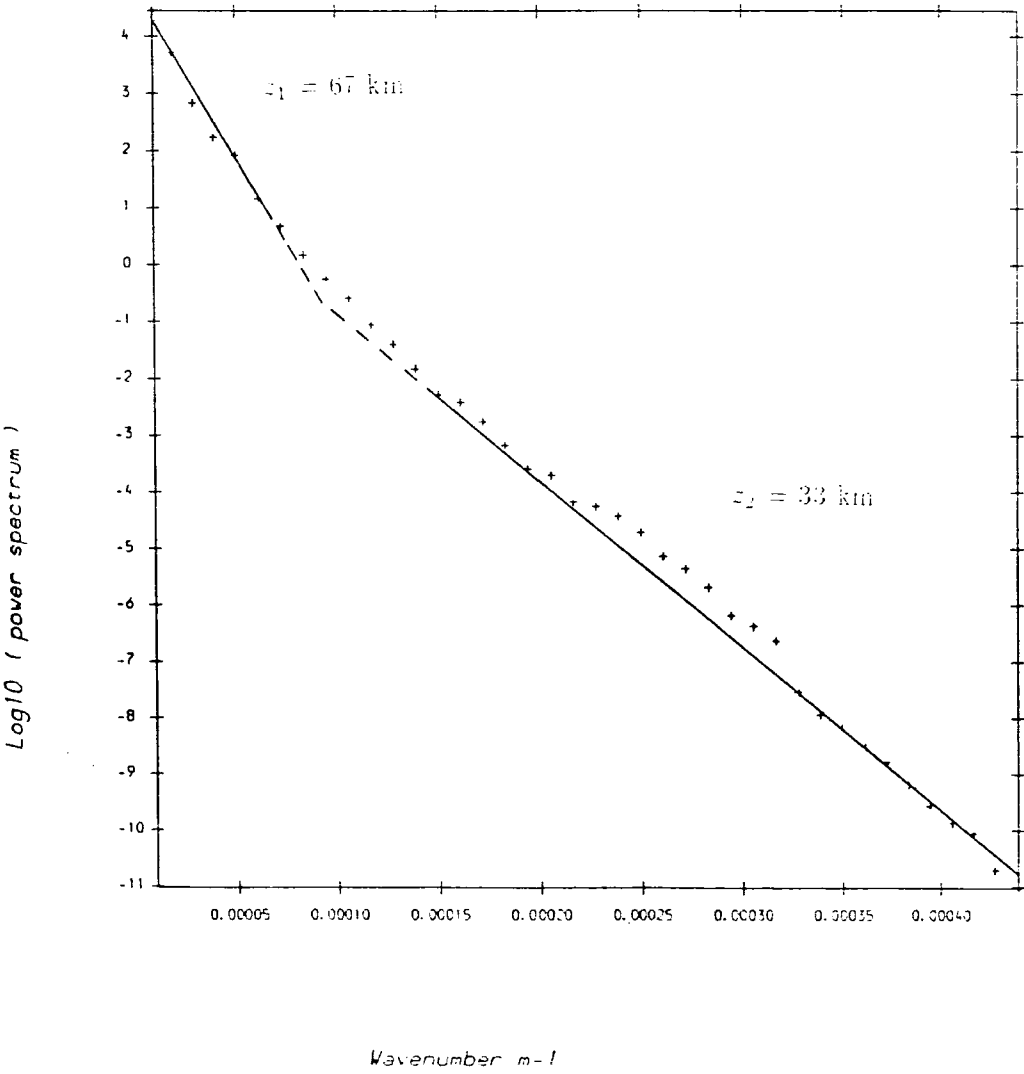
$$\log |\Delta G(\mathbf{k})|^2 = \log C_0 - \alpha \log k - 2kz \log e \quad C_0 = (2\pi G \Delta \rho)^2 \cdot C \quad 5.52$$

Plotting the normalised power spectrum $\log |\Delta G(\mathbf{k})|^2 + \alpha \log k$ against k should give a straight line of gradient $-2z \log e$. The value of α cannot be observed directly but an estimate may be determined from a plot of $\log |H(\mathbf{k})|^2$ against $\log k$. Although this estimate refers to the surface topography and not the true interface the estimate should be more realistic than assuming the spectrum is white.

The effectiveness of these methods was investigated by using them to estimate the mean depth of the Airy root from the gravity anomalies calculated for the theoretical Airy compensation of the topography of the UK (figure 5.4). The mean depth of the root was approximately 30 km. The power spectrum of the gravity anomalies was averaged over 40 linearly spaced annuli in the wavenumber domain.

The results for the first method are shown in figure 5.25. The spectrum displays two distinct linear segments which provide depth estimates of 67 and 33 km. All of the best

Figure 5.25. Logarithm of the azimuthally averaged power spectrum of the vertical gravitational attraction of the theoretical local Airy isostatic compensation of the topography of the UK and adjacent regions as a function of radial wavenumber.



fit lines are estimated by eye. The distortion of the spectrum in the wavenumber region $0.0002 < k < 0.0003 \text{ m}^{-1}$ is the result of edge effects. Note that the wavenumber 0.00005 m^{-1} corresponds to a wavelength of only 125 km. The estimate of the depth from the low wavenumber segment ($k < 0.0001 \text{ m}^{-1}$) is clearly too large. The estimate for the higher wavenumber segment appears to be more realistic.

The plot of $\log |H(k)|^2$ against $\log k$ shown in figure 5.26 comprises two roughly linear segments. To normalize the gravity power spectrum the gradient of the lower wavenumber segment ($k < 0.00015 \text{ m}^{-1}$) was used. A value of 2.88 was obtained for α . The best fit to the slope of the normalised power spectrum gave a depth of 28 km (figure 5.27).

For a single density contrast the normalised spectrum provides a slightly more consistent estimate. The raw spectrum gives a reasonable estimate only for high wavenumbers. At high wavenumbers the variation in the gravity power spectrum owing to upward continuation probably dominates the variation generated by the topographic power spectrum of the interface. The low wavenumber estimate is inaccurate. This is of particular importance because the low wavenumber estimate is required to determine the depth of loading for the intermediate and long wavelength response estimates. Therefore, the normalised spectrum approach appears to be the more useful technique.

The results of the application of these techniques to the Bouguer gravity grid are not conclusive (figures 5.28 and 5.29). The raw power spectrum comprises three linear segments associated with depths of 50, 14 and 7 km. The earlier results suggest that the 50 km depth may be erroneous. The other depths are valid only for relatively short wavelengths ($\lambda < 80 \text{ km}$). At such wavelengths the effects of spectral overlap between the Bouguer anomalies produced by broad, shallow features such as the large sedimentary basins and deeper sources may be significant. The normalised power spectrum does not display a distinct gradient within the region for which the value of α is valid and no depth estimate can be obtained. This may be caused by an incorrect value of α or the initial assumptions may not be accurate.

The influence of spectral overlap was reduced by calculating the Bouguer anomalies

Figure 5.26. Logarithm of the azimuthally averaged power spectrum of the topography of the UK and adjacent regions as a function of the logarithm of the radial wavenumber.

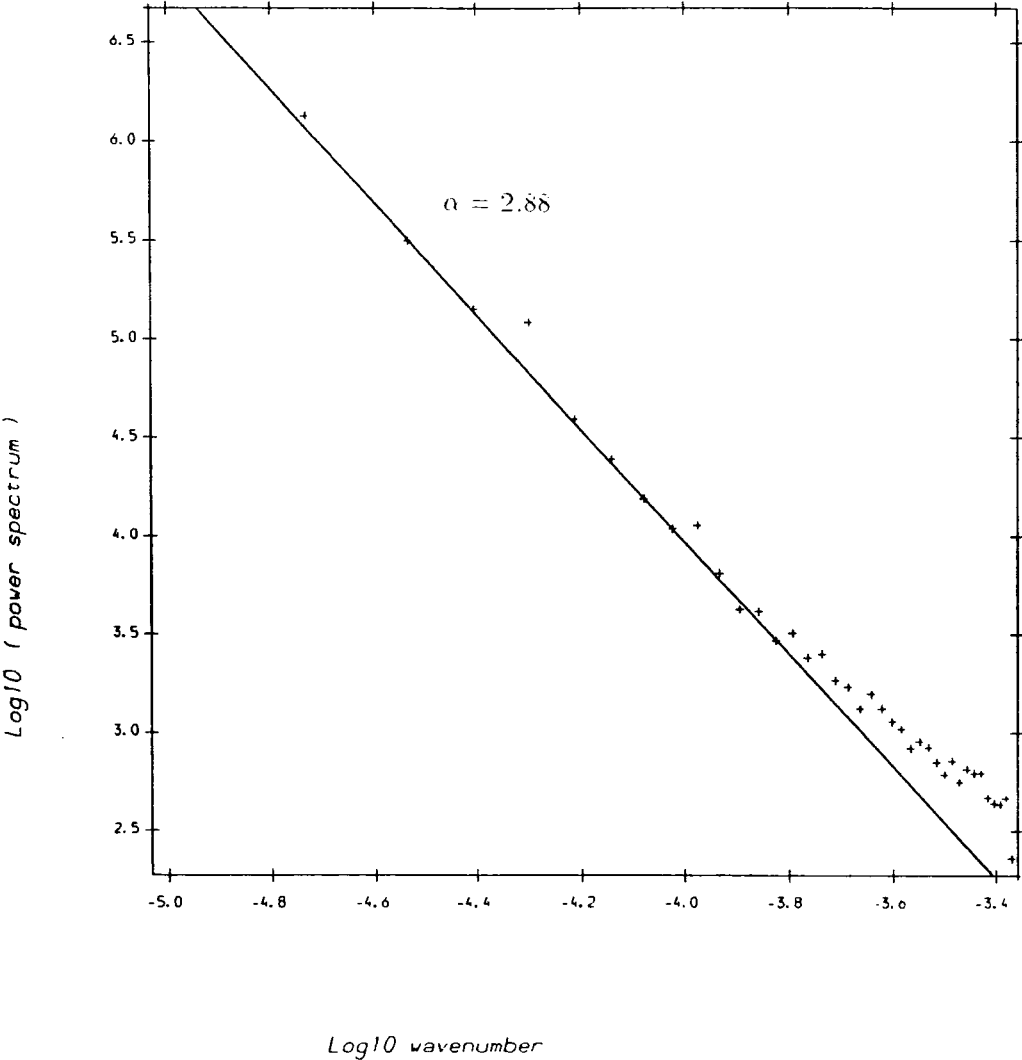


Figure 5.27. Normalized logarithm of the azimuthally averaged power spectrum of the vertical gravitational attraction of the theoretical local Airy isostatic compensation of the topography of the UK and adjacent regions as a function of radial wavenumber.

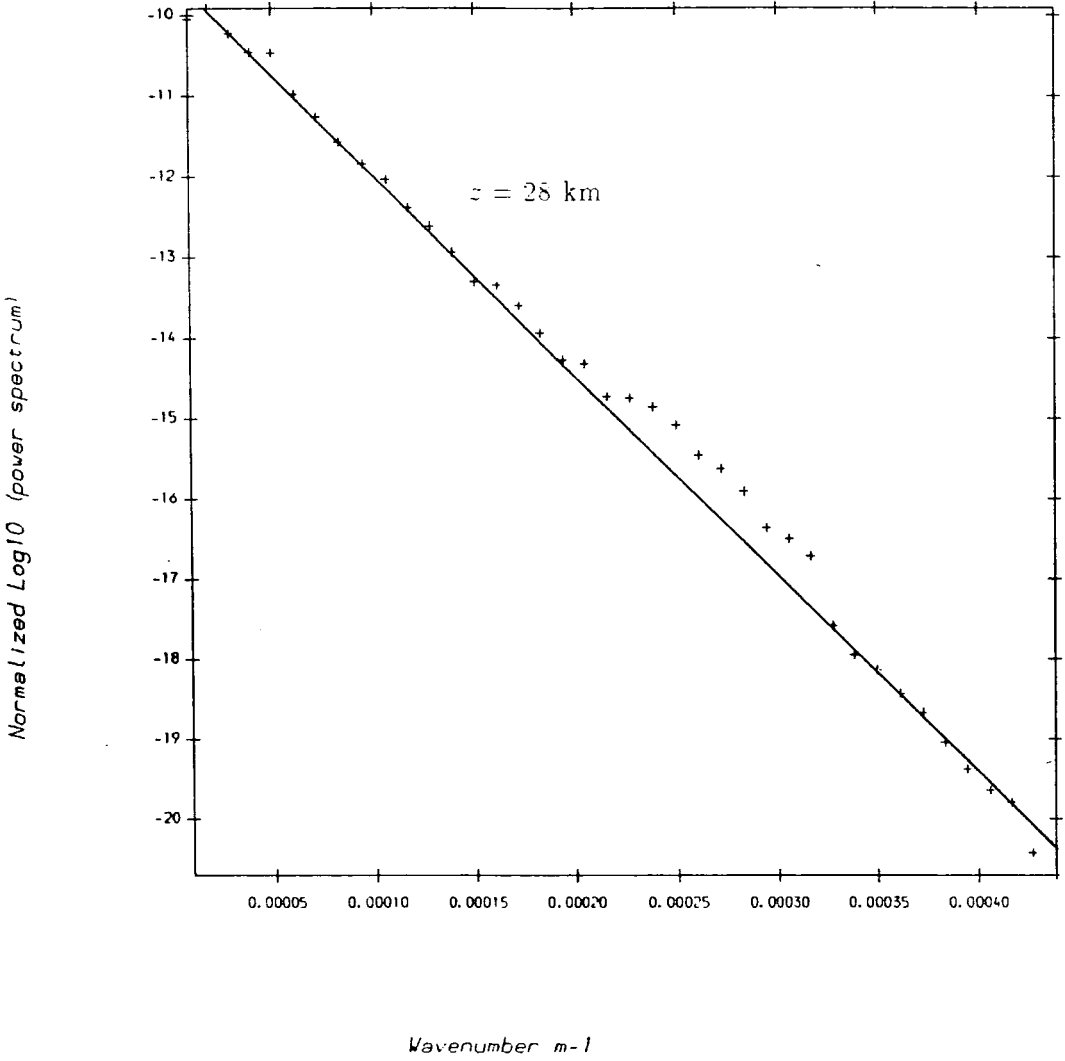


Figure 5.28. Logarithm of the azimuthally averaged power spectrum of the Bouguer anomaly gravity of the UK and adjacent regions as a function of radial wavenumber.

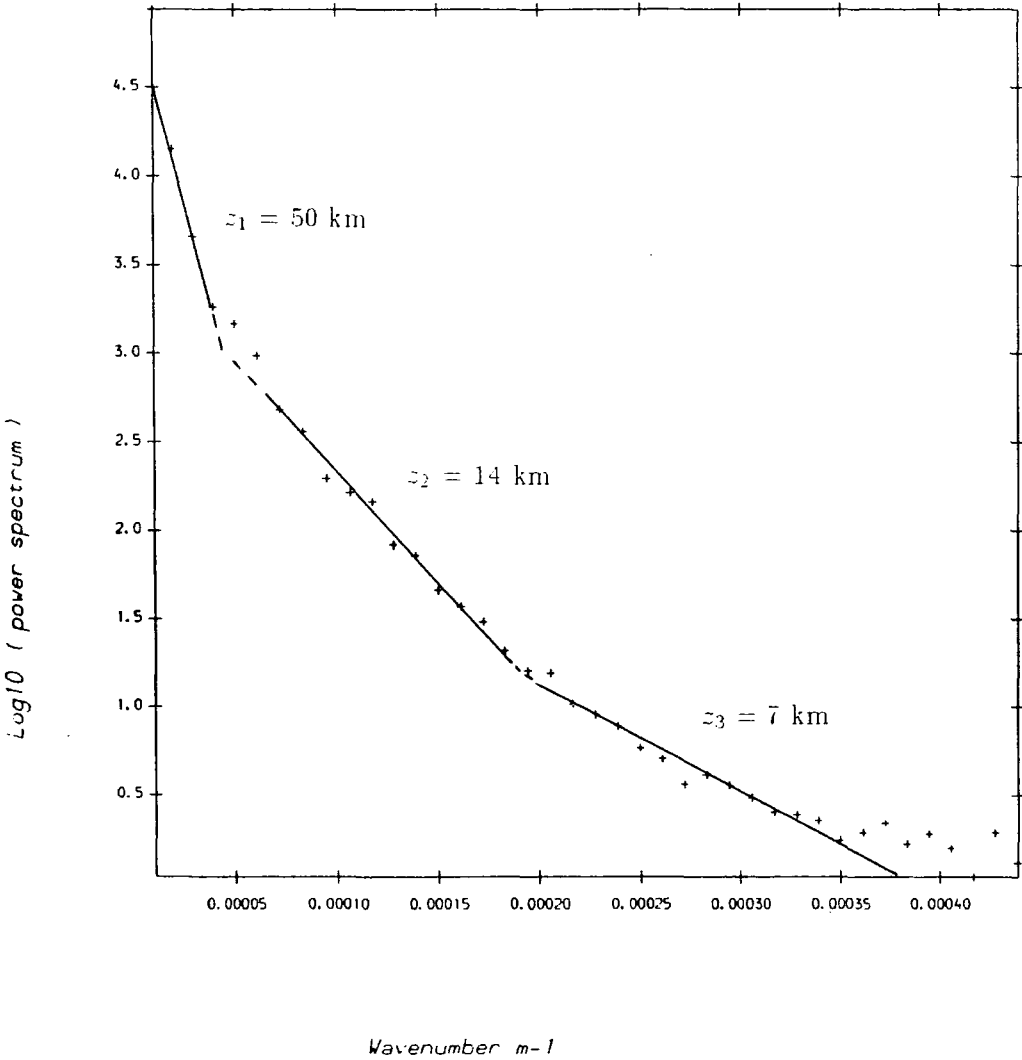
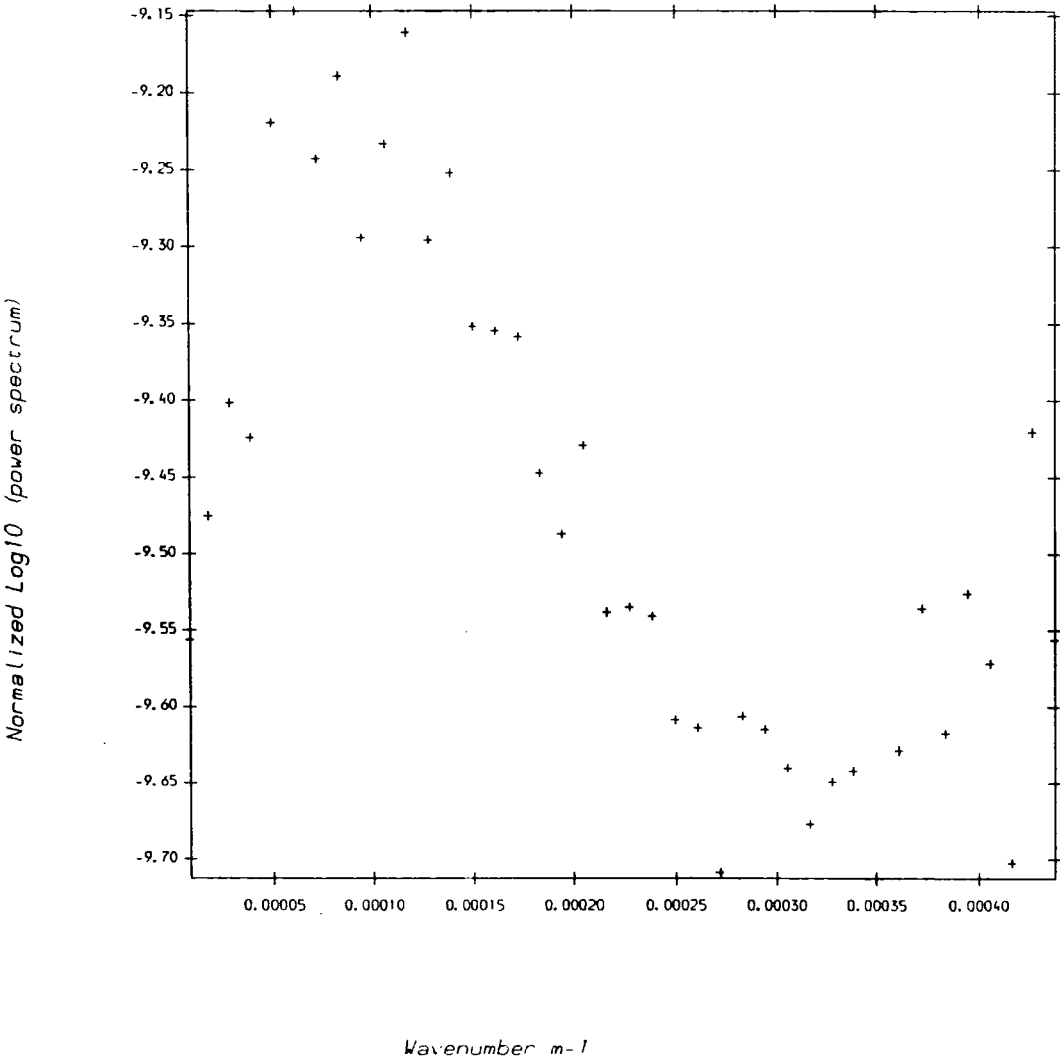


Figure 5.29. Normalized logarithm of the azimuthally averaged power spectrum of the Bouguer anomaly gravity of the UK and adjacent regions as a function of radial wavenumber.



generated by the major sedimentary basins of the UK region and subtracting them from the observed Bouguer anomalies. On land the depth to the Variscan basement was digitized onto a 10×10 km grid using data from Whittaker (1985). The depth to the base of the Tertiary was additionally digitized for the Wessex basin. The marine sediment depths were digitized onto a 20×20 km grid which was interpolated onto a 10×10 km grid. The deepest mapped formations were digitized. In the central North Sea the depth to base Zechstein was digitized from Day et al. (1981). Elsewhere, the depth to the Upper Permian was digitized from Ziegler (1978). In the central North Sea the depth to the Top Cretaceous was also digitized. The majority of the main post-Palaeozoic sedimentary basins of the UK region were digitized except for the basins of the NW Approaches and the Hebrides region about which insufficient data was available.

The gravity anomalies produced by the basins were calculated using Parker's method (Parker, 1972). Average density contrasts of -250 kg m^{-3} for the pre-Tertiary deposits and -500 kg m^{-3} for the Tertiary and Quaternary deposits were used. The instability of the wave domain calculation required the gravity anomalies to be determined on a plane 10 km above sea level. The results of the calculation are shown in figure 5.30. The coarse resolution of the digitization grid and the use of average density contrasts will cause the calculation to be only an approximation of the true anomalies. Before the gravity anomalies produced by the basins were removed from the main Bouguer gravity grid the Bouguer gravity was upward continued 10 km above sea level.

The radially averaged power spectrum of the residual Bouguer anomalies is shown in figure 5.31. The corrected depths are 33 and 6 km respectively. The first depth may indicate a source at depths similar to the Moho but as observed earlier the low wavenumber estimate may be anomalous. The normalised spectrum does not display a clear linear segment in the low wavenumber region (figure 5.32).

The depth of compensation may be estimated from the predicted gravity. The normalised power spectrum of the predicted gravity for the grids with the isostatic influence of the granites removed is shown in figure 5.33. In contrast to the earlier

Figure 5.30. Contour map of the gravity anomalies produced at a height of 10 km above sea level by the low density sediments in the major sedimentary basins of the UK and adjacent regions. The contour interval is 5 mGal. The gridding interval is 10 km. The scale is approximately 1:6,500,000 and the border annotation denotes Ordnance Survey grid coordinates in km.

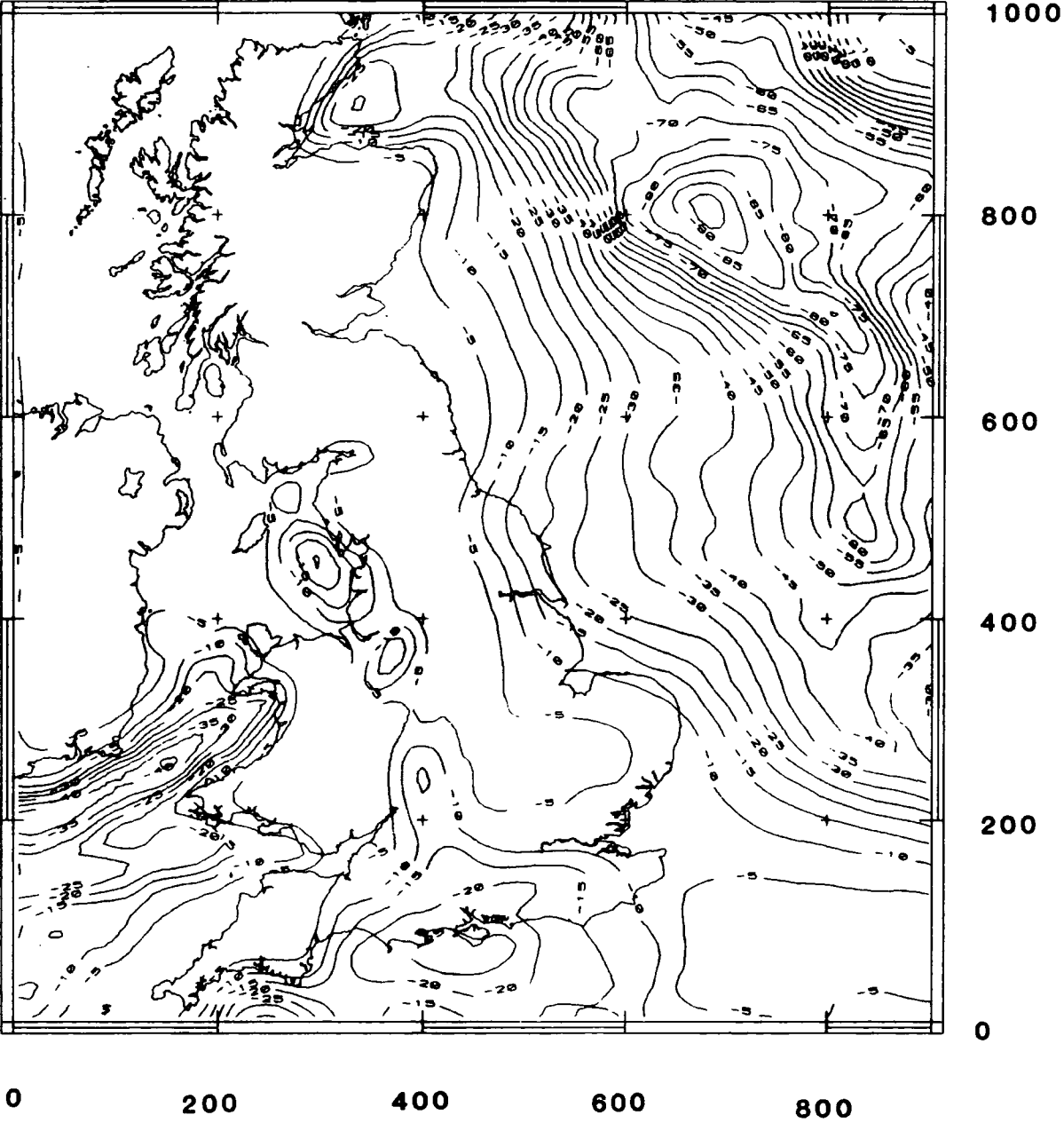


Figure 5.31. Logarithm of the azimuthally averaged power spectrum of the residual Bouguer anomaly gravity of the UK and adjacent regions after the removal of the gravity anomalies generated by the low density sediments in the major sedimentary basins as a function of radial wavenumber.

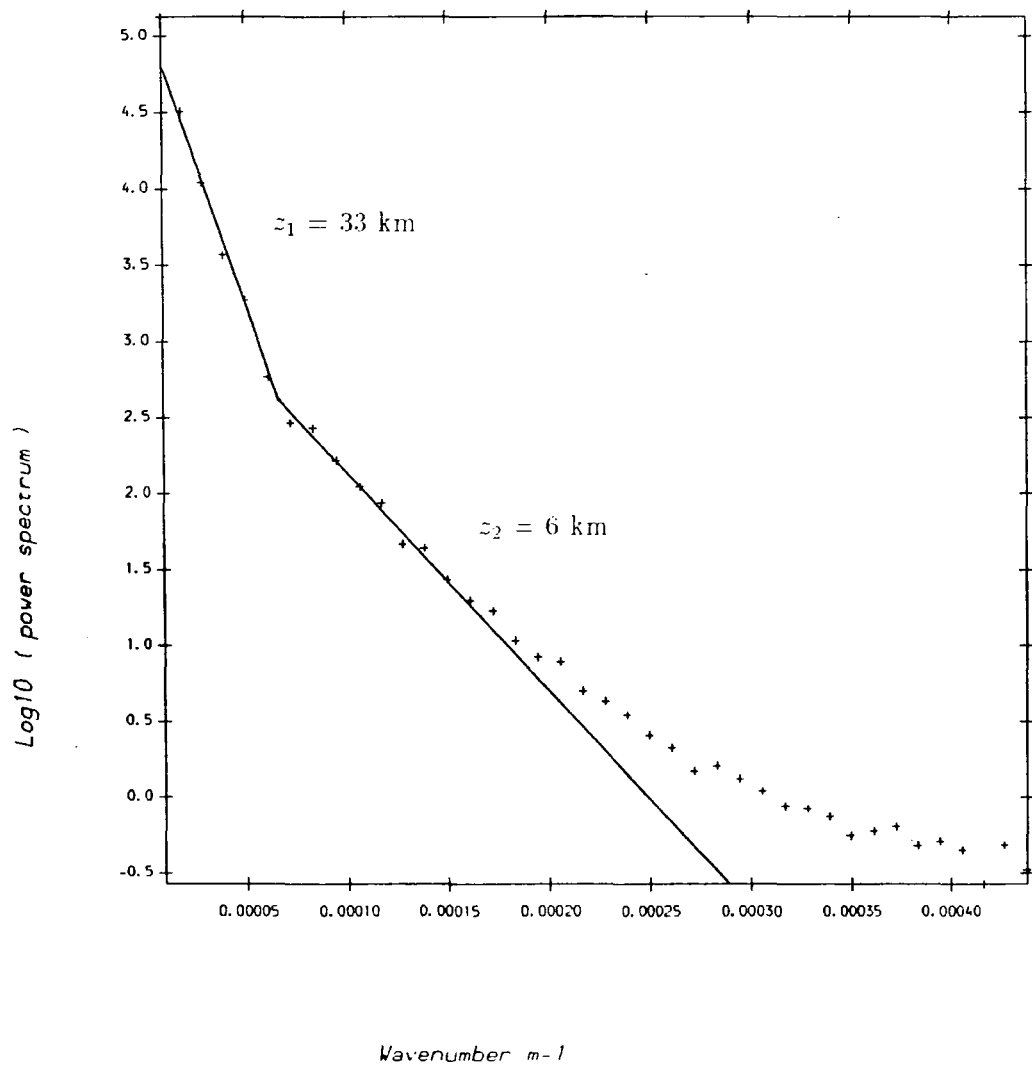


Figure 5.32. Normalized logarithm of the azimuthally averaged power spectrum of the residual Bouguer anomaly gravity of the UK and adjacent regions after the removal of the gravity anomalies generated by the low density sediments in the major sedimentary basins as a function of radial wavenumber.

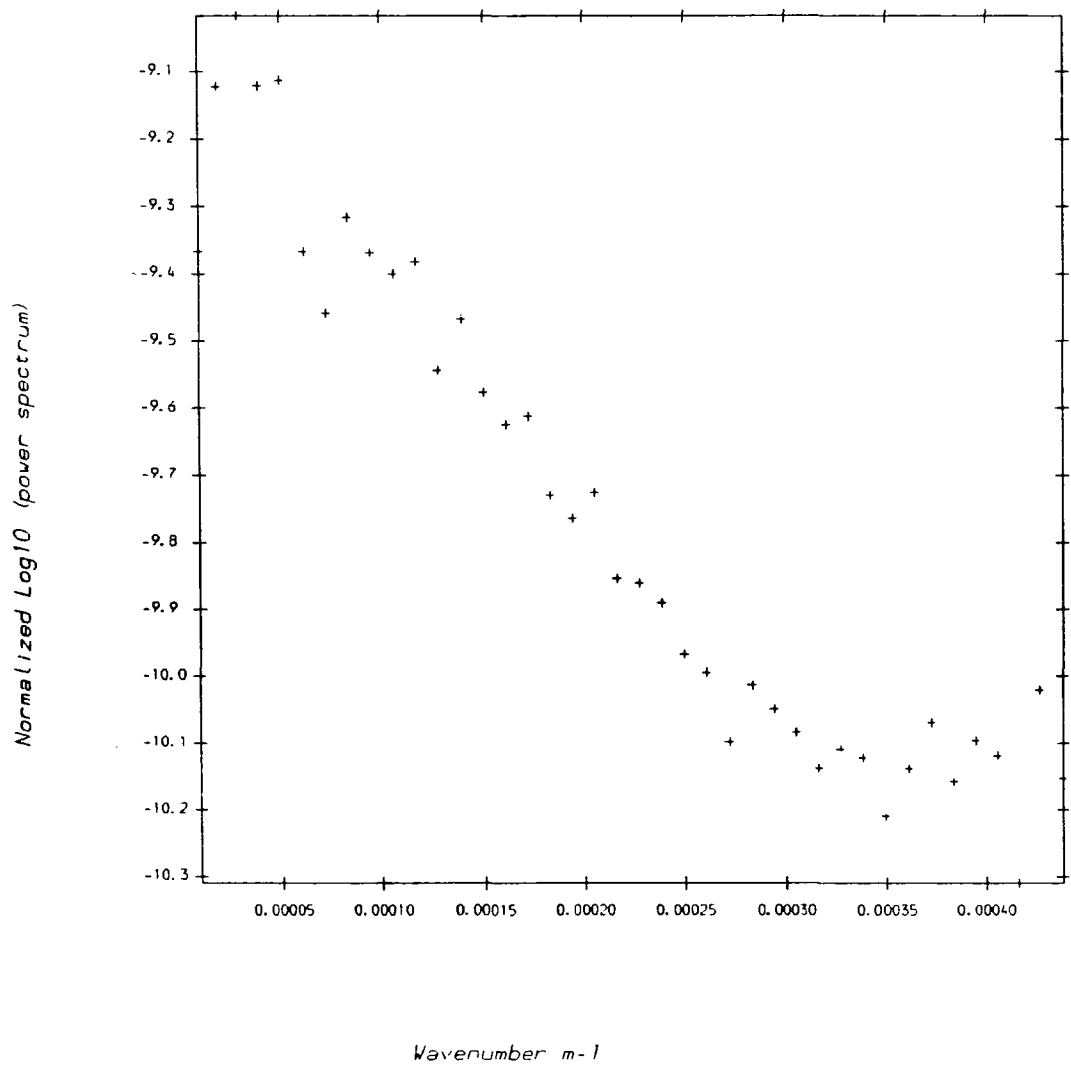
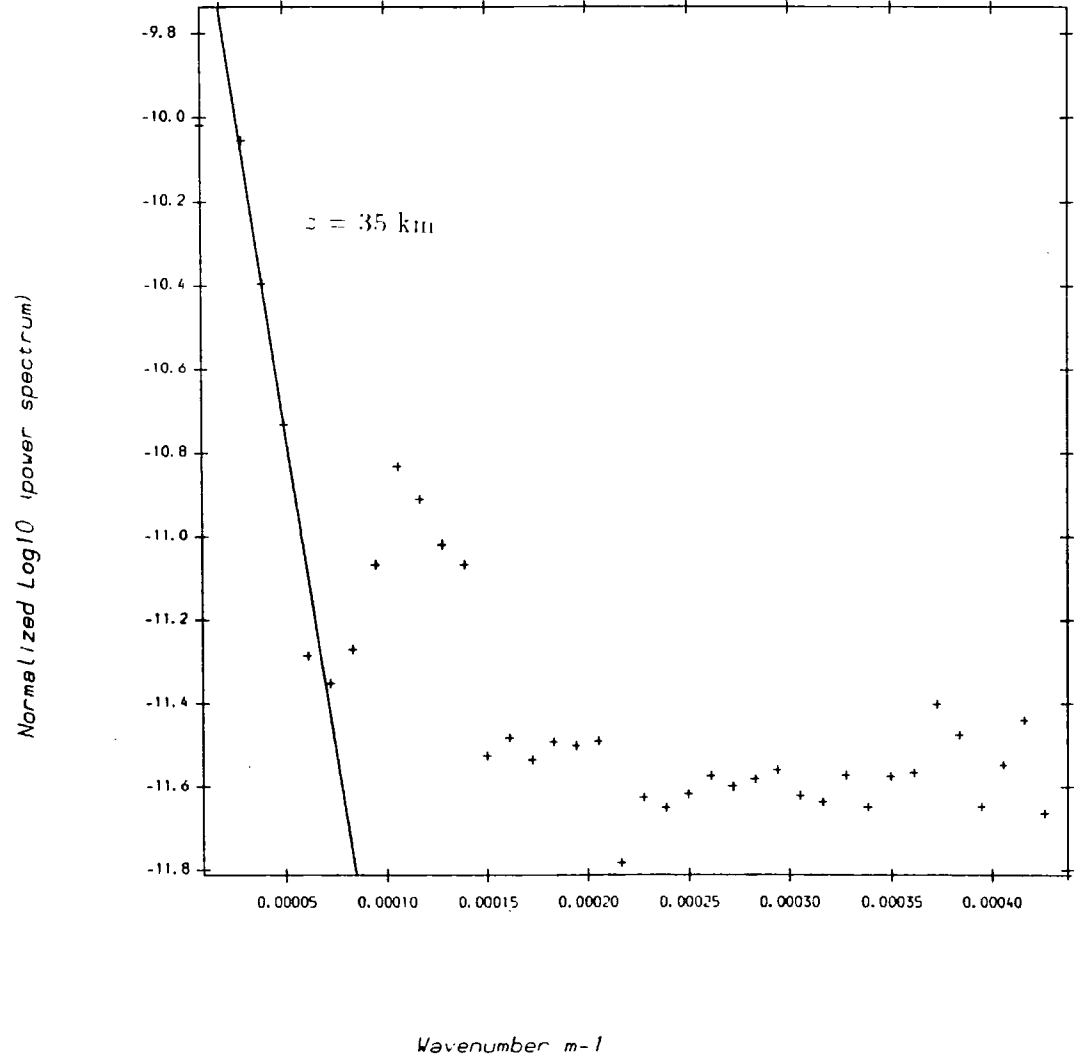


Figure 5.33. Normalized logarithm of the azimuthally averaged power spectrum of the 'predicted gravity' of the UK and adjacent regions generated by filtering the topography with the observed response function as a function of radial wavenumber.



figures, a clear linear segment in the low wavenumber region gives a depth of 35 km. This indicates that part of the compensation may originate from depths approximate to that of the Moho.

In conclusion, the results of the Airy isostasy test case indicated that the slope of the power spectrum may be used to obtain a reasonable estimate of the depth of a single density contrast. However, the results for real data are less conclusive. There is little consistency within the depth estimates. The normalised spectra are particularly difficult to interpret, although the normalised spectrum gave the best results for the Airy compensation test. Therefore, although the techniques are theoretically sound their application to real data does not appear to provide clear or useful interpretations of the depths of loading.

The difficulty in identifying discrete depths of loading from the Bouguer gravity data makes Forsyth's (1985) suggestion of downward continuation of the Bouguer anomaly to define the subsurface loads unrealistic. Further, if there is more than one depth of loading the individual loads can only be defined by splitting the observed spectrum on the basis of the linear segments (see Bechtel et al., 1987). In practice, this is unlikely to reproduce the exact configuration of the loading because of spectral overlap between the various sources.

The failure of the power spectrum method of depth estimation means that the depths of loading must be determined by other less direct methods. Interpretations of individual Bouguer anomalies suggest that the average depth of loading for the sedimentary basins is about 2–3 km (Bott, 1964; Bott and Young, 1971) and roughly 5 km for the granites (Bott et al., 1958; Bott 1967; Bott 1974; Hipkin and Hussain, 1983). Additional loading may occur within the upper crust, at the upper–lower crustal boundary, within the lower crust, at the Moho and within the upper mantle. Further constraints on the form of some of these density contrasts can be derived from other geophysical methods, in particular seismic refraction and reflection.

5.11.2 Seismic reflection and refraction data

Seismic refraction data is interpreted to determine the velocity–depth structure of

the crust. Estimates of density may then be obtained from the velocity data using the Nafe–Drake (1957) curve for sediments and the velocity–density relationships described by Woollard (1959) for the crystalline crust.

Deep seismic reflection profiles such as those interpreted by COCORP, BIRPS and DEKORP give less velocity information but reveal much more of the complex structure of the upper and lower crust. Since 1981, the BIRPS (British Institutes Reflection Profiling Syndicate) programme has recorded over 9000 km of seismic reflection data for the UK continental shelf (McGeary et al., 1987). The BIRPS profiles show a remarkably consistent pattern of reflectivity throughout much of the continental shelf (Matthews and Cheadle, 1986). A typical BIRPS profile indicates that the crust comprises three main units (McGeary et al., 1987):

- (1) a region of shallow sedimentary basins marked by continuous reflectors of shallow dip;
- (2) a generally non-reflective upper crust;
- (3) a highly reflective lower crust.

The base of the reflective lower crust is considered to correspond to the Moho. The thickness of this unit is highly variable but averages roughly 4 seconds two way travel time.

The results of seismic refraction experiments broadly agree with this interpretation. Simple models of refraction profile data usually define three main boundaries (Setto and Meissner, 1987):

- (1) the base of the sedimentary basins which are marked by compressional (p) wave velocities smaller than 6 km s^{-1} ;
- (2) an intracrustal boundary sometimes known as the Conrad boundary where p wave velocities show a sudden increase from velocities in the region of 5.8 to 6.3 km s^{-1} to values greater than 6.5 km s^{-1} ;
- (3) the crust–mantle boundary at the Moho where p wave velocities increase to values greater than 8.1 km s^{-1} .

The latter two boundaries are often also identified from the $P_C P$ and $P_m P$ wide

angle reflections respectively. This model is probably an over simplification of the true structure. For example, a three layer crust was imaged in northern Scotland by the LISPB seismic refraction project (Bamford et al., 1978).

Gravity and seismic data have been jointly investigated to interpret the structure of the southwestern region of the UK continental shelf using the SWAT (Southwestern Approaches Traverse) profiles (BIRPS and ECORS, 1986). In an interpretation of profiles 2, 3 and 10 which traversed the North Celtic Sea graben, the South Celtic Sea graben and the English Channel basin respectively Setto and Meissner (1987) modelled four main density units:

- (1) the low density sediments (2500 kg m^{-3});
- (2) the upper crust down to a depth of about 10 km ($\approx 2650 \text{ kg m}^{-3}$);
- (3) the lower crust (2850 kg m^{-3});
- (4) the upper mantle (3300 kg m^{-3}).

Modifications of this general model have been used to calculate theoretical response functions and coherences for two loading configurations. The first assumes loading occurs at the surface, mid crustal depths and the Moho. The second configuration replaces the mid crustal loading by a shallow, low density loading layer intended to represent part of the loading produced by the sedimentary basins. The purpose of these models is to determine the relative importance of the two subsurface loads and to estimate the value of T_e for the continental lithosphere in the UK region.

A four layer loading model would represent the known loading configuration more accurately but would require a much more complex isostatic model and as will be seen later may not have provided much more information.

5.12 Isostatic model

An isostatic model comprising the lithosphere loaded at the surface, Moho and an intermediate layer has been developed by Bechtel et al. (1987). The development of this model and the modifications required to generalise the parameters is described below.

After flexure and compensation the relief on the three interfaces comprises components from the loading on each interface. If the final relief of the surface, intermediate and Moho layers are denoted H, V and W respectively then

$$H = H_H + H_V + H_W$$

$$V = V_H + V_V + V_W \quad 5.53$$

$$W = W_H + W_V + W_W$$

For the extent of this proof the wavenumber argument will normally be omitted for clarity. The subscripts H, V and W identify the loading responsible for each component. For example, H_H is the surface topography which results from the initial surface load H_I and V_W is the relief on the intermediate interface owing to the initial loading loading at the Moho, and so on. The initial, preflexure relief on each interface is given by

$$H_I = H_H - W_H = H_H - V_H$$

$$V_I = V_V - W_V = V_V - H_V \quad 5.54$$

$$W_I = W_W - H_W = W_W - V_W$$

The relationships between the components of relief can be determined from the thin elastic plate equation. For surface loading

$$W_H = V_H = -\rho_0 H_H / \Delta \rho_1 \xi \quad 5.55$$

where ρ_0 is the density of the surface topography and $\Delta \rho_1 = \rho_m - \rho_0$. ξ is the flexural parameter $= 1 + Dk^4 / (\Delta \rho_1 g)$. For loading at the intermediate interface

$$W_V = H_V = -\Delta \rho_2 V_V / ((\rho_m - \Delta \rho_2) \psi) \quad 5.56$$

where $\Delta\rho_2 = \rho_c - \rho_0$, ρ_c is the density of the intermediate layer and ψ is the flexural parameter $= 1 + Dk^4/((\rho_m - \Delta\rho_2)g)$. Finally, for the relief on the Moho

$$W_W = -\rho_c H_W \phi / \Delta\rho_3 \quad 5.57$$

where $H_W = V_W$, $\Delta\rho_3 = \rho_m - \rho_c$, ρ_m is the density of the upper mantle and $\phi = 1 + Dk^4/\rho_c g$.

The theoretical response function and coherence are calculated from the cross spectrum and the power spectra of the topography and gravity signals. If the intermediate interface lies at a depth z_c beneath sea level and the Moho lies at a depth of z_m the cross spectrum is given by

$$C = \langle (2\pi G \Delta\rho_2 V e^{-kz_c} + 2\pi G \Delta\rho_3 W e^{-kz_m}) H^* \rangle \quad 5.58$$

$$= \langle H_H^* W_H \alpha + H_H^* V_H \beta + H_V^* W_V \alpha + H_V^* V_V \beta + H_W^* W_W \alpha + H_W^* V_W \beta \rangle \quad 5.59$$

where $\alpha = 2\pi \Delta\rho_3 e^{-kz_m}$ and $\beta = 2\pi \Delta\rho_2 e^{-kz_c}$. Cross terms such as $H_H^* V_W$ are eliminated by the ensemble averaging. The power spectrum of the topography is given by

$$\langle H \cdot H^* \rangle = \langle H_H^2 + H_V^2 + H_W^2 \rangle \quad 5.60$$

where $H_H^2 = |H_H|^2 = \text{Re}^2(H_H) + \text{Im}^2(H_H)$. The determination of the gravity power spectrum is more controversial. The gravity effect of the interfaces is given by

$$\Delta G = 2\pi G \Delta\rho_2 V e^{-kz_c} + 2\pi G \Delta\rho_3 W e^{-kz_m} \quad 5.61$$

If V and W are considered to be statistically independent the power spectrum is given by

$$\langle \Delta G \Delta G^* \rangle = \langle W_H^2 + W_V^2 + W_W^2 \rangle \alpha^2 + \langle V_H^2 + V_V^2 + V_W^2 \rangle \beta^2 \quad 5.62$$

(Bechtel et al., 1987). However, the initial loads V_I and W_I are considered to be statistically independent but the final relief of the interfaces V and W is not entirely independent. If we consider the components of V and W then $V_H = W_H$ and the component pairs W_V and V_V , and W_W and V_W are related by the expressions (5.56) and (5.57). Therefore, the components of V and W cannot be considered to be entirely

independent and they will not be eliminated by the ensemble averaging. In this case the gravity power spectrum should be given by

$$\begin{aligned} \langle \Delta G \Delta G^* \rangle = & \langle \alpha^2 (W_H^2 + W_V^2 + W_W^2) \rangle \\ & + \langle \alpha \beta (V_H W_H^* + V_V W_V^* + V_W W_W^* + V_H^* W_H + V_V^* W_V + V_W^* W_W) \rangle \\ & + \langle \beta^2 (V_H^2 + V_V^2 + V_W^2) \rangle \end{aligned} \quad 5.63$$

Note also that α and β have been kept inside the ensemble average for reasons that will be explained later. The expected response and coherence may be calculated from equations (5.14) and (5.21). In a study of the isostatic compensation in the vicinity of the East African rift Bechtel et al. (1987) split the observed Bouguer gravity spectrum into two components. These two components were downward continued to define V and W . From V and W the initial loads and the components of the present relief of the interfaces were determined and the coherence and theoretical response calculated for a given flexural rigidity.

This direct approach does not appear to be applicable to the UK region and a more general loading model is assumed. The requirements of this model are only that the initial loads are statistically independent and the ratio of the loads are constant for all wavenumbers. The model is an approximation but it is more likely to provide useful information than the earlier approach. As with the two layer model ratios between the initial intermediate and Moho loads, and the initial surface load are defined

$$f_1 = \frac{\Delta \rho_2 |V_I|}{\rho_0 |H_I|} \quad f_2 = \frac{\Delta \rho_3 |W_I|}{\rho_0 |H_I|} \quad 5.64$$

From these ratios and the earlier relationships $|H_V|$ and $|H_W|$ may be expressed in terms of $|H_H|$

$$\begin{aligned} |H_V| &= |H_H| \frac{f_1 (\rho_0 + \rho_0^2 / \Delta \rho_1 \xi)}{\Delta \rho_2 (1 + (\rho_m - \Delta \rho_2) \psi / \Delta \rho_2)} \\ |H_W| &= |H_H| \frac{f_2 (\rho_0 + \rho_0^2 / \Delta \rho_1 \xi)}{\Delta \rho_3 (1 + \rho_c \phi / \Delta \rho_3)} \end{aligned} \quad 5.65$$

For simplicity, these relationships may be expressed as

$$|H_V| = \sigma |H_H| \quad |H_W| = \mu |H_H| \quad 5.66$$

From the earlier relations the components of relief of V and W may be expressed in terms of H_H , H_V and H_W . Therefore, if we re-express H_V and H_W in terms of H_H

the formulae for the cross and power spectrum become

$$\langle \Delta G H^* \rangle = \langle |H_H|^2 \left(-\frac{\rho_0 \alpha}{\Delta \rho_1 \xi} - \frac{\rho_0 \beta}{\Delta \rho_1 \xi} + \sigma^2 \alpha - \frac{\sigma^2 (\rho_m - \Delta \rho_2) \psi \beta}{\Delta \rho_2} - \frac{\rho_c \mu^2 \phi \alpha}{\Delta \rho_3} + \mu^2 \beta^2 \right) \rangle \quad 5.67$$

$$\langle H H^* \rangle = \langle |H_H|^2 (1 + \sigma^2 + \mu^2) \rangle \quad 5.68$$

$$\begin{aligned} \langle \Delta G \Delta G^* \rangle = & \langle |H_H|^2 \left(\left(\frac{-\rho_0}{\Delta \rho_1 \xi} \right)^2 + \sigma^2 + \left(\frac{-\rho_c \mu \phi}{\Delta \rho_3} \right)^2 \right) \alpha^2 \rangle \\ & + 2 \langle |H_H|^2 \left(\left(\frac{-\rho_0}{\Delta \rho_1 \xi} \right)^2 - \frac{\sigma^2 (\rho_m - \Delta \rho_2) \psi}{\Delta \rho_2} - \frac{\rho_c \phi \mu^2}{\Delta \rho_3} \right) \alpha \beta \rangle \\ & + \langle |H_H|^2 \left(\left(\frac{-\rho_0}{\Delta \rho_1 \xi} \right)^2 + \left(\frac{-\sigma (\rho_m - \Delta \rho_2) \psi}{\Delta \rho_2} \right)^2 + \mu^2 \right) \beta^2 \rangle \end{aligned} \quad 5.69$$

In the final expressions for the theoretical amplitude response $Q(k)$ and coherence $\gamma^2(k)$ in terms of the cross spectrum and power spectra the $|H_H|^2$ terms cancel if the ensemble average for a single, constant value of k is considered. This allows the theoretical amplitude response and coherence to be evaluated for any given values of f_1 , f_2 and T_e . However, a note of caution is required before comparing the theoretical response and coherence with the observed data because the observed data is determined from discrete observations of the cross spectrum and power spectra averaged over finite wavebands. This explains why initially I kept the terms α and β inside the ensemble average. Providing that the amplitude of the initial surface load H_I does not vary rapidly with changes in the wavenumber k investigations have shown that the error between the theoretical models and the averaged estimates should be negligible at long and intermediate wavelengths. For the models shown later the estimated maximum fractional error is roughly 5% and generally the error is much less. The error discussed here is probably significantly less important than the approximation in the assumption of statistical independence between the different loads.

This problem also applies to equations (5.36) and (5.47) which are the analogous equations for the two layer lithosphere model. Note that the equations are correct. The problem arises in the comparison of analytical formulae with averaged discrete observations. This difficulty is widespread throughout the study of isostatic response and admittance functions because theoretical functions of the wavenumber k are compared with a series of averages of discrete estimates which at best describe an averaged version of the theoretical relationship.

The coherence calculated from this model is similar to that for the two layer model. There is a rapid transition from incoherence to coherence. The wavelength of the transition is dependent upon the elastic thickness of the lithosphere and the loading ratios f_1 and f_2 . The weighting of the ratios f_1 and f_2 appears to be fairly even. Therefore, f_1 and f_2 cannot be determined from the coherence alone. When f_1 and f_2 are close to zero the response is similar to that for surface loading. If f_1 and f_2 are both greater than 1.5 the response is similar to that of the two layer model with significant subsurface loading. When f_1 and f_2 are both close to 1.0 the response is characterized by a rapid rise in amplitude followed by a levelling off of the response (see figure 5.34). This form of response is significant because it matches the observed form of the data for the UK response at intermediate wavelengths.

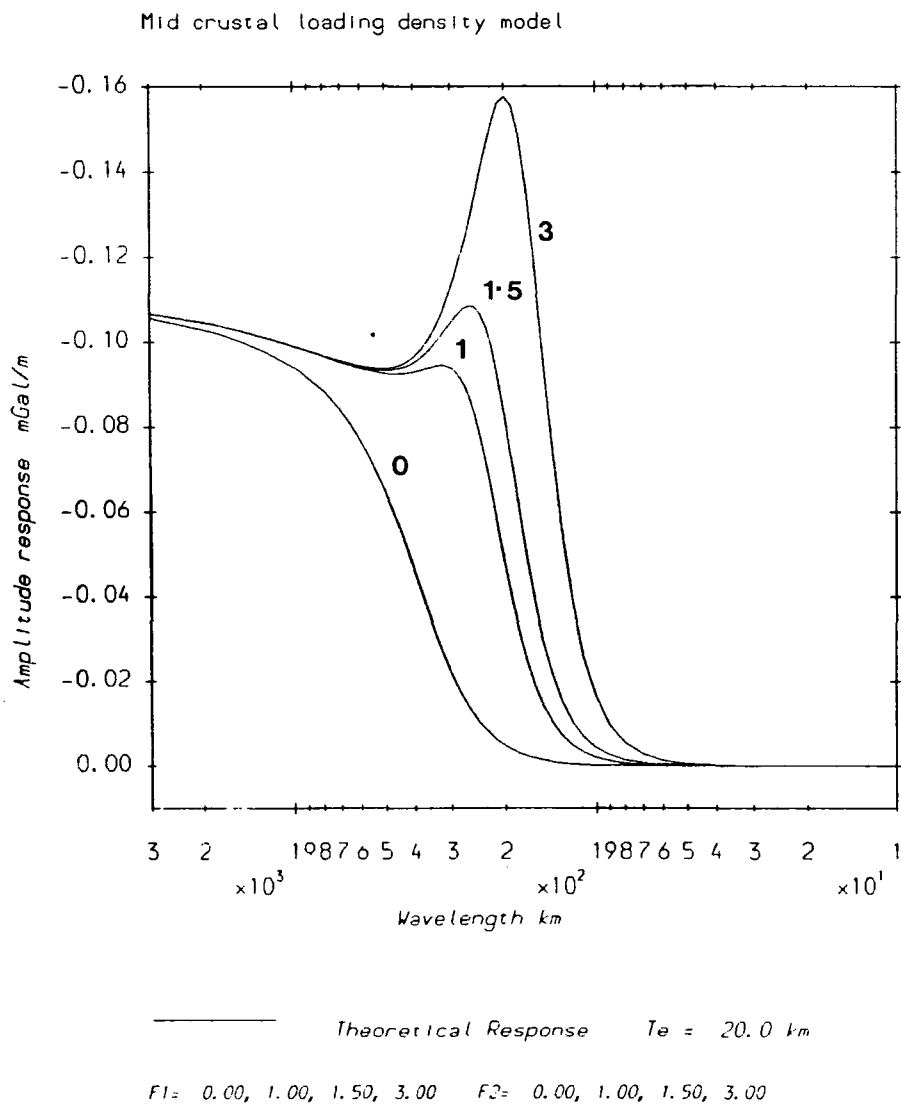
The amplitude of the response is also controlled by the depths z_c and z_m . The amplitude of the response decreases as the depths increase. The response is not particularly sensitive to small changes in ρ_c and ρ_m but the value of ρ_0 controls the asymptotic level of the amplitude response at long wavelengths.

5.13 Modelling the observed response and coherence

The observed response and coherence for the modified grid with the isostatic influence of the granites removed has been modelled using the three layer model. The models were only an approximation of the true isostatic system because the actual loading probably occurs at more than three distinct levels. However, it may be possible to determine the depth of the most important loads and to estimate the elastic thickness of the lithosphere.

The modelling is performed in the same manner as for the two layer model except that there are now two loading ratios. The observed response is modelled only for the intermediate wavelengths ($200 < \lambda < 700$ km) where the characteristics of the observed response roughly match those of the theoretical model. The application of a priori models is considered more appropriate than using an optimization approach to fitting the observed response because there are very few points to model and a significant

Figure 5.34. Theoretical amplitude response for the three layer isostatic model for various values of the loading ratios f_1 and f_2 . The amplitude response curve annotation denotes the values of the loading ratios f_1 and f_2 for each curve. The values of f_1 and f_2 are identical for each curve. The additional parameters in the amplitude response formula are $T_e = 20$ km, $\rho_0 = 2650$ kg m⁻³, $\rho_c = 2850$ kg m⁻³, $\rho_m = 3300$ kg m⁻³, $z_c = 10$ km and $z_m = 30$ km.



number of variables.

The first model investigated the influence of the mid crustal density contrast and comprises an upper crustal layer of density 2650 kg m^{-3} extending to a depth of 10 km, a lower crustal layer of density 2850 kg m^{-3} terminating at a depth of 30 km and the upper mantle which was assigned a density of 3300 kg m^{-3} . The second model comprises a layer of density 2400 kg m^{-3} extending to a depth of 2.5 km representing the loading produced by the shallow density contrasts, a crustal density of 2700 kg m^{-3} and an upper mantle density of 3350 kg m^{-3} . The sediment and upper mantle densities applied in the second model are more general than those of the model of Setto and Meissner (1987).

5.13.1 Mid crustal loading

The best fit (by eye) models of the coherence and response for the mid crustal loading model are shown in figures 5.35 and 5.36. The fit between the observed and theoretical coherence is poor. Therefore, the initial rise from incoherence to partial coherence has been used to estimate the elastic thickness of the lithosphere. This means that the estimated value of T_e may be an underestimate or the values of the loads f_1 and f_2 may be overestimates or a combination of both these factors may occur. However, the modelling of the amplitude response should constrain these factors. The theoretical response roughly matches the form of the observed estimates within the intermediate wavelength region.

The estimated amplitude of the loading on each interface appears to be roughly constant because $f_1 = f_2 = 1.0$. This is interesting because the density contrast at the surface is much greater than the internal density contrasts. However, the wavelengths of interest are quite large ($\lambda > 200 \text{ km}$) and the topography of the initial internal interfaces must be greater than that of the surface for these wavelengths. The estimated elastic thickness of the lithosphere is 24.5 km. This value is unusual because it means that the elastic thickness of the lithosphere is less than the depth to the deepest modelled density contrast at the Moho. Therefore, the Moho density contrast may not deform elastically. Detailed rheological studies of the continental lithosphere suggest that stress in the lower

Figure 5.35. Comparison between the observed coherence between the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical coherence predicted by the mid crustal loading isostatic model assuming a uniform elastic thickness for the continental lithosphere.

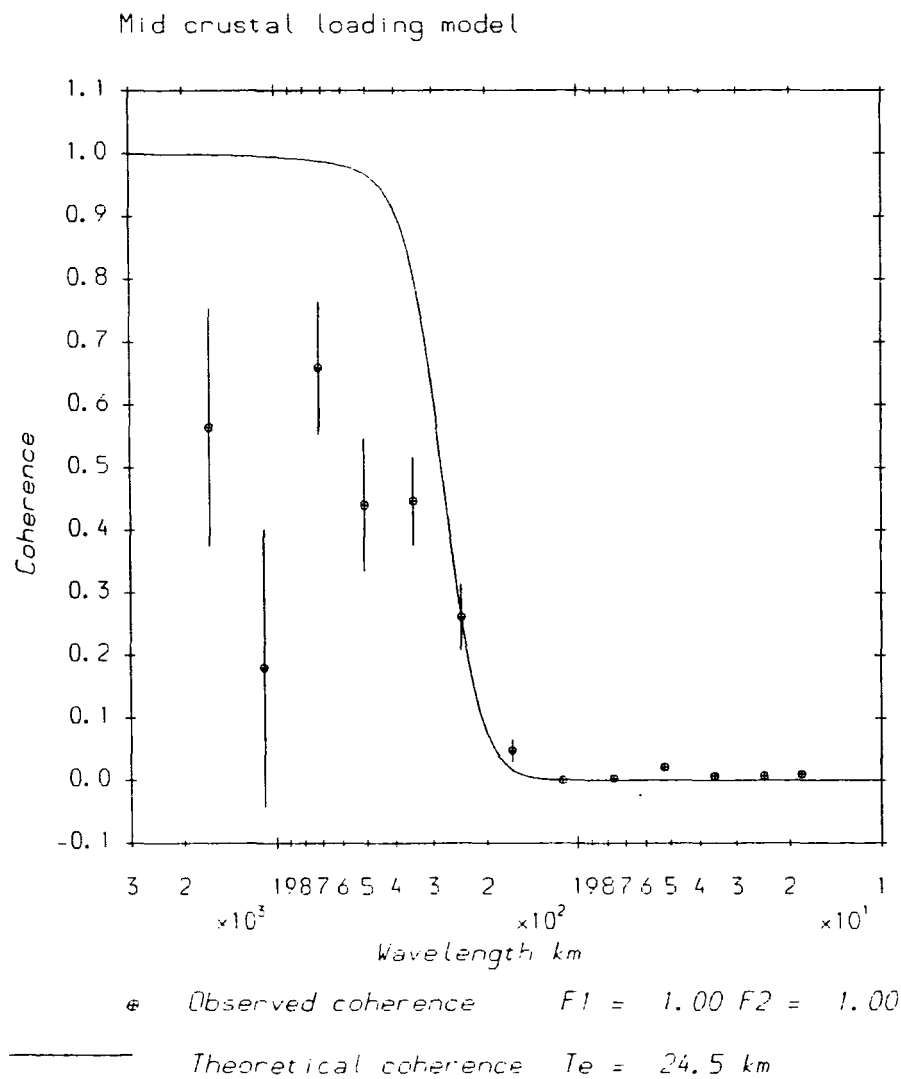
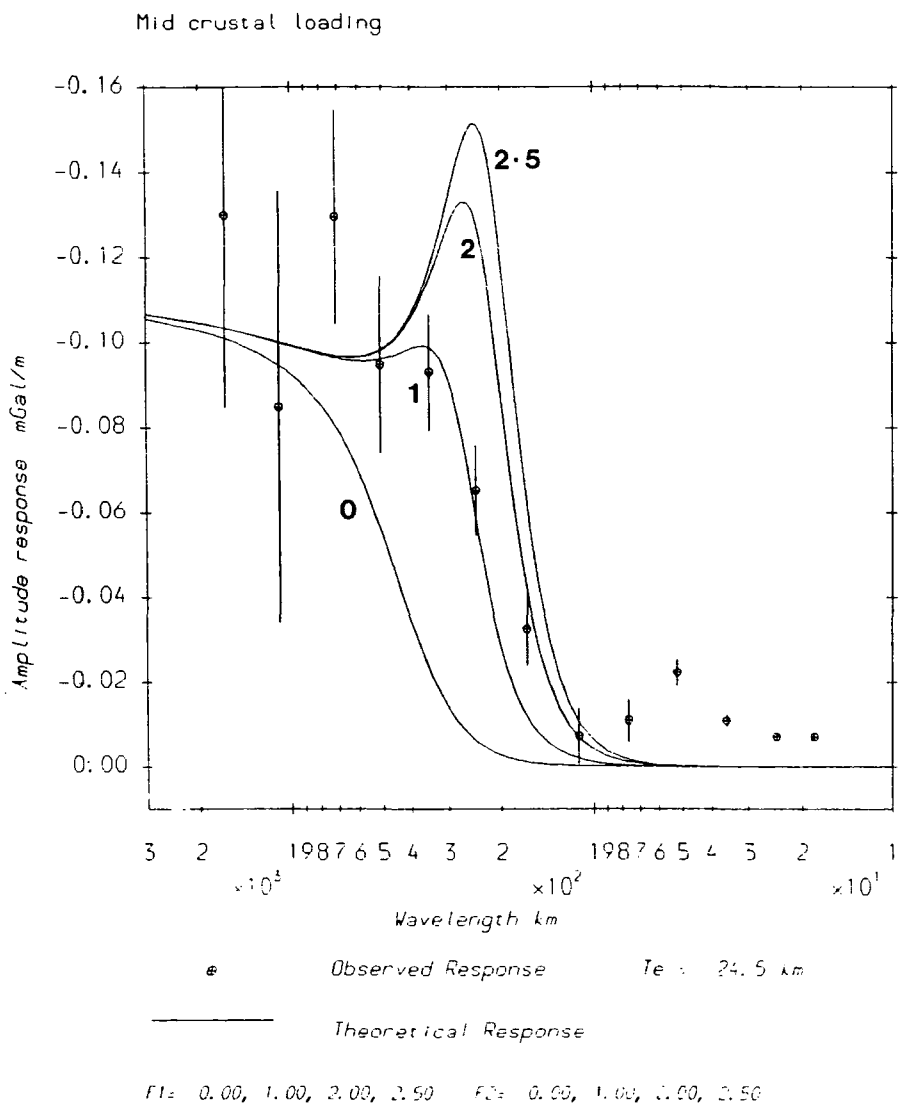


Figure 5.36. Comparison between the observed amplitude response determined from the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical amplitude response predicted by the mid crustal loading isostatic model assuming a uniform elastic thickness for the continental lithosphere.

The amplitude response curve annotation denotes the values of the loading ratios f_1 and f_2 for each curve. For each curve the values of f_1 and f_2 are identical.



crust–upper mantle may be released by processes such as creep (see *Kusner* and Park (1987) for example). Banks et al. (1977) suggested that at depths greater than the elastic thickness of the lithosphere, the initial deformation may be elastic but with time creep processes will modify the deformation until a more local form of compensation is achieved. However, it is difficult to calculate the initial elastic deformation of the whole lithosphere followed by the relaxation of stress in the lower crust–upper mantle by creep processes for the type of general loading model required for cross spectral analysis. Therefore, at present the thin elastic plate model provides a useful model for preliminary analysis but the limitations of the model must be appreciated. As discussed earlier the value of T_e estimated from the coherence may also be a minimum estimate.

5.13.2 Shallow loading model

Again the fit between the observed and theoretical coherence is poor (figure 5.37). At the intermediate wavelengths the fit between the observed and theoretical response is of a similar quality to that of the mid crustal model (figure 5.38). The loading ratios are identical to the previous model, but a slightly lower estimate of the elastic thickness of 22.5 km is required. The amplitude of the response at long wavelengths is less than for the other model owing to the smaller value of ρ_0 . The large errors in the estimates of the response at long wavelengths make it difficult to use the values to distinguish between the two densities.

5.14 Discussion

From the interpretation of the response function and coherence alone it is not possible to distinguish clearly which of the two models is most *appropriate*. This is because very few of the observed estimates of the response and coherence are being modelled and the theoretical response is very flexible so that quite good fits can be obtained for both data sets despite the constraints imposed by simultaneously modelling the coherence. Therefore, the cross spectral relationships cannot be used to define a specific ‘best fit’ depth of loading within the crust. This lack of definition also reflects the fact that in reality loading occurs at a number of depths within the crust. However,

Figure 5.37. Comparison between the observed coherence between the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical coherence predicted by the shallow loading isostatic model assuming a uniform elastic thickness for the continental lithosphere.

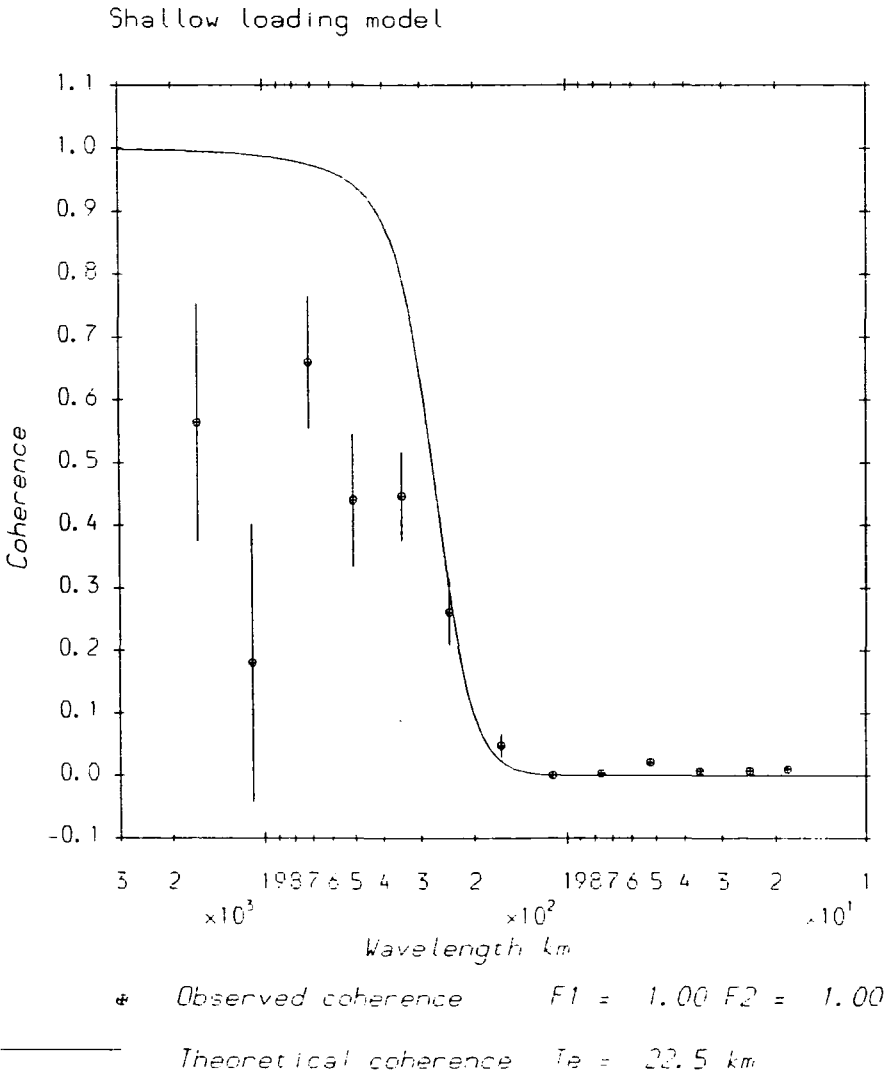
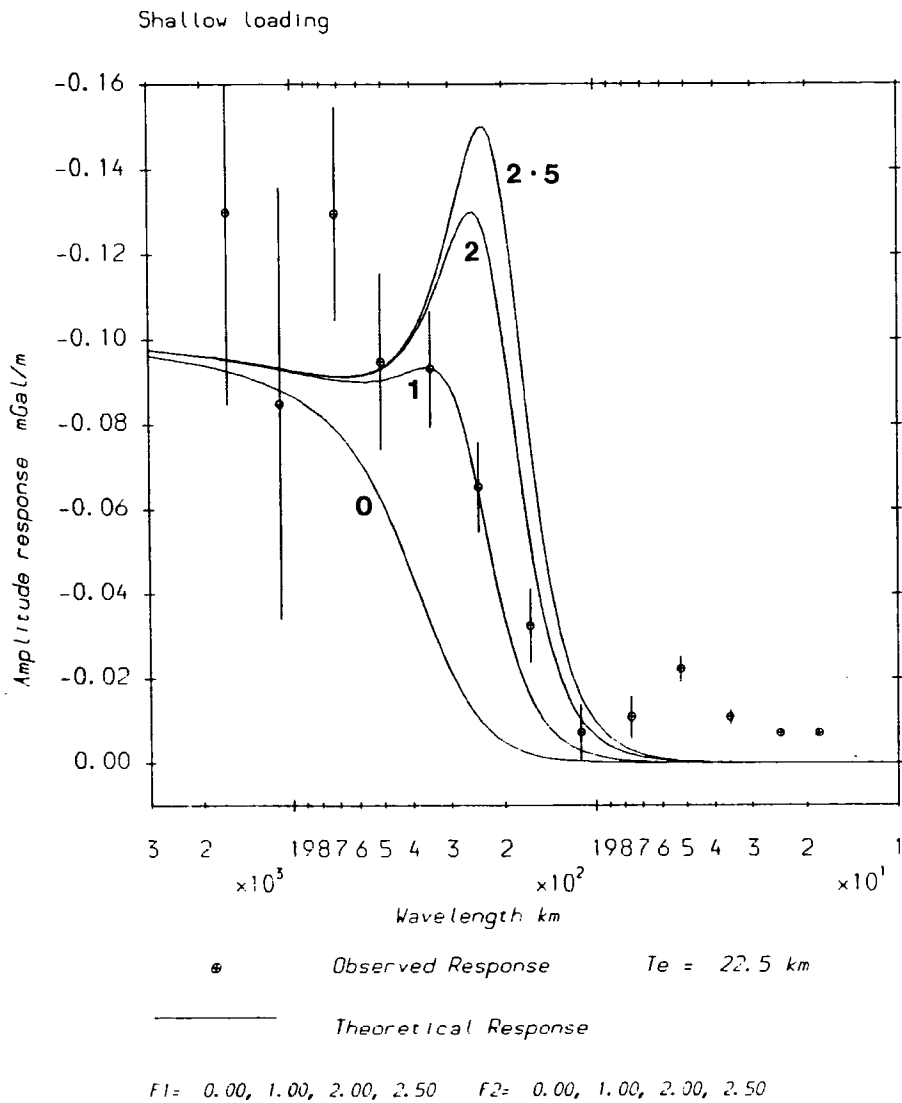


Figure 5.38. Comparison between the observed amplitude response determined from the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical amplitude response predicted by the shallow loading isostatic model assuming a uniform elastic thickness for the continental lithosphere.

The amplitude response curve annotation denotes the values of the loading ratios f_1 and f_2 for each curve. For each curve the values of f_1 and f_2 are identical.



the estimates of the elastic thickness of the lithosphere are reasonably consistent. The best fit elastic thickness is of the order of 22.5 to 24.5 km. The assumption of a uniform elastic thickness for the lithosphere, though, may be erroneous. This is discussed in the next section.

5.15 The effects of integrating the response and coherence over different tectonic provinces

The predicted coherence for the theoretical models poorly matches the observed data. This is primarily because the theoretical transition from incoherence to coherence is much more rapid than that observed for the real data. The sharp transition is indicative of a uniform elastic thickness. If the elastic thickness of the lithosphere varies over the UK region the transition would develop a more gradual slope (see Forsyth, 1985). The three layer model has been modified to determine the theoretical coherence and response for a population of provinces with elastic thicknesses uniformly distributed between $T_{e_{min}}$ and $T_{e_{max}}$. The assumptions used for the calculations are the same as were used earlier except that the more complex three layer model is averaged.

The expected value of $\hat{Q}(k)$ is given by

$$\hat{Q}(k) = \frac{\int_{T_{e_{min}}}^{T_{e_{max}}} Q_3 \cdot H \cdot H^* dT_e}{\int_{T_{e_{min}}}^{T_{e_{max}}} H \cdot H^* dT_e} \quad 5.70$$

where Q_3 is the response determined for the three layer model for each value of k and T_e . The coherence is given by

$$\gamma^2(k) = \frac{\left(\int_{T_{e_{min}}}^{T_{e_{max}}} \Delta G \cdot H^* dT_e \right)^2}{\int_{T_{e_{min}}}^{T_{e_{max}}} H \cdot H^* dT_e \int_{T_{e_{min}}}^{T_{e_{max}}} \Delta G \cdot \Delta G^* dT_e} \quad 5.71$$

The cross spectrum and power spectra are evaluated from equations (5.67), (5.68) and (5.69). The component H_H is dependent upon T_e and it cannot be eliminated from the expression. The initial load H_I is independent of T_e and if H_H is expressed in terms of H_I the initial load may be eliminated from the expression. The required relationship is derived as follows

$$W_T(k) = -\rho_0 H_I(k) / \rho_m \left(\frac{Dk^4}{\rho_m g} + 1 \right) \quad 5.72$$

$$H_T(\mathbf{k}) = -W_T(\mathbf{k})(\rho_m - \rho_0) \left(\frac{Dk^4}{(\rho_m - \rho_0)g} + 1 \right) / \rho_0 \quad 5.73$$

Using these relationships the observed response and coherence have been remodelled. The error between the theoretical model and the observed data discussed earlier is present again. Although the estimated maximum error is slightly greater than before, the error is probably almost negligible considering the approximations of the theory.

5.15.1 Mid crustal loading

The fit between the observed and theoretical coherence is much better than for the uniform elastic thickness model but the slope may still be a little steep (figure 5.39). The main transition of the observed response from low to high amplitudes is modelled quite well, but the theoretical response is too large for the 505 km estimate (figure 5.40). The loading ratios have increased significantly to $f_1 = f_2 = 2.0$. The range of the population of elastic thicknesses ranges from 8 to 90 km. Airy isostasy cannot be included in the model because reducing $T_{e_{min}}$ causes the rise in the coherence and amplitude response to occur at unreasonably short wavelengths.

5.15.2 Shallow loading

The results are similar to those obtained for the intermediate model (figures 5.41 and 5.42). The loading ratios are the same as before but the range of the elastic thicknesses has changed slightly to 6 to 86 km. These models indicate that the regional variation of T_e maybe an important factor in the response for the UK region. The results based on the uniform population of provinces only indicate the applicability of this technique. A uniform distribution is used for mathematical convenience but the true distribution of elastic thicknesses is most probably different. A further assumption of this method is that the area of each tectonic province is much greater than the wavelengths of interest. Otherwise the flexural formulae for a uniform elastic thickness used in the component loading equations become invalid.

5.16 The long wavelength response and coherence

The long wavelength estimates of the response and coherence are anomalous. The-

Figure 5.39. Comparison between the observed coherence between the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical coherence predicted by the mid crustal loading isostatic model assuming that the elastic thickness of the continental lithosphere for a series of distinct tectonic provinces of equal area is uniformly distributed between the values of 8 and 90 km.

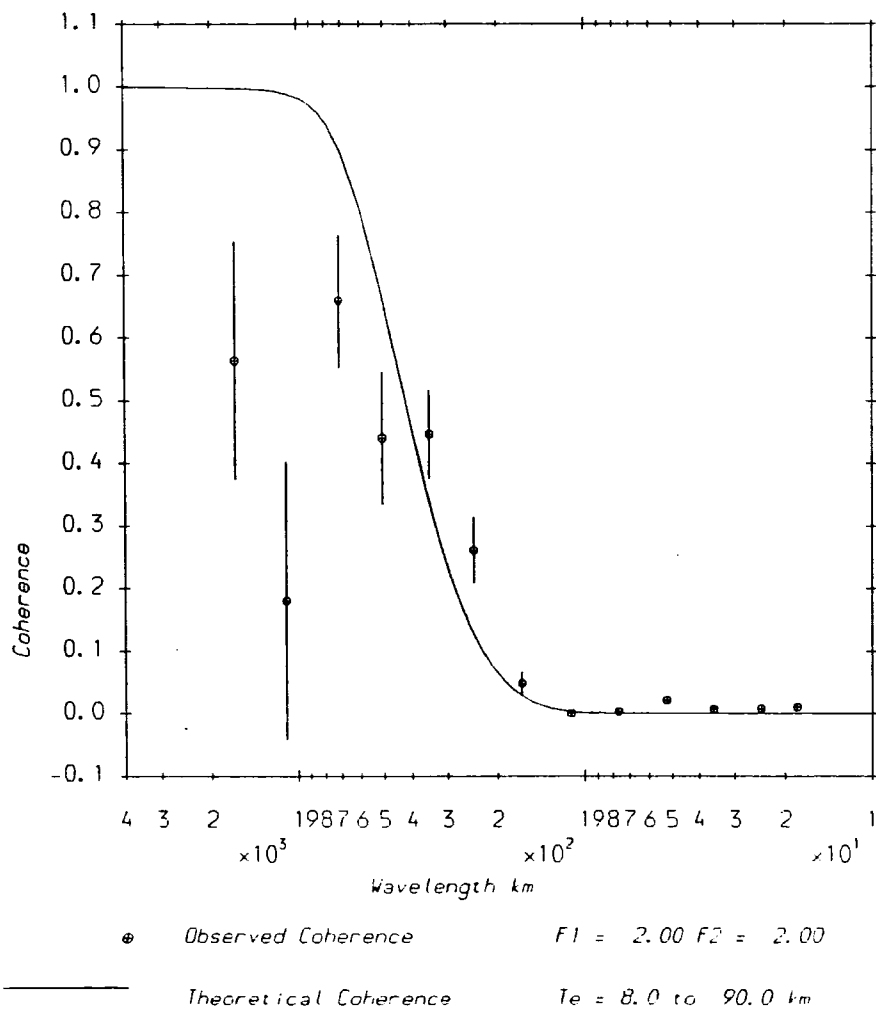


Figure 5.40. Comparison between the observed amplitude response determined from the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical amplitude response predicted by the mid crustal loading isostatic model assuming that the elastic thickness of the continental lithosphere for a series of distinct tectonic provinces of equal area is uniformly distributed between the values of 8 and 90 km.

The amplitude response curve annotation denotes the values of the loading ratios f_1 and f_2 for each curve. For each curve the values of f_1 and f_2 are identical.

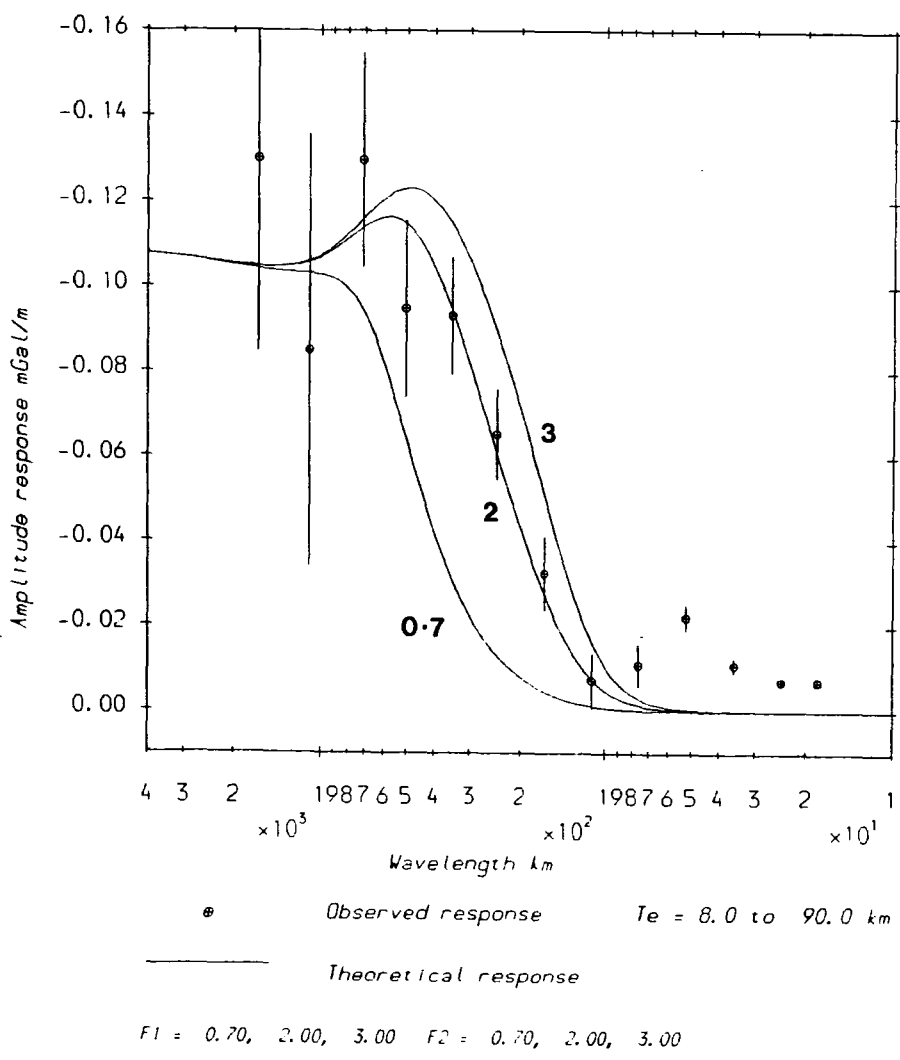


Figure 5.41. Comparison between the observed coherence between the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical coherence predicted by the shallow loading isostatic model assuming that the elastic thickness of the continental lithosphere for a series of distinct tectonic provinces of equal area is uniformly distributed between the values of 6 and 86 km.

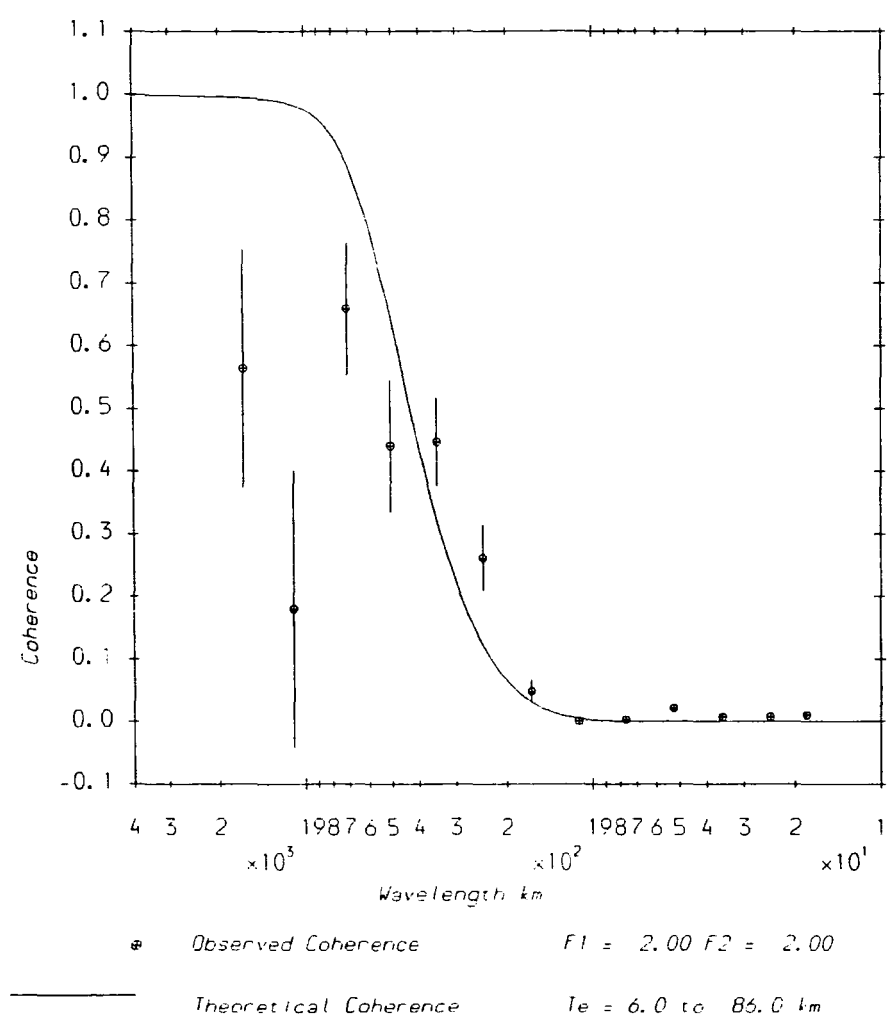
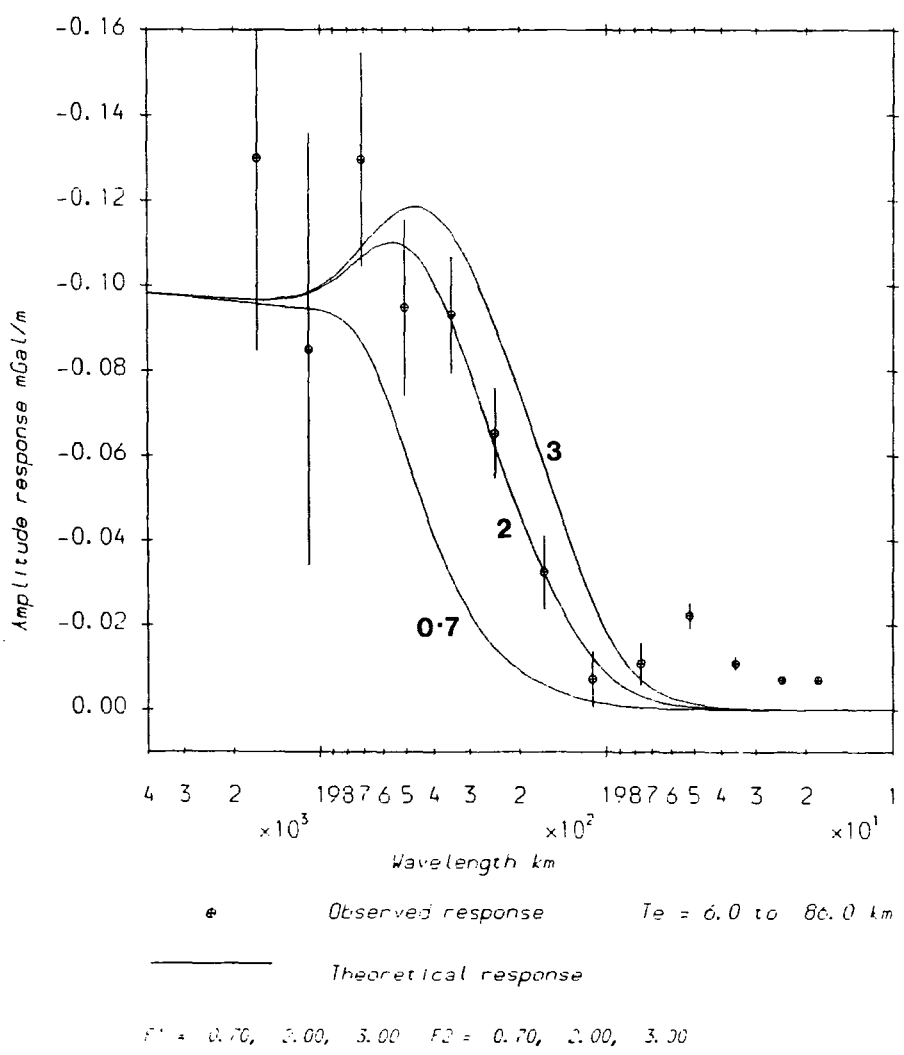


Figure 5.42. Comparison between the observed amplitude response determined from the topography and Bouguer anomaly gravity of the UK and adjacent regions and the theoretical amplitude response predicted by the shallow loading isostatic model assuming that the elastic thickness of the continental lithosphere for a series of distinct tectonic provinces of equal area is uniformly distributed between the values of 6 and 86 km.

The amplitude response curve annotation denotes the values of the loading ratios f_1 and f_2 for each curve. For each curve the values of f_1 and f_2 are identical.



ory predicts that at long wavelengths the real part of the response should tend to the asymptotic value of $-0.11 \text{ mGal m}^{-1}$ and the imaginary part should be zero. The coherence should stabilise at a value of 1.0.

The observed results show a positive correlation between topography and gravity, the values of $\hat{Q}_{real}$ being 0.118, 0.0771 and 0.0057 mGal m^{-1} for the 1647, 1093 and 713 km wavelength estimates respectively. The imaginary components are also significant, especially the imaginary component of the 713 km wavelength estimate which has a value of 0.13 mGal m^{-1} . The coherence is low. The value for the 1093 km wavelength estimate is only 0.18. The theoretical coherence for the two layer lithosphere model should equal 1.0 for a wavelength of 1000 km unless the lithosphere has an elastic thickness greater than 40 km.

The accuracy of these results is questionable because the initial grid dimensions were only $700 \times 1000 \text{ km}$. The estimates for wavelengths greater than 1000 km are obtained as a by-product of the zero padding. However, the results of the Airy isostasy test suggested that these estimates may be accurate. An error will arise in the long wavelength estimates because the response is not sampled at all azimuths owing to the shape of the initial grids. Therefore, noise in the gravity signal will not be as effectively suppressed as for the higher wavenumber estimates. Theoretically there should not be much noise at long wavelengths but this does not appear to be the case for the UK. This difficulty probably arises because of the low amplitude of the topography.

The anomalous form of the response at long wavelengths is not surprising because the observed Bouguer anomalies clearly differ from the form of those expected for the simple isostatic support of the topography. The highest regions of topography occur in the north and centre of the region, whereas the Bouguer gravity shows a strong west-east gradient across the region. The wavelength of this gravity anomaly can be determined from the distance between the central low of the southern North Sea basin and the centre of the Irish Sea high. This distance is roughly 450 km. Therefore, the wavelength is approximately 900 km.

Positive correlations between free air gravity anomalies and topography may re-

sult from convective processes in the mantle. Morgan (1972) suggested that positive anomalies should occur over rising regions of the mantle because the gravity anomaly is the sum of both the mass deficiency of the rising region and the mass of the deformed surface area. The rising region is associated with the uplift of surface topography. McKenzie et al. (1974) showed that this was true for a constant viscosity convective system but if the viscosity of the mantle is temperature dependent topographic and gravity anomalies may be either positive or negative over rising regions (McKenzie, 1977).

Sclater et al. (1975) determined a positive correlation with a slope of 0.03 mGal m^{-1} between $5^\circ \times 5^\circ$ averages of gravity and residual topography depths for the North Atlantic in the vicinity of the Azores and Cape Verde Isles. Watts (1976) obtained a similar correlation of slope $0.022 \text{ mGal m}^{-1}$ for the southeastern end of the Hawaiian ridge.

Mantle convection could be a significant factor in the long wavelength response of the UK because the region lies on the edge of the geoid high associated with the Icelandic hot spot. This may partially explain the strong west-east Bouguer gravity gradient. However, the positive correlations observed by Sclater et al. (1975) and Watts (1976) have low amplitudes of about 0.03 mGal m^{-1} . The positive correlation for the UK data is greater than this and applies to the Bouguer gravity and not the free air gravity. The admittance obtained for the correlation between free air anomalies and topography is related to the isostatic response function by

$$\hat{z}(k) = \hat{Q}(k) + 2\pi G\rho e^{-kz_t} \quad 5.74$$

where z_t is the depth from sea level to the topographic surface (McNutt, 1980). Therefore, the isostatic response function would be expected to show a more negative correlation than the admittance.

The low coherence indicates that there cannot be a single, simple relationship between gravity and topography. This could be caused by the interference of two gravity-topography relationships such as those of flexurally and dynamically supported topography.

5.17 Conclusions and discussion

The results of this investigation indicate that the simple, surface loading model of isostasy cannot adequately explain the observed relationship between topography and gravity for the UK region. The assumptions made for this technique are applicable only to young oceanic regions where the lithosphere is laterally homogeneous and the surface loading approximation is acceptable. The heterogeneous nature of the much older continental lithosphere causes these assumptions to be inadequate.

The form of isostatic compensation occurring within the continental lithosphere appears to be dependent upon scale. The continental lithosphere is characterized by numerous shallow density contrasts, in particular granitic intrusions and sedimentary basins. The form of these short wavelength features is often partly controlled by brittle tectonics within the upper crust. The granite complexes tend to achieve isostatic compensation through the uplift of fault bounded blocks. Some of the granite complexes may remain under or overcompensated as a result of erosion and other processes. Fault bounded half graben may remain out of isostatic equilibrium. Therefore, at short wavelengths isostatic equilibrium is not always achieved and when isostatic equilibrium does occur the mechanism by which equilibrium is achieved may not be lithospheric flexure.

At intermediate wavelengths lithospheric flexure becomes important. The rise in coherence at wavelengths of roughly 200 km marks the onset of this wavelength region for the UK. The interpretation of the lithospheric flexure is complicated by a number of factors:

- (1) loading of the lithosphere at a number of depths;
- (2) the variation of the elastic thickness of the lithosphere;
- (3) the evolution of thermo-mechanical systems such as those responsible for the formation of the larger sedimentary basins of the UK.

The variable elastic thickness of the lithosphere is a consequence of the complex tectonic evolution of the region. The variation in T_e raises some interesting questions. For instance, is each province in isostatic equilibrium or are the stresses within the lithosphere generated by applied loads transmitted through the whole region? If the

provinces achieve isostatic equilibrium independently this may be facilitated by differential movement along the major basement fractures that define the boundaries of the major provinces as discussed in Chapter 3.

The thermo-mechanical models of sedimentary basin formation discussed earlier also produce more complex relationships between topography and gravity than accounted for by the three layer loading model. Similarly, other complex mechanical models of the continental lithosphere such as those applied to the major mountain chains by Karner and Watts (1983) produce low coherences between topography and gravity. These interpretations suggest that the simple loading model used in the interpretation of the cross spectral analysis may be a significant simplification of the true loading.

At long wavelengths (> 800 km) processes such as convection within the mantle and deep isostatic processes may be important. However, the poor quality of the long wavelength response for the UK makes the conclusive identification of such processes difficult.

The variation of the form of isostatic compensation with wavelength is important because if there is an overlap between the wavelengths at which the different forms of isostasy occur the curvature of the observed response will be modified. As the curvature of the response is a diagnostic feature in the determination of T_e for the lithospheric flexure model (McNutt, 1980) any interference will produce erroneous interpretations.

The interpretation of the response and coherence for the region of flexurally supported loads requires a knowledge of the depths of loading. The investigations into estimating these depths from the gradient of the gravity power spectrum suggest that although the technique works in theory, in practice, it does not provide conclusive results. The best explanation for this is that the actual sources of the Bouguer anomalies do not take the statistical form assigned to them for the theoretical models.

Despite these complications a few conclusions may be drawn from the modelling of the observed response and coherence. Assuming a uniform elastic thickness for the lithosphere the two loading configurations modelled indicated that the 'best fit' elastic

thickness lies in the region of 22.5 to 24.5 km. However, the form of the coherence argues against a uniform elastic thickness. Although the true distribution of provinces is unknown the chosen distribution suggests a range of elastic thicknesses from a minimum of 6–8 km to a maximum of 86–90 km. This suggests a broad range of values may occur but local Airy isostasy does not appear to be significant. Specific values of the elastic thickness of the lithosphere can only be determined from modelling the effect of specific loads.

The most interesting results of the study concern the low coherences. The flexure theory provides two explanations for these apart from the variation in T_e . The loading ratios f_1 and f_2 may vary with wavelength (Forsyth, 1985). A decrease in the ratios with increasing wavelength would force the coherence to be lower than predicted. However, this cannot be investigated in detail without defining the initial loads which is difficult. A further error arises from the assumption of statistical independence between the loads. For example, the low density sediments within the North Sea graben are compensated by thinning of the crust (Wood and Barton, 1983, Sclater and Christie, 1980). Therefore, these loads may be considered to be statistically dependent. The St. George's Channel basin does not appear to be compensated by an antiroot but the basin is underlain by an anomalous region of lower crust (Blundell and Parks, 1969). In the case of other basins intracrustal detachment zones may separate the effects of upper crustal rifting and deeper extension. The loading may then appear to be independent.

The influence of the basins may be put on a semi-quantitative basis by determining the response and coherence for the Bouguer gravity grid with the gravity anomalies which result from the major basins removed (see section 5.11.1). Note that no topographic correction has been made for the removal of the basin loads. A measure of total fraction of the gravity power linearly related to topography can be determined from

$$F_G = \frac{\sum_{i=1}^n C^2(k_i)G^2(k_i)}{\sum_{i=1}^n G^2(k_i)} \quad 5.75$$

where n is the number of averaging annuli and k_i signifies the average wavenumber for each annulus (Banks and Swain, 1978). For the initial UK data grids the value of F_G was 0.467. After the removal of the gravitational influence of the basins the value of

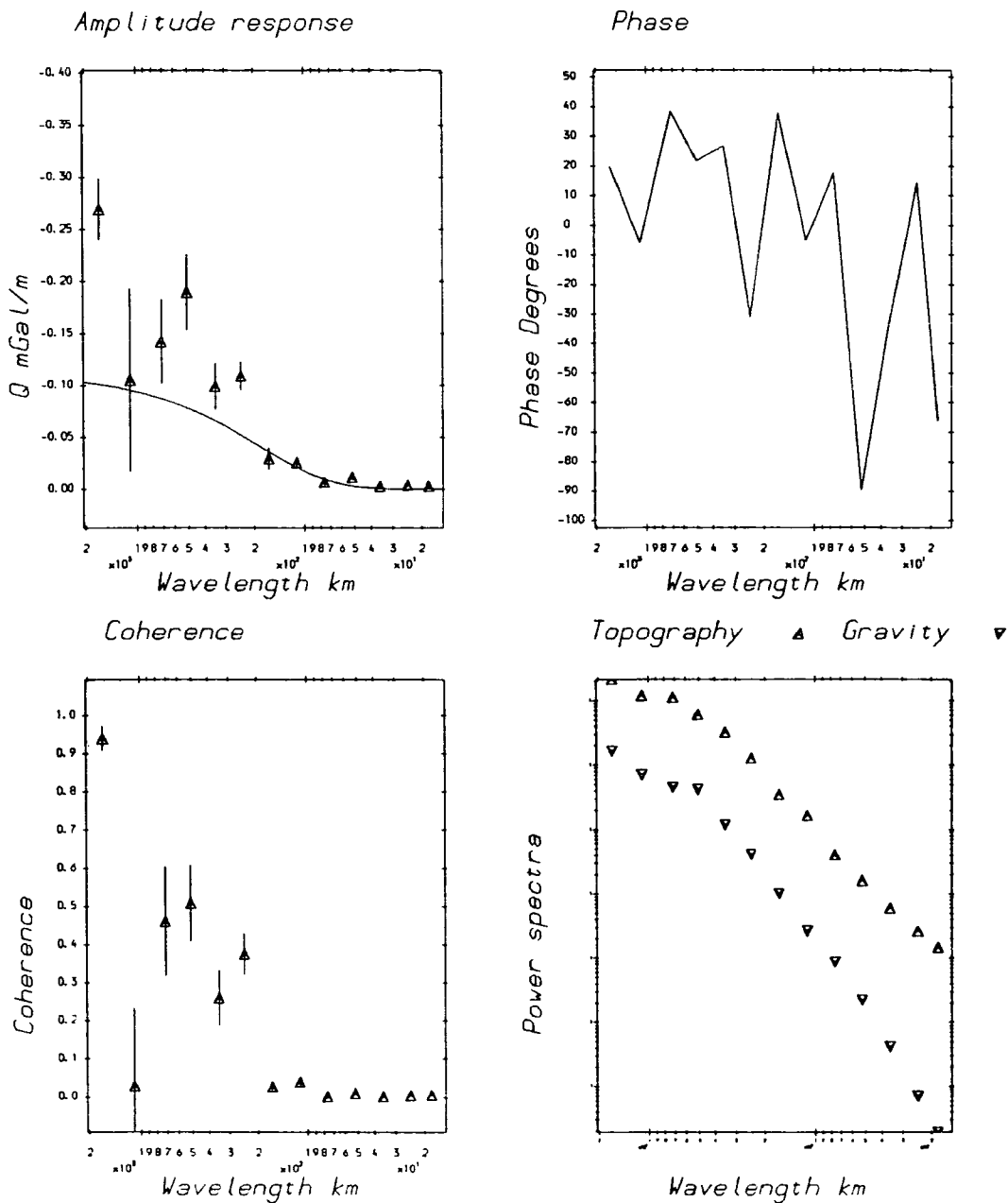
F_G increased to 0.599. The response and coherence obtained for the modified data are shown in figure 5.43. The coherence is still low though; the high value at the 1647 km wavelength probably accounts for most of the improvement of F_G . This still leaves a fraction of roughly 0.4 of the gravity power unrelated to topography.

The low coherence cannot be explained by the higher order terms of the gravity. This was verified by determining the coherence between the isostatic anomaly for the initial data grids and the square of the topography. The total fraction of the residual topography linearly related to the square of topography was only 0.005.

In the light of these observations the best explanation for the low coherence is the interference between different relationships between topography and gravity operative within the UK region. This may arise from either different forms of isostatic compensation such as flexural and dynamic mechanisms or from the averaging of the relationships between gravity and topography over distinctly different tectonic provinces. From the improvement in the fit of modelled coherence for the models with a population of elastic thicknesses the results of this study suggest that the second explanation is more appropriate for the UK region.

Figure 5.43. The isostatic response function, coherence and power spectra determined from the topography and residual Bouguer anomaly gravity of the UK and adjacent regions. 13 waveband estimates have been determined for each component.

The solid line on the amplitude response graph shows the theoretical amplitude response for local Airy isostasy with the parameters $\rho_0 = 2700 \text{ kg m}^{-3}$ and $z_m = 30 \text{ km}$.



CHAPTER 6

The structure of the lower crust beneath the Tertiary

igneous complexes of Mull and Skye, NW Scotland

6.1 Introduction

This chapter presents a tentative interpretation of the structure of the lower crust beneath the Tertiary igneous complexes of the Isles of Mull and Skye. The interpretation is developed from a consideration of the volumes of the central complexes and a novel examination of the observed Bouguer anomalies for the surrounding region. Listings of the computer programmes used to calculate the gravity anomalies produced by bodies with axisymmetric symmetry and the flexure of the lithosphere beneath the load of the central complexes are presented in Appendix D.

6.2 The geology of the central igneous complexes of Mull and Skye

The Hebridean region of NW Scotland forms part of the North Atlantic or Thulean province that was subjected to intense volcanic activity approximately 50–65 Ma ago during the early Tertiary. The extrusion of basaltic plateau lavas over the region was followed by the intrusion of a series of central complexes. The Tertiary centres occupy a roughly north–south zone extending from northeastern Ireland to NW Scotland and the Hebrides. The complexes show little obvious relation to pre-Tertiary structures intruding a variety of different tectonic domains.

The central complexes are formed from various intrusive bodies. Examples include ring dykes, multiple cone sheets, dykes, sills, volcanic plugs, large layered intrusions and the products of explosive vents. Intrusions of both granitic and basic/ultrabasic compositions occur.

The central complex of Mull was formed by three major periods of intrusive activity

(Bailey et al., 1924; Skelhorn et al., 1969). The brief description of the complex given here is derived from a short summary of the previous work given by Bott and Tantrigoda (1987). During the three periods of intrusive activity the centre of activity migrated northwest towards Loch Bà. The first period of activity was centred on Glen More. This period involved the intrusion of a series of mostly early granophyres followed by olivine gabbros, with associated cone sheets and volcanic vents. The second period was concentrated in the vicinity of Beinn Chaisgidle. This period was dominated by the Glen More ring intrusions. The final stage of activity concerned the intrusion of granophyres and felsites centred on Loch Bà.

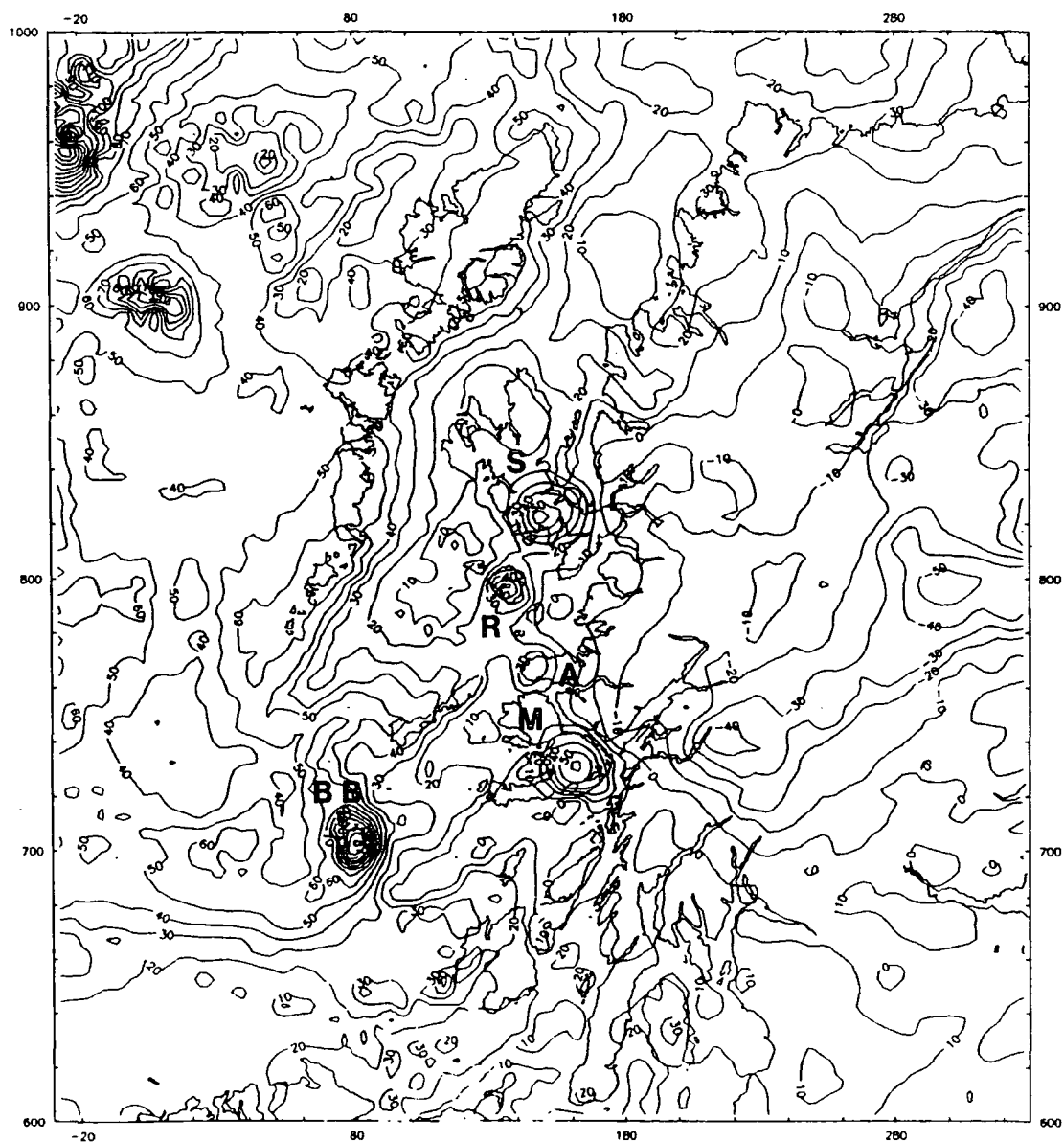
The Skye central complex consists of four main igneous centres, namely the Cuillin, Strath na Creitheach, Western Red Hills and Eastern Red Hills centres (Bell 1976; Emeleus 1982). The Cuillin complex is a layered basic intrusion with some ultrabasic components such as peridotite and allivalite. The other three complexes consist mainly of granitic material.

The intrusion of a generally NW–SE trending dyke swarm extending from the Outer Hebrides, through Mull, to north eastern England accompanied the intrusion of the central complexes (Skelhorn et al., 1969). The majority of the dykes consist of tholeiitic and alkali olivine–dolerites. The intrusion of the dykes in the local vicinity of the centres was associated with upper crustal extension of the order of 10%.

6.3 Gravity anomaly interpretations

The central complexes of Mull and Skye are associated with spectacular positive Bouguer anomalies. These are clearly defined in the Bouguer anomaly map of the region displayed in figure 6.1. The Mull complex is marked by an approximately circular anomaly with a radius of about 12 km (Bott and Tantrigoda, 1987). The maximum observed anomaly is 67.2 mGal. The anomaly background level is roughly 17 mGal. The roughly circular nature of the anomaly is offset by the slight NW–SE elongation of the complex and the relatively low Bouguer anomaly values over the granophyres of the Loch Bà centre.

Figure 6.1. Bouguer anomaly map of central and western Scotland, the Hebridean region and part of the Northwestern Approaches. The contour interval is 10 mGal. The gridding interval is 5 km. The scale is approximately 1:2,500,000 and the border annotation denotes Ordnance survey grid coordinates in km.



Identification of the major Tertiary central igneous complexes of the Hebridean region and western Scotland: S = Skye; R = Rhum; A = Ardnamurchan; M = Mull; BB = Blackstones Bank.

The Skye complex is similarly marked by a nearly circular, positive Bouguer anomaly. A maximum anomaly of 73 mGal occurs over the complex (Bott and Tuson, 1973). The regional anomaly background is estimated to be roughly 20 mGal. As with the Mull complex, the circular nature of the anomaly produced by the central complex is distorted by the shallow granitic intrusions.

The steep Bouguer anomaly gradients over the complexes indicate a shallow origin for the anomalies and the most probable cause is a continuation of the dense basic and ultrabasic rocks observed at the surface down into the metamorphic basement. Tuson (1959) modelled the Mull complex as a dense, cylindrical body extending to a depth of 17 km with a radius of 8 km. The density contrast between the complex and the metamorphic basement was assumed to be 200 kg m^{-3} . Bott and Tuson (1973) developed a more complex model of a truncated cone which extends to a depth of 14 km if rocks of gabbroic composition are dominant within the complex. The most detailed model presented to date is that of Bott and Tantrigoda (1987). The densities of the modelled formations, excluding the central complex at depth, were as follows: Moine assemblage 2750 kg m^{-3} , Lewisian 2800 kg m^{-3} , gabbro and eucrite from Ben Buie 2930 kg m^{-3} and 2970 kg m^{-3} respectively. The density of the complex was assumed to be 3000 kg m^{-3} if the complex comprises mainly olivine tholeiite or 3100 kg m^{-3} if the complex is picritic.

Assuming a density of 3000 kg m^{-3} , the complex extends to a depth of 13 km and occupies a volume of approximately 3650 km^3 . If the complex has a picritic composition it extends to a depth of 6.5 km. The volume occupied by the complex is then roughly 2000 km^3 . The granitic centres observed at the surface form only a small part of the volume of the complex. They occupy between 5 and 9% of the total volume depending on the composition of the complex.

Tuson (1959) explained the origin of the Skye anomaly as a dense, cylindrical body extending to a depth of 17 km with a radius of 8 km. The density contrast between the body and the metamorphic basement was assumed to be 200 kg m^{-3} . The densities of the main formations were determined by Bott and Tuson (1973). The Lewisian gneiss

of the metamorphic basement has a density of $2800 \pm 30 \text{ kg m}^{-3}$. The densities of the intrusive rocks observed at the surface were estimated to be $2950 \pm 60 \text{ kg m}^{-3}$ for the gabbros and $2580 \pm 30 \text{ kg m}^{-3}$ for the granites. Bott and Tuson (1973) estimated the minimum density contrast between the complex and the basement to be 180 kg m^{-3} . Therefore, the density of the complex at depth is greater than the measured average density for the gabbros. Assuming a density of 3010 kg m^{-3} for the complex and 2800 kg m^{-3} for the Lewisian the observed Bouguer anomaly can be explained by a body similar in form to a truncated cone extending to a depth of about 14 km. The body widens from a half width of about 6 km at the surface to 9 km at the base. This body occupies a volume of approximately 3500 km^3 . A second subsurface model consistent with the observed anomaly assumes a density of 3150 kg m^{-3} for the basic and ultrabasic rocks of the complex. This interpretation requires a depth of 5.5 km to the base of the complex. The volume of the intrusive material was estimated to be 1500 km^3 .

6.4 Mechanisms of emplacement

The information on the volume of the complexes obtained from gravity modelling and current knowledge on the rheological properties of the upper and lower crust provides useful constraints on the mechanisms of emplacement of the complexes. These constraints were first discussed in detail for the Mull complex by Bott and Tantrigoda (1987).

There are two main processes by which the large circular plugs of dense igneous material which form the central complexes could be emplaced at high levels within the upper crust. These processes are forceful emplacement and stoping. Richey (1924) proposed that the centres developed above local cupola shaped magma reservoirs which were located above an elongated magma chamber at depth. The dip of the cone sheets on Mull indicates that the cupolas rose to a depth of roughly 5 km. Above the cupolas magmatic material was intruded in the form of cone sheets when the magma pressure was high and as ring dykes when the pressure was low. The majority of the space

provided for intrusion was generated by subsidence and forms of stoping (Richey, 1924).

For the Mull complex the total volume of intrusive material accommodated by forceful emplacement, early doming preceding cauldron formation and uplift from cone sheet development was estimated to be about 10% or less of the total volume of the intrusive complex (Bott and Tantrigoda, 1987). The brittle nature of the upper crust makes diapiric intrusion of magmatic material at the depths of the complexes unlikely. Therefore, the emplacement of the complexes was more likely to have occurred through fracture of the country rock. Stopping occurs when intrusive emplacement is facilitated by the fracture of country rocks producing space for emplacement. The broken fragments of country rock are denser than the magma and sink beneath the magma of the intruded complex. Bott and Tantrigoda (1987) showed that the density of the magma was unlikely to have been over 2720 kg m^{-3} near the surface or over 2750 kg m^{-3} at a depth of 11 km. Therefore, the density of the magma would have been less than the density of the metamorphic basement and the emplacement of the complexes by stoping would be feasible.

This interpretation presents an interesting space problem which is investigated in the following sections of this chapter. The magma must have originated within the mantle. The lower crust has a more ductile rheology than the upper crust and was presumably penetrated by the diapiric intrusion of the magma. The lower crust would then be forced downwards and sideways to accommodate the magma. As the magma rose through the upper crust by stoping the space in the lower crust would be filled by the sinking country rock. Therefore, a slight thickening of the lower crust beneath the central complexes should be observed. Assuming a volume of 2500 km^3 for the Mull complex a thickening of 1 km could occur over a region of $50 \times 50 \text{ km}^2$. This thickening would also have the effect of providing isostatic support for the complexes and their associated high topography.

6.5 Annular averaging

The vertical gravitational attraction of the proposed thickening of the lower crust

beneath the central complexes is difficult to detect because of the large variations in the Bouguer gravity field caused by near surface structures such as the Sea of the Hebrides trough, the Inner Hebrides trough and the central complexes themselves. However, the axial symmetry of the complexes can be exploited. The central complexes have a roughly circular form and presumably the subsequent lower crustal thickening has a roughly circular distribution also. Therefore, if the Bouguer anomalies are averaged around annuli centred on the central complexes of interest, the vertical gravitational attraction of the thickening should be enhanced at the expense of the more irregularly distributed Bouguer anomalies originating at shallower depths.

In order to average the Bouguer anomalies around the annuli an estimate of the Bouguer anomaly at each sampling point on each annulus must be determined. This was achieved by fitting a bicubic spline to the point observations of the Bouguer anomalies recorded for the regions around each complex. The coefficients of the bicubic spline could then be used to estimate the Bouguer anomaly at any specified point. The Bouguer anomaly point observations used for this study were taken from the topography and gravity data base and an additional marine data set covering the NW Approaches region was kindly provided by the Marine Operations Research Programme of the B. G. S. . The marine data set covers the region 56° N – 59° N / 5° W – $9^{\circ}\text{ 30}'\text{ W}$ and consists of ship tracks sampled every $10'$.

For the Mull complex the annuli were centred on the maximum Bouguer anomaly of approximately 67 mGal which is roughly positioned at the centre of the complex. The OSGB national grid coordinates of this point are 160.625, 730.313 km. A bicubic spline was fitted to the Bouguer anomaly point observations within the region bounded by the national grid coordinates 80.000, 260.000, 600.000, 825.000 km. The size of this region was restricted by the quality of the density of data coverage because the bicubic spline fit becomes unstable in regions of poor data coverage. The chosen area included some 10814 data points. The RMS deviation between the Bouguer anomaly observed at each data point and the value estimated by the bicubic spline is 2.40 mGal. A contour map of the Bouguer anomaly values estimated by the bicubic spline over the region is

shown in figure 6.2 for comparison with the original Bouguer anomaly map presented in figure 6.1. In general, the agreement between the observed and estimated values is good considering the variation in the Bouguer anomalies over the region.

The annuli around the Skye complex were centred on the national grid coordinates 151.875 and 825.000 km. This point lies at the centre of the circular Bouguer anomaly over Skye but is offset from the region of the greatest Bouguer anomalies which overlies the Cuillin centre. A bicubic spline was fitted to the Bouguer anomaly point observations in the region bounded by the national grid coordinates 18.750, 275.000, 693.750, 950.000 km. This area contains 15253 data points. The estimated RMS deviation for the spline fit is 2.02 mGal. A contour map of the Bouguer anomaly estimates provided by the bicubic spline is shown in figure 6.3.

The concentric annuli around each complex were spaced at radial intervals of 2 km. The average for each annulus was calculated from 180 estimates of the Bouguer anomalies sampled every 2° around the annulus.

6.6 Results of the annular averaging

For each igneous complex, the average values of the estimated Bouguer anomalies around each annulus have been plotted against the radial distance of the annulus from the assumed centre of the complex. The plot for the Mull complex shows a distinct central high over the complex bounded by a broad regional low (figure 6.4). To determine the amplitude of the regional low an estimate of the background regional is required. If the long wavelength component of the Bouguer anomaly field is roughly planar the outermost annuli should give an indication of the amplitude of the background regional anomaly. The outermost annuli for the Mull complex display a steady increase in the average Bouguer anomaly with increasing radial distance making such an estimate difficult. However, the annular averages for the Skye complex suggest the background regional is about 16 mGal and this value is probably reasonable for Mull also. Bott and Tantrigoda (1987) applied a similar background level of 17 mGal deduced from local observations for their interpretation of the Mull complex Bouguer anomaly. Assuming

Figure 6.2. Bouguer anomaly gravity in the vicinity of the Mull central igneous complex estimated from the coefficients of a bicubic spline. The contour interval is 10 mGal. The grid interval is 5 km. The scale is approximately 1:1,800,000 and the border annotation denotes Ordnance Survey grid coordinates in hundreds of km.

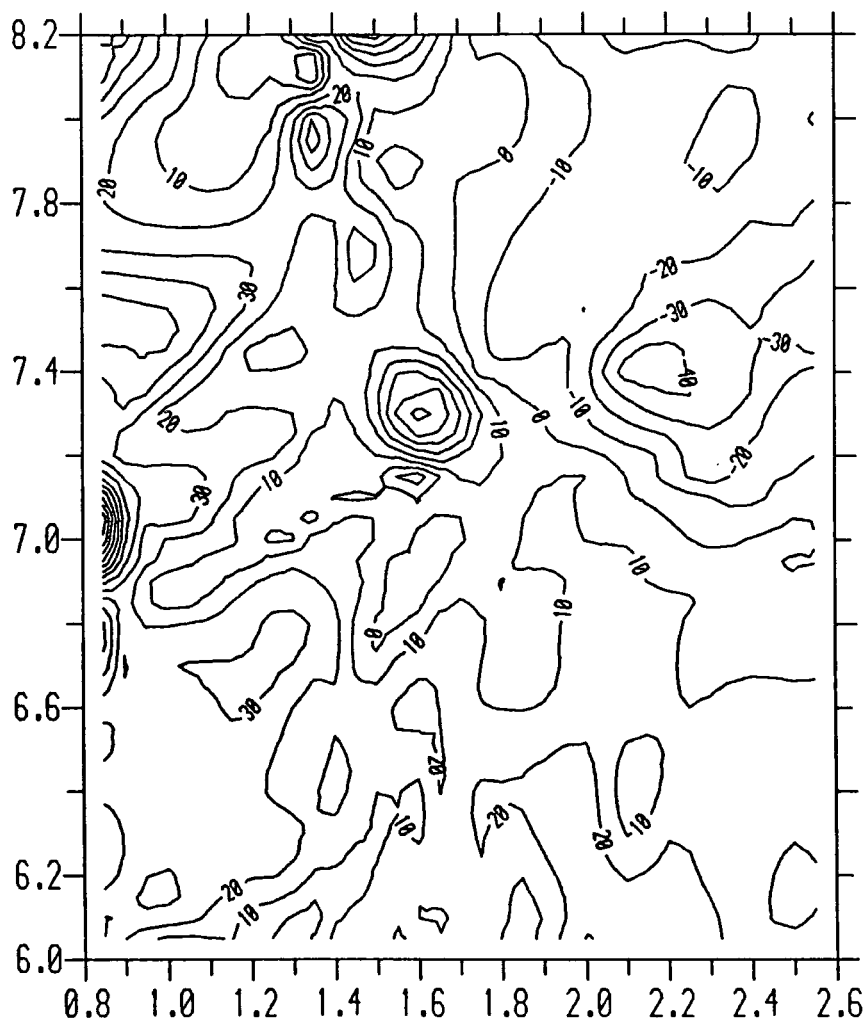


Figure 6.3. Bouguer anomaly gravity in the vicinity of the Skye central igneous complex estimated from the coefficients of a bicubic spline. The contour interval is 10 mGal. The grid interval is 5 km. The scale is approximately 1:2,300,000 and the border annotation denotes Ordnance Survey grid coordinates in hundreds of km.

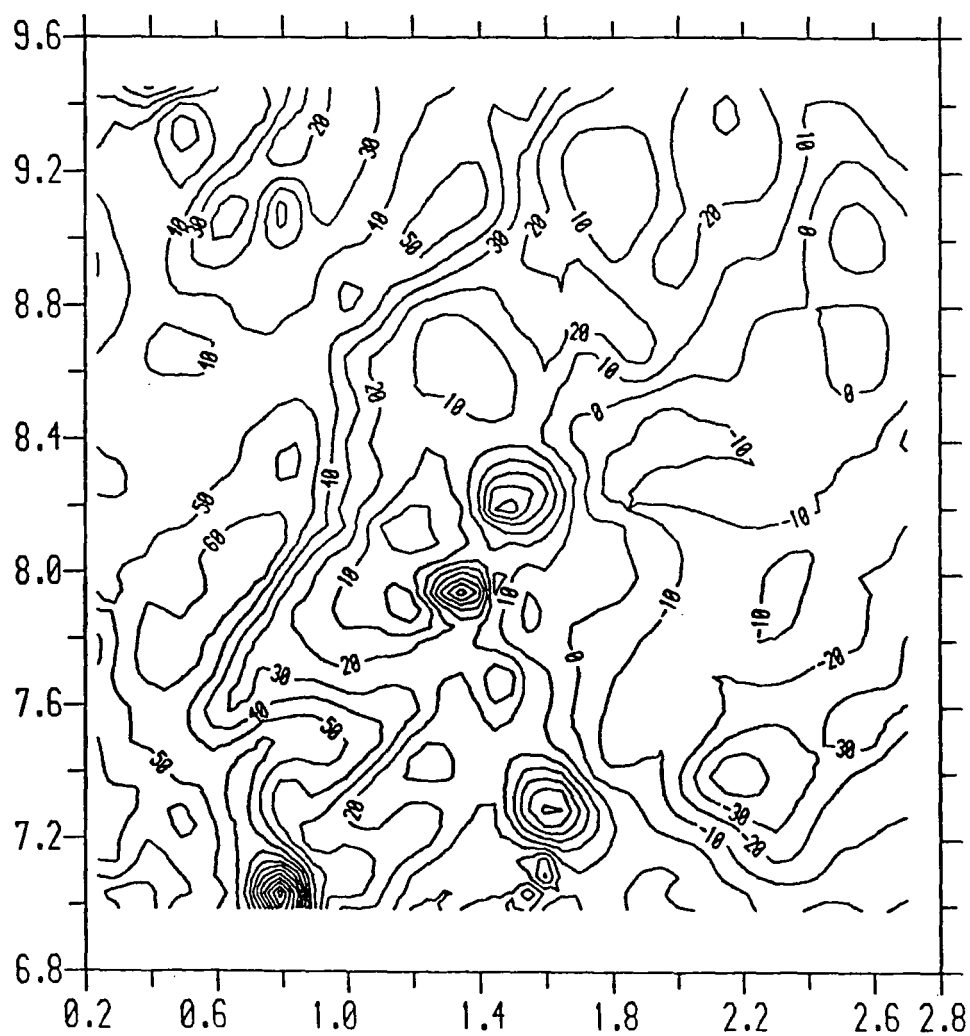
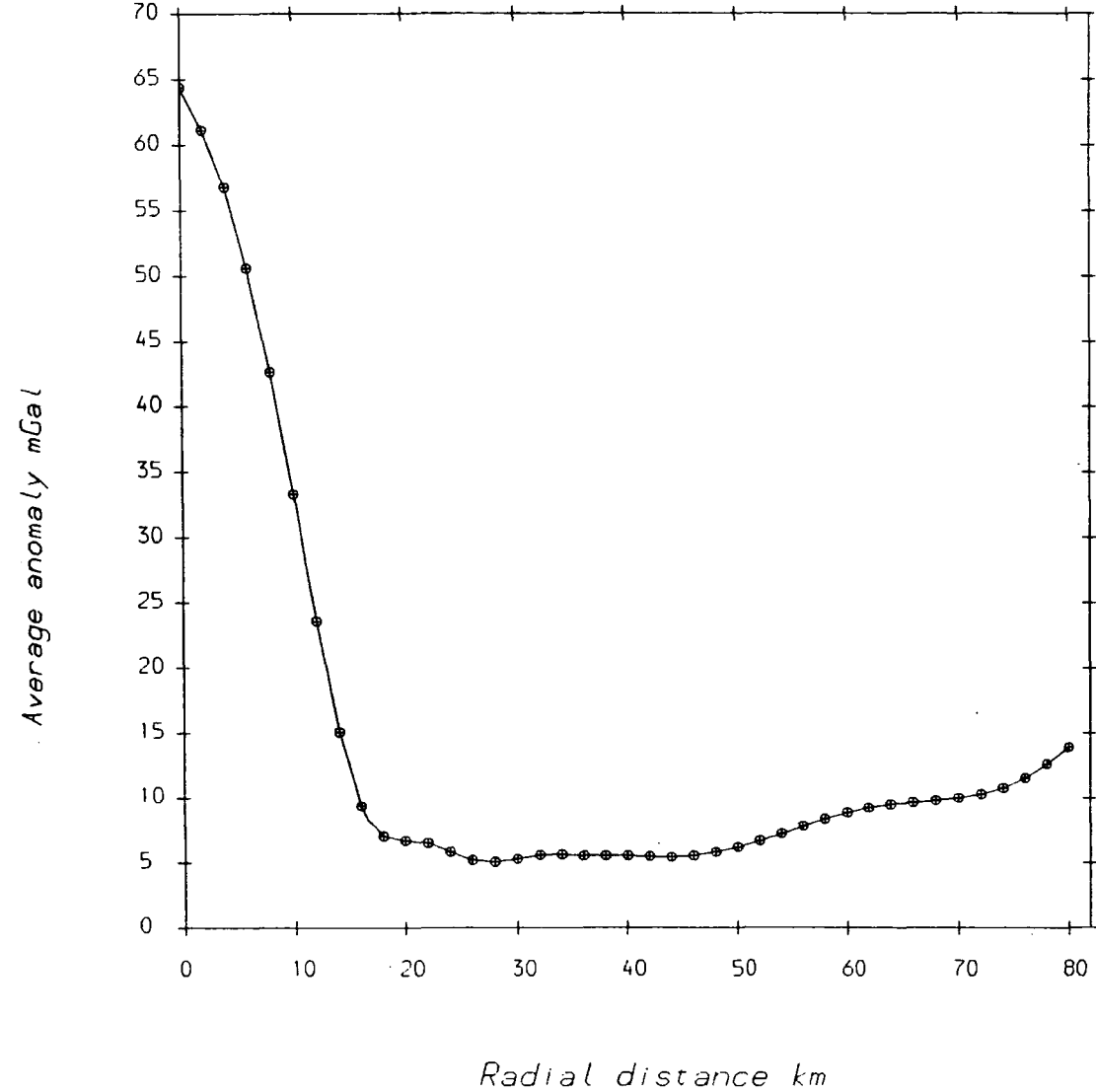


Figure 6.4. Radial profile of the annular averages of the Bouguer anomaly gravity determined for the Mull central igneous complex.



this background anomaly the broad, circular low has a radius of at least 80 km and an amplitude of approximately 10 mGal.

The features of the plot for Skye are similar to those for Mull except that the broad, regional anomaly low is bounded by an outer high (figure 6.5). The circular anomaly low has a radius of 70 km and an amplitude of about 10 mGal. Beyond the outer high the outermost annuli begin to level out at around 16 mGal. The distortion of the annular averages at radii of approximately 35 km is a result of the high, positive Bouguer anomaly values over the Rhum complex.

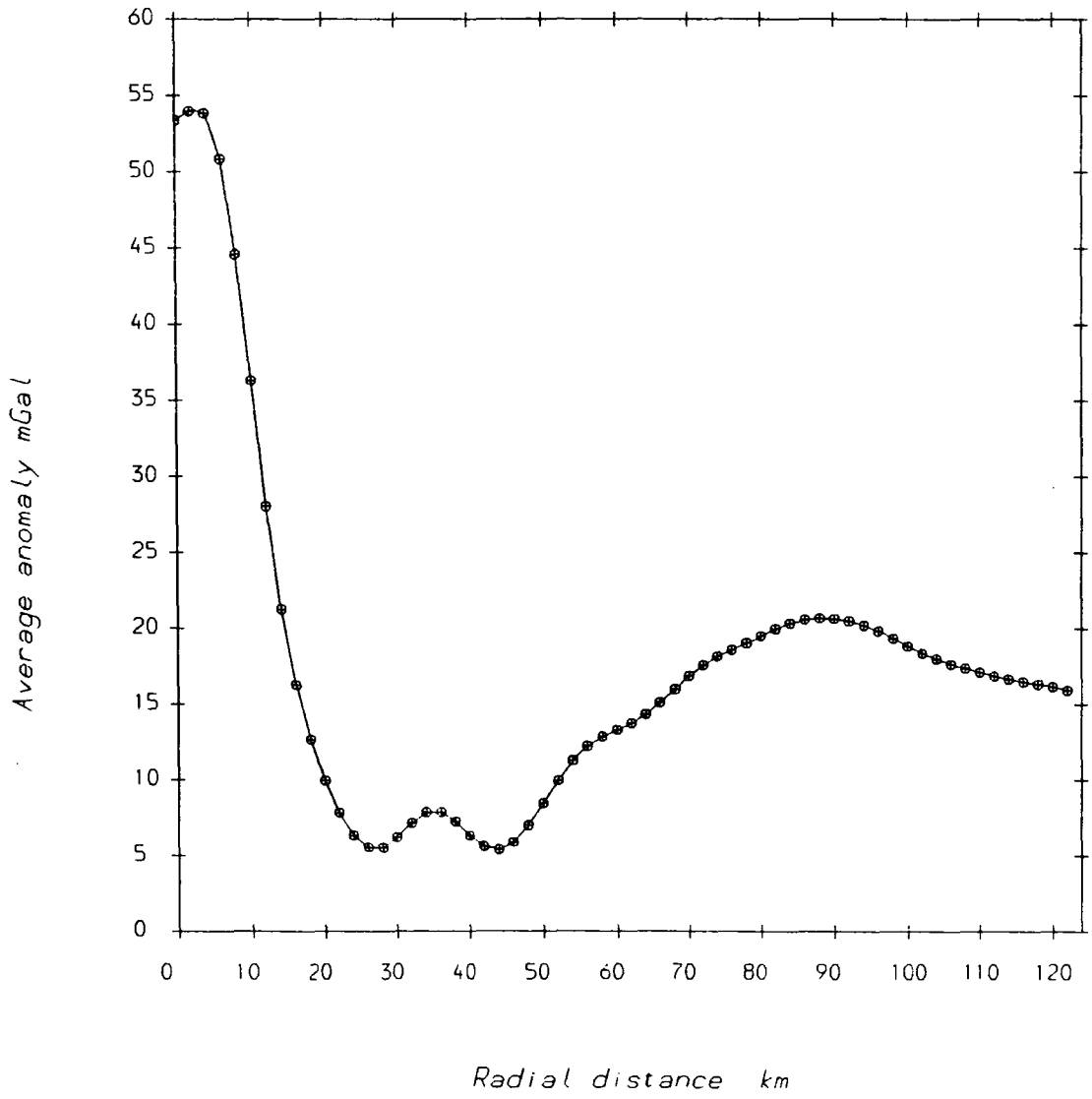
The results of the annular averaging indicate that the central complexes of Mull and Skye are surrounded by annular Bouguer anomaly lows that may reflect a thickening of the lower crust beneath the complexes. To examine the proposed thickening in more detail the radial profiles of the annular Bouguer anomaly averages have been modelled to determine the volume of the thickening.

6.7 The determination of the vertical gravitational attraction of axially symmetric bodies

The axial symmetry of the radial profiles of the annular averages requires the modelled density contrasts to be axially symmetric. The vertical gravitational attraction of such bodies has been calculated in the ^{wavenumber} domain using a one-dimensional Fourier transform as described by Bodine and Karner (1981). The main advantages of this approach are that only a simple, radial cross section of the body or bodies is required as input and that the method is most efficient for large bodies which produce long wavelength gravity anomalies. Traditional space domain methods are inefficient for such bodies because integrals of slowly convergent Bessel functions are required.

The derivation of the gravitational attraction of the axially symmetric bodies is a modification of Parker's method (Parker, 1972) with the additional symmetry being exploited to make the computation simpler. Consider the gravity anomaly produced at the surface by a topographic surface $h(x, y)$ about a mean depth d which represents a density contrast $\Delta\rho$. The wave domain representation of this gravity anomaly is given

Figure 6.5. Radial profile of the annular averages of the Bouguer anomaly gravity determined for the Skye central igneous complex.



by

$$F(\Delta g(x, y)) = 2\pi G \Delta \rho e^{-|k|d} \sum_{n=1}^{\infty} \frac{|k|^{n-1}}{n!} F(h^n(x, y)) \quad 6.1$$

where F denotes the two dimensional fourier transform operator, $|k|$ is the modulus of the two dimensional wave vector and G is the gravitational constant (Parker, 1972). The assumption of axial symmetry allows the two dimensional fourier transform to be reduced to a one dimensional transformation (Bracewell, 1978). The two dimensional transformation is given by

$$F(h(x, y)) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(x, y) e^{-i(k_x x + k_y y)} dx dy \quad 6.2$$

which may be rewritten in terms of the polar coordinates (r, θ)

$$F(h(r, \theta)) = \int_0^{\infty} r h(r) \int_0^{2\pi} e^{-ikr \cos(\theta - \psi)} d\theta dr \quad 6.3$$

where $x + iy = re^{i\theta}$ and $k_x + ik_y = |k|e^{i\psi}$. The inner integral may be replaced by an equivalent function containing a zero order Bessel function $J_0(kr)$ to remove the azimuthal dependence (Bracewell, 1978). The required relationship is

$$2\pi J_0(kr) = \int_0^{2\pi} e^{-ikr \cos(\theta - \psi)} d\theta \quad 6.4$$

which allows the fourier transform to be expressed in terms of the Hankel transform

$$F_H(h(r)) = 2\pi \int_0^{\infty} r h(r) J_0(kr) dr = H(k) \quad 6.5$$

The inverse Hankel transform is given by

$$F_H(F_H(h(r))) = \frac{1}{2\pi} \int_0^{\infty} k H(k) J_0(kr) dk \quad 6.6$$

The axially symmetric gravity anomaly produced at the surface by the topography $h(r)$ of the density contrast $\Delta \rho$ of a mean depth d can now be expressed in terms of the Hankel transform

$$F_H(\Delta g(r)) = 2\pi G \Delta \rho e^{-|k|d} \sum_{n=1}^{\infty} \frac{|k|^{n-1}}{n!} F_H(h^n(r)) \quad 6.7$$

The Hankel transform of $h(r)$ can be determined by the equivalent operation of first performing an Abel transform and then a one dimensional fourier transform (Bracewell,

1978). An algorithm to perform the discrete computation of the Hankel transform by this method has been developed by Oppenheim, Frisk and Martinez (1978). The Abel transform maps the axisymmetric distribution of the topography $h(x, y)$ onto a single radius assumed to lie along the x axis. In xy space the analytic transform is defined by

$$p(x) = \int_{-\infty}^{\infty} h(x, y) dy \quad 6.8$$

where $x^2 + y^2 = r^2$. The discrete representation of the Abel transform is given by

$$p(l\Delta x) = \Delta y \sum_{m=-\infty}^{\infty} h(\sqrt{(l\Delta x)^2 + (m\Delta y)^2}) \quad 6.9$$

For a finite Abel transform of N discrete terms the Hankel transform is given by the one dimensional discrete fourier transform of the weighted function $p(l\Delta x)$

$$F_H(h(l\Delta x)) = \frac{\Delta x}{2\pi} \sum_{l=0}^{N-1} p(l\Delta x) e^{-i2\pi lk/N} \quad 6.10$$

The discrete Hankel transform is determined at N equally spaced intervals of Δk where $\Delta k = 2\pi/N\Delta x$. Note that the Hankel transform integral comprises only real valued coefficients. Therefore, the discrete Abel transform of N terms should be reflected about the last component of the series to ensure that the resulting discrete Hankel transform is real.

6.8 Gravity modelling of the radial Bouguer anomaly profiles

The radial profiles of the averaged Bouguer anomalies have been modelled using the technique described in the previous section. Before modelling the radial profiles a background regional was removed from the profiles. The background level chosen for Mull was 16 mGal and that for Skye was 15.92 mGal, the value of the outermost average. The value for Skye may be marginally high because the average anomalies for the outer annuli are still decreasing slightly with increasing radius.

The central complex beneath Mull has been assigned a density of 3000 kg m^{-3} . A thin layer of gabbroic material of density 2900 kg m^{-3} has been modelled overlying the main complex. The upper crust consists of two units. The Moine assemblage has

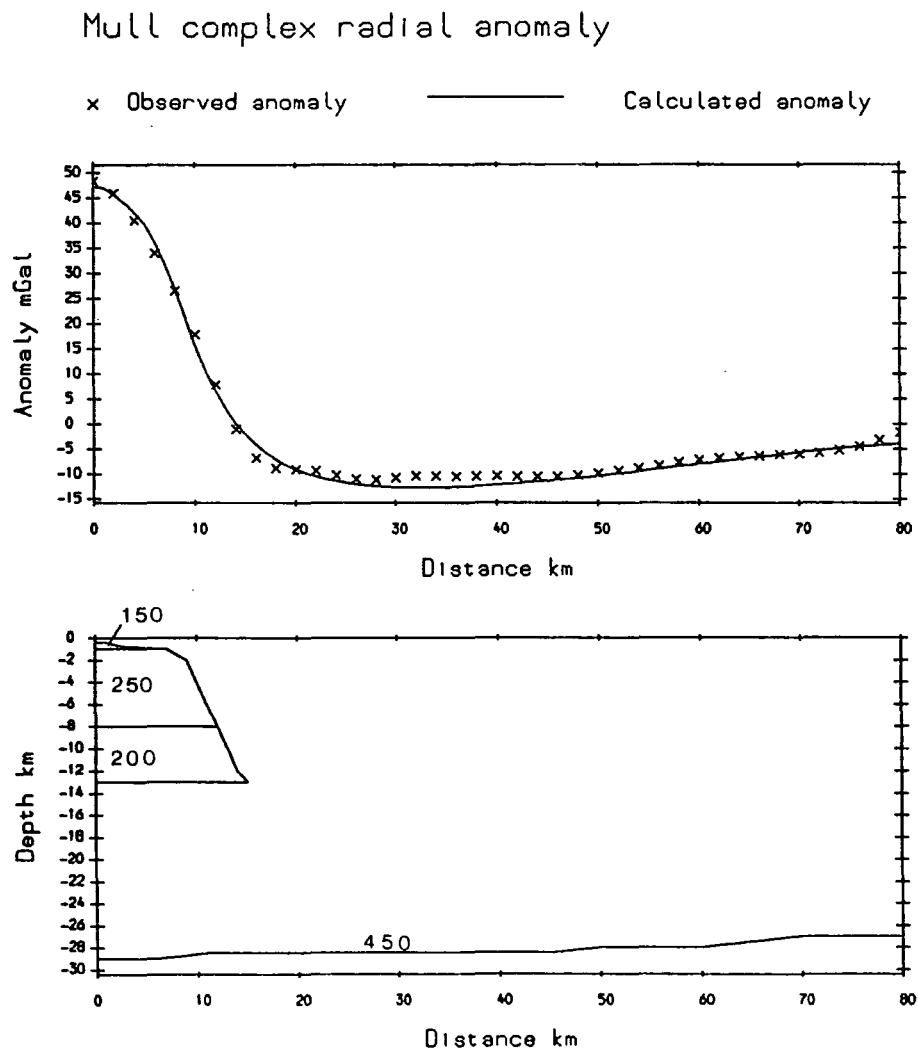
been assumed to extend to a depth of about 8 km and is assumed to have a density of 2750 kg m^{-3} . The Moine assemblage is underlain by Lewisian gneisses with a density of 2800 kg m^{-3} . These density contrasts are the same as those assumed by Bott and Tantrigoda (1987). The density contrast at the Moho is taken to be 450 kg m^{-3} . The lower crust is considered to have a density of about 2850 kg m^{-3} and the upper mantle a density of 3300 kg m^{-3} . The mean depth of the Moho in this region has been estimated to be 27 km from explosion seismology investigations (Bott et al., 1979).

A density model of the Mull complex consistent with the observed Bouguer anomalies is shown in figure 6.6. The central complex is shaped like a truncated cone extending from a depth of 1 km to 13 km. The radius of the body is 7 km at the top and widens to 15 km at the base. The volume of the complex is roughly 5100 km^3 . This estimate is somewhat greater than the estimate of Bott and Tantrigoda (1987) of 3650 km^3 . This discrepancy arises because the modelled crustal thickening lowers the local background anomaly in the vicinity of the central complex. The crustal thickening required to produce the observed outer Bouguer anomaly low reaches a maximum thickness of 2 km beneath the complex. At a radius of 6 km the thickening begins to decrease to 1.5 km, a thickness that is maintained out to a radius of 45 km. Between radii of 45 and 70 km the thickening reduces to zero. The total volume of the crustal thickening is approximately $17,000 \text{ km}^3$. This is significantly greater than the estimated volume of the complex. This value, though, is critically dependent on the assumed background anomaly level.

The density structure of the Skye complex is simpler than that of the Mull complex. The intrusive centre has been assigned a density of 3010 kg m^{-3} . This density corresponds to either a dense gabbro or a mixture of about 75% average gabbro and 25% ultrabasics similar to those of eastern Rhum (Bott and Tuson, 1973). In contrast to Mull, the Lewisian basement is present at shallow depths. The density contrast at the Moho and its mean depth are considered to be identical to the values used for Mull.

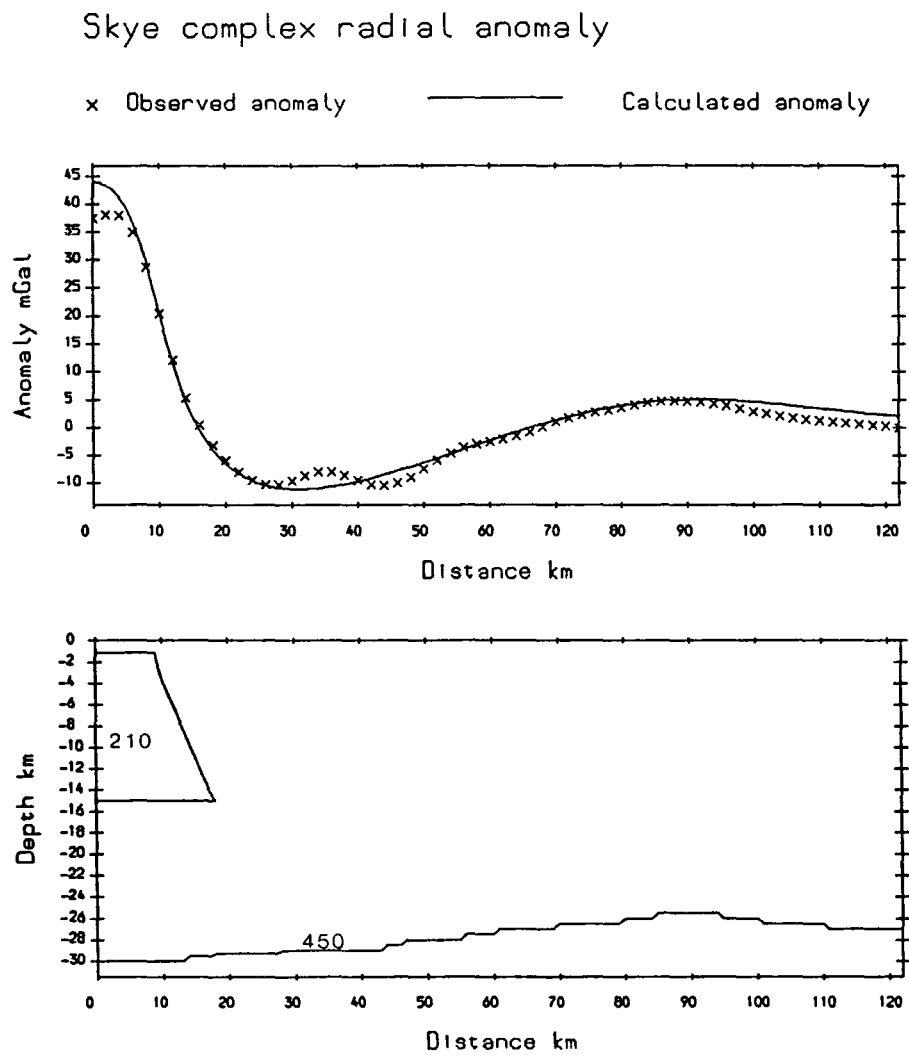
A density model of the complex is displayed in figure 6.7. The poor fit between the observed and calculated gravity anomalies at very short radii ($r < 5 \text{ km}$) results

Figure 6.6. Density model of the Mull central igneous complex and the structure of the lower crust beneath the complex.



Density contrasts given in kg m^{-3}

Figure 6.7. Density model of the Skye central igneous complex and the structure of the lower crust beneath the complex.



Density contrasts given in kg m⁻³

from the gravitational effect of the shallow granitic centres. The shape of the complex is similar to a truncated cone. Assuming the modelled density contrast is correct the complex extends from a depth of 1.1 km to 15 km. The radius of the complex increases from 9 km near the surface to 18 km at the base. The total volume of the complex is estimated to be 7790 km^3 .

The positive Bouguer anomaly over the central complex is bounded by two further anomalies. An inner, broad anomaly low of amplitude 10 mGal extends out to a radius of approximately 70 km. This is bounded by an outer anomaly high of approximate amplitude 5 mGal which extends out to a radius of at least 120 km. The inner low has been modelled as the product of the thickening of the lower crust beneath the complex. The origin of the outer high has been modelled as a slight thinning of the lower crust. Although the cause of this thinning is difficult to explain, this was considered to be a more realistic assumption than the presence of an annular density contrast encircling the complex at shallower depths. Changes in the mean thicknesses of the upper and lower crust could also contribute to the high but the associated density contrast is small compared to that of the Moho.

The crustal thickening extends outwards to a radius of approximately 60 km reaching a maximum thickness of 3 km beneath the complex. The total volume of the crustal thickening is estimated to be $18,000 \text{ km}^3$ which is roughly the same as that estimated for Mull. This volume is over twice that estimated for the central complex. The thinning of the crust modelled at greater radii reaches a maximum of 1.5 km at a radius of roughly 90 km.

The inconsistency between the volumes of the intrusive complexes and the volumes of the lower crustal thickening suggests that the initial assumptions may be an oversimplification and that other factors should also be considered.

6.9 Lithospheric flexure and the central complexes

If the observed annular lows around the central complexes are genuine and are not the product of crustal thickening generated by the addition of magmatic intrusives what

other phenomena can explain their presence? One mechanism that has been observed to generate similar anomaly patterns, albeit usually on a larger scale, is the flexure of the lithosphere beneath topographic or geological features which approximate point loads. Examples of such loads are seamounts. A good example is the Great Meteor seamount which is located in the Atlantic ocean at 30° N, $28^{\circ} 30'$ W, 1280 km west of Africa and 720 km south of the Azores. The seamount rises from a base level of 4400–4800 m below sea level to a summit at a depth of 250 m (Pratt, 1963). The seamount consists of a broad, basal apron that rises to a depth of 2200 m capped by a steep rise to the summit. The observed free air anomalies east of the seamount show a positive anomaly of approximately +250 mGal over the seamount bounded by a broad region of low anomaly values reaching a minimum which ranges between -13 to -43 mGal. Watts et al. (1975) modelled the observed free air anomalies as the product of the flexure of the lithosphere beneath the load of the seamount. The total gravitational attraction generated after flexure is the sum of the gravitational attraction of the load and the attraction of the perturbations of the main crustal density contrasts. These are the oceanic layer 2–layer 3 density contrast and the Moho density contrast. The best fit to the observed gravity anomalies gives an estimate of the flexural rigidity of the oceanic lithosphere of 6×10^{22} Nm.

Although the central complexes of Mull and Skye represent much smaller loads than the Great Meteor seamount, they may produce a significant amount of flexure if the continental lithosphere is weak. The lithosphere of the NW Atlantic province may be weaker than usual because the province was subjected to a significant amount of reheating during the period of intense volcanic activity in the early Tertiary.

The flexure of the lithosphere in response to the loading of the central complexes has been calculated for a number of values of the elastic thickness of the lithosphere. The loads of the complexes have been modelled as simple surface loads equivalent to the mass excess of the complexes. Treating the lithosphere as a thin elastic plate overlying an inviscid fluid substratum, the axisymmetric deformation of the lithosphere $w(r)$

produced by an applied load $p(r)$ is given by

$$D\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)^2 w(r) + \Delta\rho g w(r) = p(r) \quad 6.11$$

(Turcotte, 1979) where D is the flexural rigidity of the lithosphere, $\Delta\rho$ is the density contrast between the material infilling the surface deflection of the lithosphere and the material beneath the lithosphere, and g is the gravitational attraction. As with the standard two dimensional case, the equation is easier to solve in the ^{wave number} domain. However, the axial symmetry requires the Hankel transform to be used in place of the two dimensional fourier transform. The development of the discrete Hankel transform algorithm, therefore, enables a new approach to be applied to the computation of the deflection of the lithosphere in response to loads with axisymmetrical form. The Hankel transform was defined earlier as

$$F_H(w(r)) = \int_0^\infty r w(r) J_0(kr) dr = W(k) \quad 6.12$$

Taking the Hankel transform of both sides of the thin elastic plate equation and applying the addition theorem gives the relationship

$$\int_0^\infty r \left(D \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} \right)^2 w(r) \right) J_0(kr) dr + \Delta\rho g W(k) = P(k) \quad 6.13$$

The remaining integral can be replaced using the relationship

$$\int_0^\infty r \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} \right)^2 w(r) J_0(kr) dr = k^4 W(k) \quad 6.14$$

(Sneddon, 1951). Therefore,

$$Dk^4 W(k) + \Delta\rho g W(k) = P(k) \quad 6.15$$

The final deformation of the plate is given by

$$W(k) = \frac{P(k)}{\Delta\rho g} \left(\frac{Dk^4}{\Delta\rho g} + 1 \right)^{-1} \quad 6.16$$

Equation (6.16) shows that $W(k)$ the Hankel transform of the lithospheric deflection $w(r)$ may be determined from $P(k)$ the transform of the applied load $p(r)$. This method

has been used to calculate the deflection of the lithosphere beneath the applied loads of the central complexes. The gravity anomalies produced by the flexure have also been determined and compared with the observed radial profiles.

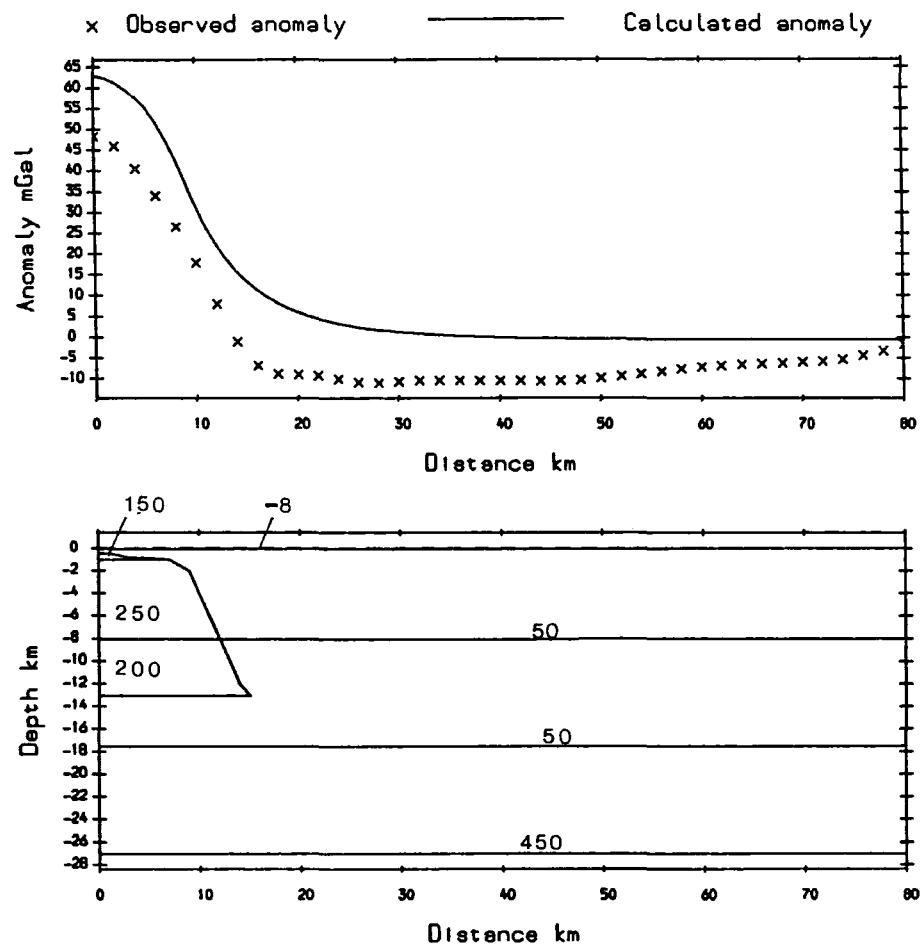
The load of the Mull complex was calculated from the density model of the complex presented in figure 6.6. The density of the surface infill was taken to be that of the Tertiary extrusives because Tertiary sediments are rare in the region (McQuillin and Binns, 1979). The mean density of the extrusives has been estimated to be 2758 kg m^{-3} by Hipkin and Hussain (1983).

The gravity anomalies produced by the complex and the flexure of the lithosphere have been calculated as follows. The change in the depth of the central complex owing to the flexure was taken to be the average deflection of the lithosphere within the maximum radius of the central complex. The deflection of the lithosphere was assumed to perturb four important density contrasts:

- (1) the density contrast between the infill material and the original surface topography;
- (2) the density contrast between the Moine and Lewisian basement at a depth of 8 km;
- (3) an additional density contrast required to mark the transition between the Lewisian basement and the lower crust which has been assigned a density of 2850 kg m^{-3} . This was assigned an arbitrary depth mid-way between the base of the Moine assemblage and the Moho;
- (4) the density contrast at the Moho.

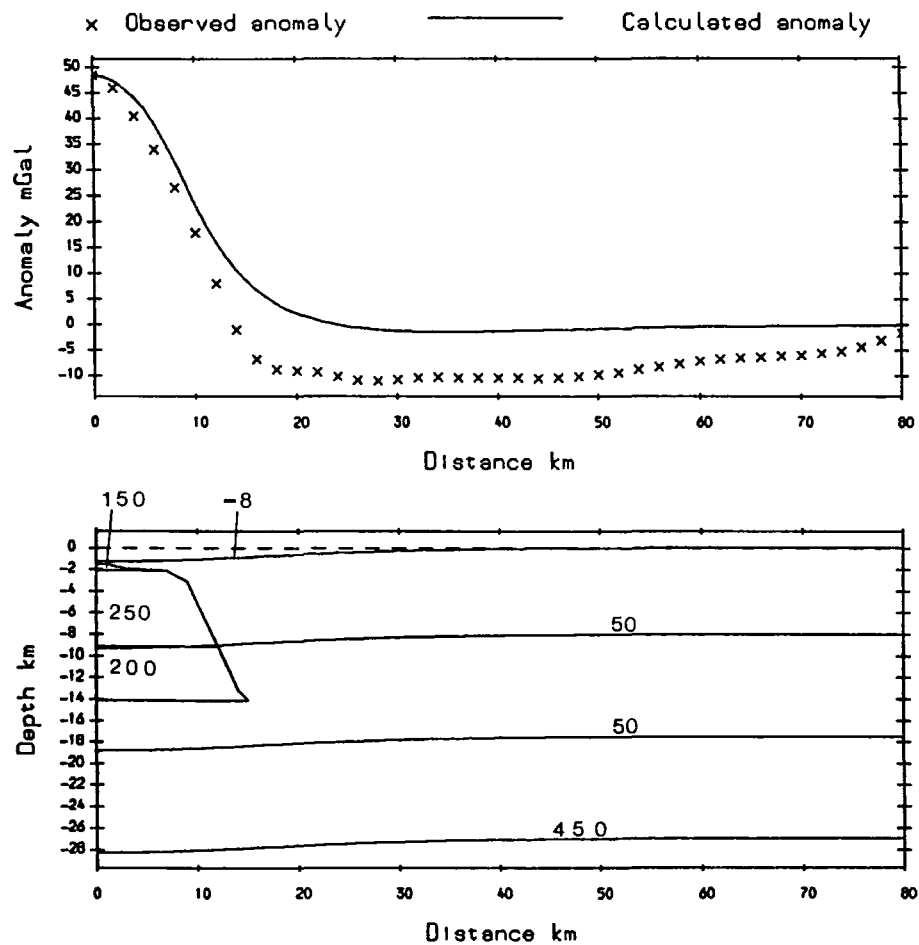
The results of these calculations for elastic thicknesses of 22.5 and 2.5 km are shown in figures 6.8 and 6.9. The elastic thickness of 22.5 was taken from Chapter 5 where it was found to produce the best fit to the observed cross spectral relationships between gravity and topography for the shallow loading model assuming a uniform elastic thickness for the continental lithosphere. For such a large elastic thickness the load of the complex produces only a slight deformation. The maximum deflection of the lithosphere observed above the centre of the Mull complex is approximately 60 m. The result of this small depression is that there appears to be no outer anomaly low. The predicted outer

Figure 6.8. Lithospheric deformation and gravity anomalies produced by the flexure of the continental lithosphere in response to the load of the Mull central igneous complex for an elastic thickness of the continental lithosphere of 22.5 km.



Density contrasts given in kg m^{-3}

Figure 6.9. Lithospheric deformation and gravity anomalies produced by the flexure of the continental lithosphere in response to the load of the Mull central igneous complex for an elastic thickness of the continental lithosphere of 2.5 km.



Density contrasts given in kg m^{-3}

anomaly low is much smaller than observed even for the elastic thickness of 2.5 km where more marked deformation is observed. The maximum depression of the lithosphere for the 2.5 elastic thickness is about 1300 m.

Note that for both of these models some of the density contrasts lie at depths greater than the elastic thickness of the lithosphere and, therefore, may not deform perfectly elastically. However, it seems unlikely that the flexure of the lithosphere beneath the load of the Mull complex could generate the form of the observed outer anomaly low and further modelling with a more complex rheological system seems unnecessary.

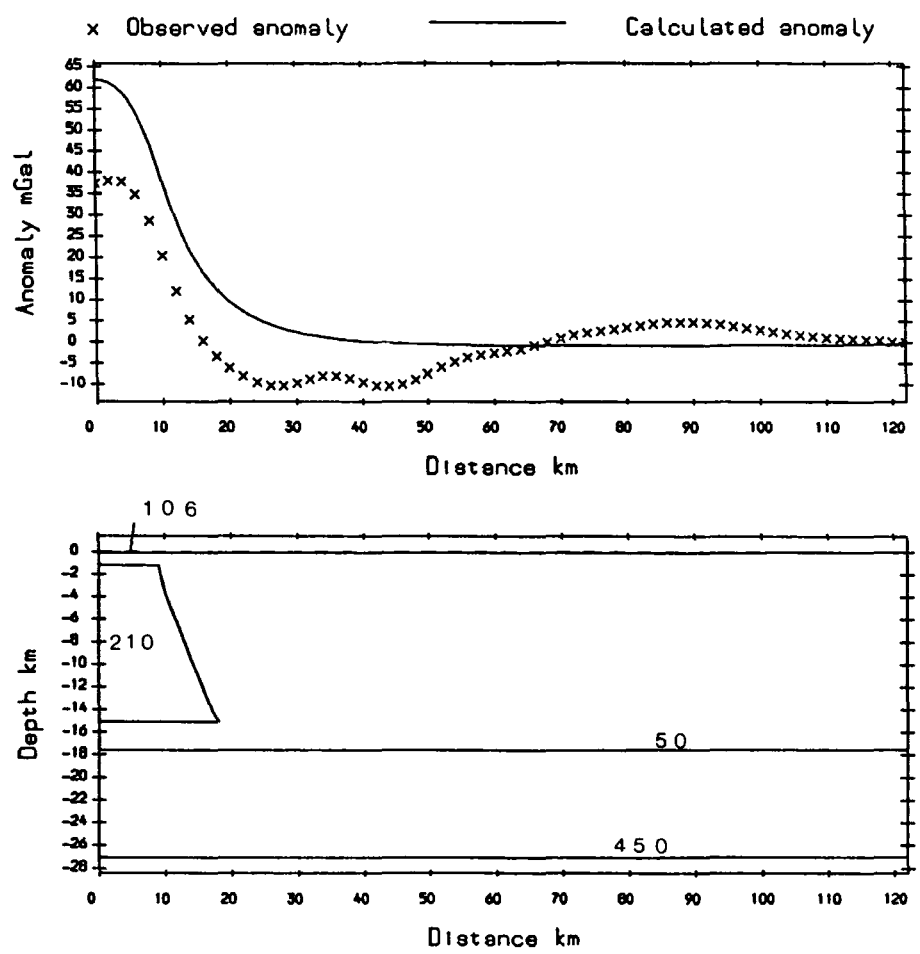
The Skye complex was modelled using the the same values for the elastic thickness of the lithosphere, but the densities modelled differed slightly from those used for Mull (figures 6.10 and 6.11). The Tertiary extrusives were assigned a slightly lower mean value of 2694 kg m^{-3} (Hipkin and Hussain, 1983) and the Moine/Lewisian density contrast is absent. However, the results are similar.

6.10 Discussion

The gravity models do not show a consistent relationship between the volume of the complexes and that of the crustal thickening. For the Mull complex the volume of the crustal thickening greatly exceeds that of the central complex. This is also true for the Skye model, but there is an added complication in that the excess volume of the crust beneath the complex is roughly matched by the volume deficiency of the crust at greater radii. However, the flexural modelling has shown that the observed annular anomaly *minimum* cannot be solely the product of the flexure of the continental lithosphere beneath the loads of the central complexes.

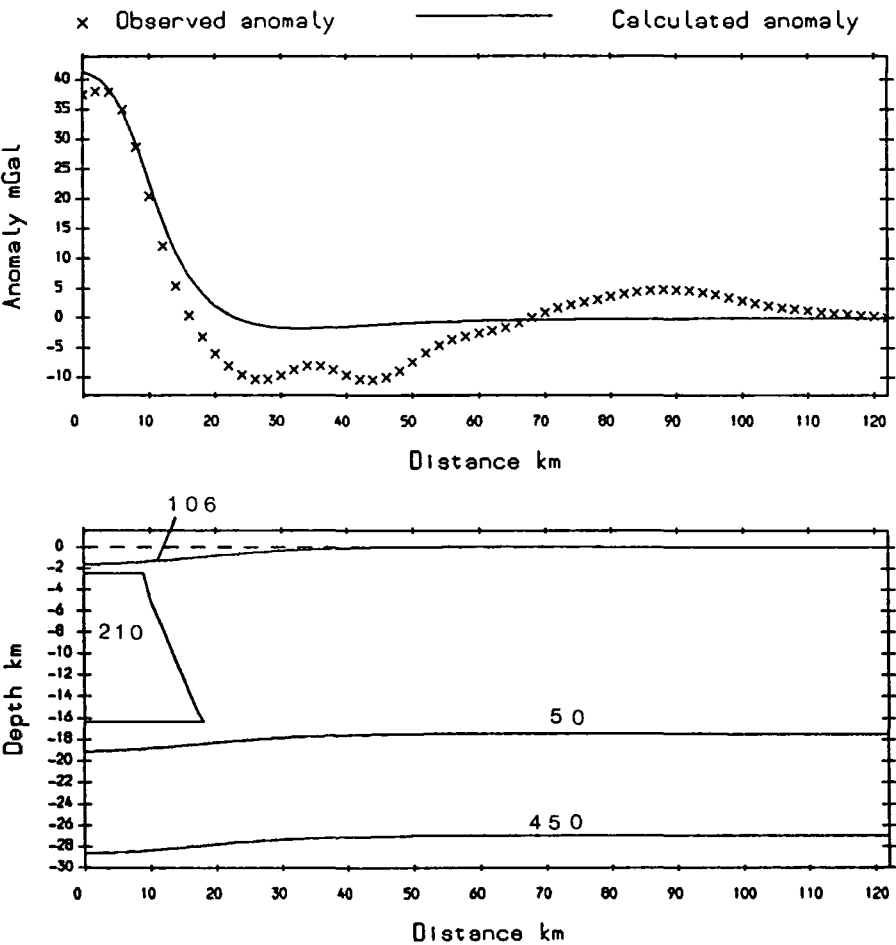
The imbalance of the estimated volumes may arise from errors in the interpretation of the Bouguer anomalies or possibly from errors in the assumed density models. The estimated volumes of the crustal thickening are critically dependent upon the treatment of the background regional Bouguer anomaly. If the background level chosen for the Mull complex was too high, the volume of the crustal thickening beneath the complex

Figure 6.10. Lithospheric deformation and gravity anomalies produced by the flexure of the continental lithosphere in response to the load of the Skye central igneous complex for an elastic thickness of the continental lithosphere of 22.5 km.



Density contrasts given in kg m^{-3}

Figure 6.11. Lithospheric deformation and gravity anomalies produced by the flexure of the continental lithosphere in response to the load of the Skye central igneous complex for an elastic thickness of the continental lithosphere of 2.5 km.



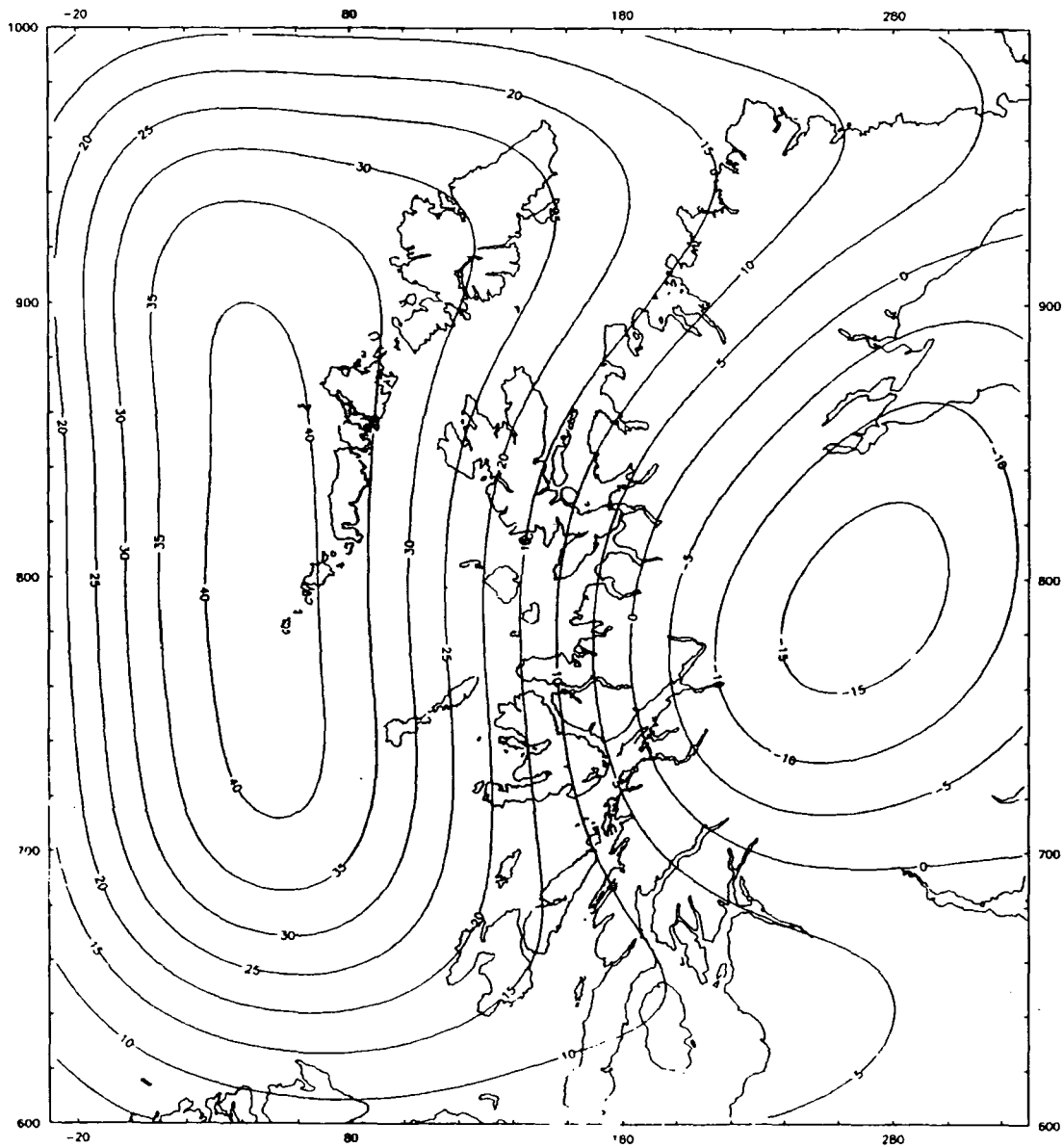
Density contrasts given in kg m^{-3}

would be overestimated. However, such a correction cannot solve the inconsistency for the Skye complex because reducing the background anomaly level would increase the amplitude of the residual outer anomaly high and the volume deficiency of the crust at large radii would have to be increased. A more subtle error is that the assumption that the long wavelength Bouguer anomaly regional has a planar form may be incorrect. If this is so, the value of the background regional may vary with radial distance from the centres of the complexes. Figure 6.12 shows a Bouguer anomaly map of the region after the application of a 300 km wavelength cut off gaussian filter. The filtered Bouguer anomaly map shows that although the long wavelength component of the gravity field is roughly a planar gradient in the vicinity of the complexes, the long wavelength field deviates significantly from this plane in central Scotland and west of the Outer Hebrides. Applying the annular averaging technique to the filtered anomaly data for the Mull complex shows that the annular averages of the "long wavelength" component of the gravity field increase by roughly 3 mGal between the innermost and outermost annuli. Therefore, the constant background regional anomaly level subtracted from the annular averages of the unfiltered data may be too high for the inner annuli causing the amplitude of the anomaly minimum produced by the crustal thickening to be overestimated. These results suggest that it may be advantageous to remove the background regional anomaly field before averaging around the annuli. However, this is complicated because it is difficult to distinguish between the background regional anomaly and the long wavelength component of the Bouguer anomalies produced by the proposed crustal thickening.

The averages for the inner annuli for both complexes may also be affected by the Bouguer anomaly minima over the Sea of the Hebrides trough, the Inner Hebrides trough and the Loch Etive granite complex (McQuillin and Binns, 1979; Hipkin and Hussain, 1983). These anomalies are sufficiently close to the complexes to perturb the averages causing them to overestimate slightly the amplitude of the annular Bouguer anomaly lows.

Errors in the density models used will also affect the estimated volumes of the

Figure 6.12. Bouguer anomaly map of western and central Scotland, the Hebridean region and part of the Northwestern Approaches after the application of a 300 km wavelength cut off gaussian filter. The contour interval is 5 mGal. The gridding interval is 5 km. The scale is approximately 1:2,500,000 and the border annotation denotes Ordnance Survey grid coordinates in km.



thickening. For example, I have not considered the gravity anomalies produced by the stoped upper crustal material which presumably lies within the lower crust beneath the complexes. However, the relatively low density contrast between the upper and lower crusts compared to the density contrast between the central complexes and the upper crust suggests that the Bouguer anomalies generated by the stoped material will be small. The density contrast assumed for the Moho is fundamental to the estimate of the volume of thickening. The value chosen for this study is quite large though, which means that the estimated volumes of the thickening are more likely to be underestimates than overestimates.

At present, the quantitative effect of these possible errors is unknown and so the possibility that the estimated volumes of crustal thickening are correct cannot be discounted. If this is so, the origin of the additional crustal material requires explanation. A number of additional factors may be taken into account. The intrusion of the central complexes was preceded by the extrusion of basaltic plateau lavas. These plateau lavas cover an extensive region around the central complexes (McQuillin and Binns, 1973). In the local vicinity of the Mull complex the lavas reach a thickness of nearly 1000 m (Bott and Tantrigoda, 1987). These lavas may, therefore, provide a significant additional load which depresses the continental lithosphere. The overall effect of this loading would be to cause an apparent thickening of the crust.

The intrusion of the central complexes was also accompanied by widespread, additional intrusive activity in the form of the emplacement of the predominantly NW-SE trending dyke swarm. The dykes appear to have been permitted into the upper crust by crustal extension. If the lower crust was also subjected to extensive intrusion the thinning of the lower crust generated by the extension may have been overcompensated for by the addition of intrusive material and a slight thickening of the crust may have occurred. The distribution of this lower crustal thickening would not be related to the central complexes in the same manner as the proposed crustal thickening associated with the emplacement of the complexes, but the vertical gravitational attraction of the thickening would be included by the annular averaging of the Bouguer anomalies.

A similar influence on the annular averages of the Bouguer anomalies will arise from the structure of the lower crust beneath the other Tertiary igneous complexes of the northwest Scotland–Hebridean region. If the Rhum, Ardnamurchan and Blackstones Bank igneous complexes have been emplaced in a similar manner to the complexes of Mull and Skye, the lower crust beneath these complexes may be slightly thickened also. The Bouguer anomaly lows generated by the crustal thickening beneath these complexes will be included in the annular averages of the Bouguer anomalies for the Mull and Skye complexes. Therefore, the estimates of the crustal thickening beneath the Mull and Skye complexes will be significantly greater in volume than the volumes of the central complexes.

It is difficult to determine a quantitative estimate of the effect of the crustal material displaced by the Rhum, Ardnamurchan and Blackstones Bank central complexes on the annular averages of the Bouguer anomalies around the Mull and Skye complexes. This is because the actual radial extent of the crustal thickening beneath each complex is unknown and the volumes of the complexes estimated for Mull and Skye from modelling the radial Bouguer anomaly profiles differ from the volumes determined from earlier studies (Bott and Tuson, 1973; Bott and Tantrigoda, 1987). Therefore, the volumes of the other complexes must be considered uncertain. However, it is reasonable to assume that the regions encircled by the maximum radii of 80 km around the Mull complex and 120 km around the Skye complex will incorporate a significant amount of the areas of thickened crust centred on the other igneous complexes. Therefore, the likely occurrence of crustal thickening beneath the Ardnamurchan, Rhum and Blackstones Bank complexes in addition to the Mull and Skye complexes provides a plausible explanation for at least part of the imbalance between the observed volumes of the central complexes of Mull and Skye and the volumes of the crustal thickening required to generate the annular Bouguer anomaly minima observed surrounding the complexes.

One final observation is that the density contrast at the Moho between the lower crustal material displaced by the rising magma of the central complexes and the upper mantle is much greater than the density contrast between the cooled central complexes

and the upper crust. Therefore, for each complex the mass deficiency at the Moho greatly exceeds the mass excess of the central complex in the upper crust. This should provide significant regional support for the high topography often associated with the central complexes.

6.11 Conclusions

The averages of the Bouguer anomalies around annuli centred on the Mull and Skye igneous complexes show that both complexes are encircled by broad, annular anomaly lows. The maximum amplitudes of these lows are estimated to be roughly 10 mGal. The maximum radii of the lows are of the order of 70–80 km.

Two possible explanations have been proposed for the the origin of the annular anomaly lows. Lithospheric flexure beneath the load of the complexes has been shown to be unable to reproduce the observed amplitude of the lows and may, therefore, be discounted as a primary cause. The amplitudes of the lows can be explained by a thickening of the lower crust beneath the complexes but the volume of the required thickening greatly exceeds that of the intrusive complexes. The imbalance of the estimated volumes may arise from errors in the interpretation of the Bouguer anomalies or possibly from errors in the assumed density models, but it is also quite likely that the observed imbalance results from a number of important factors omitted from the initial interpretation. The most important of these factors is the occurrence of a similar thickening of the crust beneath the other central complexes of the northwest Scotland–Hebridean region.

In conclusion, this chapter has only been able to present a preliminary investigation into the structure of the lower crust beneath the central complexes of Mull and Skye, but the results indicate that a slight thickening of the crust in the regions around the central complexes is plausible. However, more detailed analyses of the Bouguer anomaly data and the volumes of all the igneous intrusions of the early Tertiary period are required to investigate completely the imbalance between the estimated volumes of the complexes and the crustal thickening. Despite these difficulties, the study has

shown the advantages of relating the results of geophysical investigations to problems such as the method of emplacement of the igneous central complexes, which are usually considered from the traditional concepts of igneous petrology alone.

CHAPTER 7

Conclusions and discussion

7.1 Computer database

The computer database described in Chapter 2 was used extensively in the subsequent investigations into the regional Bouguer anomaly gravity field. The database provided an efficient data storage mechanism and a facility for the rapid retrieval of data from user specified geographical regions. This enabled gridded representations of the Bouguer anomaly and topographic data for even quite large regions to be quickly produced for analysis. New data records could be easily entered into existing or new data files. The ease with which new data could be entered into the database and the rapidity with which data grids could be generated meant that the gridded representations of the Bouguer anomaly and topographic data of the UK region could be quickly updated after receiving new data sets.

The update facilities developed for the database have been required on a number of occasions to remove either spurious data records or data sets of uncertain quality. Therefore, the time spent on the initial development of these facilities has been justified. During the investigations into the regional gravity field, a number of possible improvements to the database have been identified. On land where the density of the gravity station coverage is high, the automatic profile generation programme produces quite useful profiles but the programme is less successful for marine regions where the density of data coverage is lower and the gravity stations are generally more regularly distributed along ship tracks. An alternative approach to the automatic generation of profiles that could overcome this difficulty would be to fit a mathematical ‘best fit’ surface such as a bicubic spline to the data in the vicinity of the profile and to use the coefficients of the surface to interpolate the values of the data field or fields of interest

along the profile. However, this method would be computationally expensive for long profiles. A further improvement to the automatic profile generation facility would be to modify the programme to allow profiles based on the OSGB national grid and other commonly used reference systems, such as the Irish National grid and the UTM coordinate system to be presented. This would allow the profiles to be compared directly with published maps of surface geology and, gravity and magnetic anomalies.

With hindsight, I consider that the header record information for each data file containing the average values of the latitude, longitude, topography, observed gravity, free air gravity, Bouguer gravity and terrain correction data fields and the RMS deviations of the topography, free air gravity, Bouguer gravity and terrain correction data fields is unnecessary. This data is of general interest, but has not been required for any significant investigations. Removing the requirement to update the data file header record each time a data record is added or removed from the database would significantly simplify the data input and update operations. It is important to keep the data structure of the database as simple as possible because this greatly increases the flexibility of the database. The main requirements for a successful database are simply that the data should be accurate, easy to access and efficiently stored.

7.2 Digital image processing

The application of digital image processing techniques to the Bouguer anomaly data for the UK, the Republic of Eire and the adjacent marine regions revealed numerous lineaments which must reflect the presence of subsurface density contrasts. Many of the lineaments are considered to be associated with zones of weakness within the basement and their interpretation provides useful information on the tectonic framework of the northwest European continental shelf. Often, the basement weaknesses are not the primary cause of the observed Bouguer anomalies but the presence of the basement weaknesses has influenced the location and form of density contrasts which have developed at a later date.

The two main occurrences of this type of basement control are the modification of

the space form of intrusive granitic complexes during emplacement and the reactivation of reverse faults as extensional structures in the formation of half graben. Many examples of the possible influence of structures within the basement on the emplacement of presumed granitic complexes have been discussed. In the northern Highlands the basement fabric of the Lewisian may have influenced the northeastern subsurface margin of the granite complex considered to produce the NW–SE elongated Bouguer anomaly low which extends from Alness, near the Moray Firth, towards the vicinity of the Ben Stack line in Assynt. Similarly, the Cruachan lineament may result from a deep crustal control on the intrusion of the Caledonian post orogenic granites. The orientation of the Bouguer anomalies generated by the late Caledonian granites of the southern northwestern Highlands and the northern Grampian Highlands show a correlation with the trend of the observed basement structures. Further south, the granite complexes of the Southern Uplands and the Leinster–Isle of Man–Lake District–north Pennines arc display a distinctly Caledonian trend. In Eire, the emplacement of the Galway granite may have experienced a similar control. The Cornubian batholith is also of interest. The batholith is characterized by an ENE–WSW trend which is oblique to the roughly E–W trend of the deformation associated with the Variscan foldbelt in southwestern England. This suggests tectonic control of the emplacement of the batholith by deeper basement structures (Shackleton, 1984).

The second type of Bouguer anomaly lineament is formed by the development of half graben over the hanging walls of reverse thrusts that are later reactivated as extensional faults. Numerous examples of the formation of such lineaments have been cited. The overall pattern of the lineaments of this nature indicate that the Mesozoic–Cainozoic break up of the Pangaeian supercontinent and the opening of the Atlantic ocean were strongly influenced by zones of basement weakness developed during the earlier Lower Palaeozoic suturing of Pangaea.

The relationship between some of the presumed zones of basement weakness and the observed lineaments in the Bouguer anomaly data is complex. Sometimes the nature of the lineaments varies along strike. A good example is the anomalous NW–SW trending

zone between the northeastern margin of the Derbyshire dome Bouguer anomaly high and the Askern–Spital high lineament, and the proposed extensions of this zone to the northwest into the central Pennines and to the southeast into East Anglia. The polarity of the Askern–Spital lineament appears to be inverted to the northwest. The along strike variation observed for this zone may be influenced by changes in the orientation of the secondary structural trends. A similar complexity is observed along the margins of the Ballinalack–Slieve Aughty block in the Irish Midlands. This variation may be influenced by the swing in the orientation of the block from NE–SW in the northeast to ENE–WSW in the southwest.

The pattern of the lineaments observed within the Bouguer anomaly data may be used to infer structural fabrics within the basement. These fabrics define six major tectonic domains which are briefly summarized below:

- (1) the northwest Approaches, Scotland and the North Sea northwest of the Highland Boundary fracture zone: this zone includes all of the Caledonian orthotectonides of Scotland and part of the orthotectonides of Ireland.
- (2) Southern Scotland, northern England, the northern Irish Sea and central Ireland: this region includes part of the Caledonian paratectonide deformation belt of southern Scotland and northern England, part of the orthotectonides of Ireland and all of the paratectonides of Ireland.
- (3) the Welsh Borderland, most of Wales, and the southern Irish Sea: this region forms the remaining section of the NE–SW trending paratectonides foldbelt. The observed lineaments in the eastern part of this domain are strongly influenced by the proposed late Caledonian indentation of the Midlands microcraton (Soper et al., 1987).
- (4) the southwestern North Sea and eastern England: this region is characterized by a marked NW–SE structural trend which is the result of a concealed branch of the paratectonic Caledonides.
- (5) the Midland microcraton.
- (6) the Variscan foldbelt.

Some of these tectonic domains may be further subdivided on the basis of the amplitude of the Bouguer anomalies and the orientation and patterns of the lineaments. Two regions of particular interest have been identified. The broad region of negative Bouguer anomalies with low amplitude local variations observed in the southern North-western Highlands and the northern Grampian Highlands is considered to be the result of a widespread granitic basement. The Bouguer anomaly lineaments observed in this region may reflect a control on the topography of the roof of the granite by basement weaknesses or a more speculative relationship between the basement fractures and the density of the granitic intrusives.

The second region of interest is the anomalous NW–SE trending zone of lineaments extending from the central Pennines to East Anglia. The central geological structure associated with this zone is the Gainsborough gulf which is considered to have developed in the Carboniferous (Kent, 1966). The formation of this anomalous zone of lineaments is considered to be intimately connected with the Caledonian accretion of the Midland microcraton onto the Laurasia–Baltica landmass. The geological structures which produce these lineaments may have a similar structural relationship to the microcraton as the Church Stretton fault, the Pontesford–Linley fault and the Cheshire basin which have formed along the opposite margin of the indenter. The Bouguer anomaly lineaments observed around the northern apex of the indenter indicate a complex structure. A number of E–W striking lineaments are observed in the central Pennines suggesting a possible swing in the lineament orientation across the apex of the microcraton. However, in the digital image of the Laplacian of the Bouguer anomaly data the NW–SE trending lineaments dominate in the central Pennines. The dominance of the NW–SE structural trend may be a consequence of the N 10° E internal displacement direction of the late Caledonian deformation event noted by Soper et al. (1987).

The regional pattern of the macro geological structures as delimited by the Bouguer anomaly lineaments indicates the presence of two former zones of tectonic convergence in northern Britain, the North Sea and northern and central Ireland. These are known as the Iapetus and Tornquist convergence zones. However, the structure of the junction

between these two tectonic zones is uncertain. The structure of the basement beneath the central North Sea east of southern Scotland is of great significance to the understanding of this problem. Unfortunately, the digital images of the Bouguer anomaly data display no distinct lineaments in this area and only a few faint E–W trending lineaments are observed. The lack of any clear lineaments maybe partly accounted for by the low density of surface marine measurements within this region. Further information on the structure of the Caledonian basement from magnetic anomaly data, borehole samples and possibly additional gravity anomaly data is required before the true relationship between the NE–SW trending Iapetus zone of convergence and the NW–SE Tornquist zone of convergence is completely understood. The northeastern margin of the Tornquist zone of convergence may have been located in the eastern North Sea by a change in the seismic velocity of the upper crust observed by Barton and Matthews (1984). The change in the upper crustal velocities which occurs roughly 80 km east of the Central graben may mark the thrusting of the Caledonian basement over the Precambrian of the Fenno–Scandian shield.

Two important tectonic structures, the Iapetus suture and the Variscan front are generally indistinct and poorly imaged within the Bouguer anomaly data. There are a number of plausible explanations for the absence of a marked change in the Bouguer anomaly gravity field across these structures. The recent NEC seismic reflection profile across the proposed trace of the Iapetus suture east of the Northumberland coast revealed marked crustal variations within the lower crust which could correspond to the suture, but did not image a major change in the structure of the upper crust across the proposed location of the suture (Freeman et al., 1988). It is unlikely that the deep structures associated with the suture would produce a marked Bouguer anomaly lineament at the surface. However, it should be noted that the seismic reflection acquisition and processing parameters applied by the BIRPS group are designed to enhance the deep crustal resolution and, therefore, the resolution in the upper crust is often poor.

The SWAT seismic reflection profiles 2, 3 and 4 imaged the Variscan front as a low angle fault beneath the southern Irish Sea and Celtic Sea regions (BIRPS and

ECORS, 1986). Therefore, even if a marked density contrast were to exist at the front the geometry of the structure would tend to cause a gradual change in the amplitude of the Bouguer anomalies observed across the surface trace of the front (see figure 6, Setto and Meissner, 1987).

The nature of the basement associated with the former Iapetus convergence zone varies along strike. In Ulster and the Republic of Eire, the tectonic fabric revealed by the Bouguer anomaly lineaments is of a more discontinuous nature than that observed in Scotland and northern England. Both the southwestern continuation of the Highland Boundary fracture zone and the Southern Uplands fault are less distinct in Ireland. The most interesting feature of the digital images of the Bouguer anomaly data for Ireland is the deviation between the trend of the observed gravity lineaments in northwestern Ireland and the trace of the Fair Head–Clew Bay lineament observed in the magnetic anomaly data (Max and Riddihough, 1975). This appears to define a rare occurrence of a line of structural weakness delimited by lineaments within the Bouguer anomaly data deviating from the presumed boundary between different types of basement. This may reflect the complex structure of the basement of northwestern Ireland.

The across strike variation of structural trends as delimited by the Bouguer anomaly lineaments is observed within the paratectonide deformation belt of central Ireland. The sub-fabric of NW–SE trending Bouguer anomaly lows generated by fault bounded graben containing Permo–Triassic deposits observed in western Britain and the Irish Sea is not observed in Ireland. This sub-fabric is considered to be possibly related to a conjugate line of weakness to the main trend of the structures of the former Iapetus zone of convergence. Apart from the Mesozoic basins buried beneath the plateau lavas of Antrim and the Permo–Carboniferous basin east of Kingscourt, the Irish mainland appears to have been largely unaffected by the sedimentary basin formation which marked the Mesozoic break up of Pangaea and the opening of the Atlantic ocean elsewhere.

In conclusion, the application of digital image processing techniques to the Bouguer anomaly data for the UK and the surrounding shelf seas, and Ulster and the Republic of Eire has presented many useful insights into the tectonic evolution of these regions.

7.3 Mechanisms of isostatic compensation

The investigations into the isostatic compensation of the topography of the UK region show that the surface loading model applied to the analysis of the topography of oceanic regions (Watts, 1978; Cochran, 1979) oversimplifies the relationship between gravity and topography observed for the continental lithosphere. This is primarily because the continental lithosphere has experienced a much more complex tectonic evolution than the younger regions of oceanic lithosphere. However, some of the more complex features of the oceanic lithosphere, such as transform zones also require more complex isostatic models (Louden and Forsyth, 1982). The topography of the UK is unusual because much of the topography such as the high ground associated with many of the major granite complexes can be related to subsurface density contrasts. Several different forms of isostatic compensation appear to be operating within the region. The different types of isostatic compensation may be roughly categorized into three main groups on the basis of the wavelengths of the applied loads at which the different mechanisms are observed to operate. At wavelengths of less than 200 km, loads formed by surface topography or internal density contrasts appear to be maintained out of isostatic equilibrium by the strength of the continental lithosphere. The coherence between gravity and topography is negligible. However, the granitic complexes in general must be excluded from this observation. The complexes appear to achieve a form of local Pratt compensation within the upper crust.

Intermediate wavelength loads are supported by regional compensation through the flexure of the continental lithosphere. At long wavelengths, the effective flexural rigidity of the lithosphere is insignificant and long wavelength loads are supported by Airy isostasy. Topographic features maintained out of equilibrium must be supported by other processes such convection within the mantle and the sinking of the lithosphere.

The isostatic investigations into the relationship between gravity and topography for the UK region have concentrated on the short and intermediate wavelength loads because the long wavelength (> 700 km) information provided by the cross spectral analysis is poorly constrained. The results of the study of the gravity and topogra-

phy in the vicinity of the Cornubian batholith indicate that the topography above the complex is supported by the mass deficiency of the batholith. The observed isostatic response function may be explained as the product of a shallow form of local Airy compensation. The compensation depth is estimated to be roughly 5 km. The Cornubian massif as a whole appears to be significantly overcompensated. This may result from processes, such as erosion after the high level emplacement of the complex. The influence of the gravity and topography associated with the granite complexes of the UK and eastern Ireland on the cross spectral analysis of gravity and topography for the UK and adjacent regions as a whole is difficult to predict. Therefore, the isostatic influence of the complexes was roughly removed from the gridded representations of gravity and topography before determining the final estimates of the isostatic response function and coherence. The observed coherence indicates that regional isostatic compensation through the flexure of the lithosphere becomes significant for loads with wavelengths greater than 200 km.

The estimates of the isostatic response and coherence obtained for intermediate wavelengths have been modelled using an isostatic model which incorporates the loading of the continental lithosphere by both surface topography and internal density contrasts. The isostatic model is a simplification of the true isostatic system because a number of assumptions are required to make the calculations manageable:

- (1) the initial loading occurs at a number of discrete interfaces within the continental lithosphere and the loading on each interface may be modelled in the form of the topography of a density contrast along the interface;
- (2) the initial loads on each interface are statistically independent;
- (3) the elastic thickness of the continental lithosphere is either uniform or follows a prescribed form, such as a statistical population of tectonic provinces of equal area with various values of the elastic thickness T_e .

Two possible subsurface loading configurations have been investigated, but the lack of constraints on the parameters of the isostatic model and the small number of observations that could be modelled meant that it is impossible to determine which of the

two models is ~~more~~ realistic. Assuming a uniform elastic thickness for the lithosphere, the best fit between the theoretical and observed amplitude response and coherence are obtained for an elastic thickness of 24.5 km for the mid crustal loading model and 22.5 km for the shallow loading model.

However, the fit between the observed and theoretical coherence is poor. A better fit is obtained if the isostatic models assume that the value of the elastic thickness of the continental lithosphere varies over a series of distinct tectonic provinces. The best fit between the theoretical and observed amplitude response and coherence assuming a uniform distribution of the value of the elastic thickness over a series of tectonic provinces of equal area is obtained for a range of values of the elastic thickness between 8 and 90 km for the mid crustal loading isostatic model and between 6 and 86 km for the shallow loading model. The distribution of the values of the elastic thickness of the lithosphere assigned to the tectonic provinces for the computation of the theoretical amplitude response and coherence is unlikely to match the true distribution and it is also unlikely that area of each province is similar to that of the other provinces. However, the ranges of the values of the elastic thickness of the lithosphere for the isostatic models tend to suggest that local Airy compensation is not important.

Perhaps, the most significant observation of the cross spectral analysis of the gravity and topography data is the low amplitude of the coherence. The sedimentary basins of the northwest European continental shelf are considered to have an important influence on the low values of the coherence because they are often characterized by marked Bouguer anomalies but appear to have little effect on topography. Another important factor is that several different forms of isostatic compensation are observed to co-exist. The low coherence may, therefore, be a consequence of the interference of a number of different relationships between gravity and topography occurring within a single region.

The investigation into the nature of the isostatic compensation of the topography of the UK region has provided a number of important observations on the mechanisms of isostatic compensation occurring within the region, but more detailed examinations of the gravity anomalies and topography are required to further our understanding of

isostasy and the thermo-mechanical properties of the continental lithosphere. An important advance would be to accurately determine the vertical gravitational attraction of the sedimentary basins located within the UK region and to subtract this from the regional Bouguer anomaly gravity field. This would enable the identification and possible definition of the deeper subsurface loads. This information might allow the methods applied by Bechtel et al. (1987) to the gravity and topography in the vicinity of the East African rift to be applied to the gravity and topography of the UK region. The flexural loading of the sedimentary basins could be modelled using an equivalent layer. However, the difficulties involved in defining the depth and form of the subsurface loads from gravity data alone would have to be overcome first. A better understanding of the relationship between gravity and topography in the vicinity of the sedimentary basins of the region would also be valuable because the relationship appears to be poorly expressed by the cross spectral analysis.

Further information on the value of the elastic thickness of the continental lithosphere would also be useful, especially if an indication of the distribution of the value of the elastic thickness of the continental lithosphere within the region could be defined. However, in general the region appears to show a marked absence of the form of isolated topographical and geological loads which have been used to obtain specific estimates of the elastic thickness of the continental lithosphere elsewhere.

7.4 The deep structure of the crust beneath Mull and Skye

Gravity modelling of the crust in the vicinity of the Tertiary igneous complexes of Mull and Skye, northwest Scotland, suggests that the crust beneath the complexes has been thickened slightly. However, the estimates of the volume of the thickening of the crust beneath each complex greatly exceed the estimates of the volume of each complex. Therefore, the suggestion of Bott and Tantrigoda (1987) that the thickening of the crust beneath the complexes is a result of the diapiric intrusion of the lower crust by the magma which formed the central complexes initially appears implausible. However, the imbalance between the volumes of the complexes and the crustal thickening may

result from a number of additional factors summarized below:

- (1) the depression of the continental lithosphere beneath the load of the extrusive plateau lavas;
- (2) the volume of the intrusive material added to the lower crust during the period of early Tertiary igneous activity in the northwest Scotland–Hebridean region possibly being in excess of the crustal thinning generated by regional tension;
- (3) the vertical gravitational attraction of the proposed thickening of the lower crust beneath the Rhum, Ardnamurchan and Blackstones Bank central complexes being incorporated into the annular Bouguer anomaly minima observed around the Mull and Skye complexes causing the volume of the lower crustal thickening beneath these complexes to be overestimated.

Taking these additional factors into account, the results of the investigation indicate a certain amount of support for the observations of Bott and Tantrigoda (1987). However, more detailed research is required before more definite conclusions may be reached.

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Appendix A

Terrain correction codes

The data record for each gravity and topographic point observation contains a single character terrain correction code which identifies the nature of the terrain correction applied during the reduction of the Bouguer anomaly. The character codes used and the type of terrain corrections they represent are listed below.

Codes A–M. These code letters signify that ‘flat–Earth’ terrain corrections of the type described by Hammer (1939) have been applied. The actual letter used identifies the Hammer zone out to which the terrain correction has been applied.

Code Q. This code letter signifies that the terrain correction is indeterminate or of questionable status.

Code Z. The terrain correction is zero.

Code X. This code signifies that the terrain correction is a ‘whole–topography’ terrain correction determined out to a distance of 48.6 km on a curved Earth. The ‘whole–topography’ terrain correction is the Bouguer–slab correction minus the gravitational attraction of the actual topography above or below sea level.

Code V. This code signifies that the terrain correction is a ‘whole–topography’ terrain correction determined out to an outer radius of 64 km on a curved Earth.

Code T. This code denotes a ‘whole–topography’ terrain correction determined out to a radius of 166.7 km.

Code U. This code signifies a similar terrain correction to Code T but the inner zone corrections are not available and so a value of 0.20 mGal has been assumed

for the terrain corrections for the Hammer zones A to M.

These details were provided by Mr. G. Turnbull of the Regional Geophysics Research Group of the B. G. S. in a personal communication to Dr. G. D. Karner.

Appendix B

Database software

Brief outline of database software structure

Appendix B contains the computer software which forms the database described in Chapter 2. The software is written in Fortran 77 but some MTS and external subroutines are also used. The main program_{mes} are listed individually and the subroutines are contained within a subroutine library. A brief description of each program_{me} is presented here to describe the overall pattern of the database structure. The software may be classified into three main categories, namely database generation and file information, data update, and data presentation and manipulation program_{mes}.

Database generation and file information program_{mes}

The program_{me} Dbin.2 generates the database data and index files and adds new data to the existing files. The program_{me} Archive generates a MTS source file which can be used to transfer the database data and index files to or from a magnetic tape archive. The program_{me} Dbinwrite and Ibinwrite provide formatted listings of the unformatted data and index files.

Data update program_{mes}

The Program_{me} Line.del enables a specific data record to be deleted from the database. The program_{me} C.index processes the database datafiles within a specified geographical region updating the contributor index file CNTIDX. The program_{me} Contr.del removes all the data within the database supplied by a specified contributor. The deleted data is saved in an external file to allow the data to be reprocessed if required.

Data presentation and manipulation programmes

The programme `Liner` generates profiles of the free air gravity, topography and Bouguer anomaly gravity along user specified geodesic curves assuming a spherical Earth. The programme `Grid.proj` generates grid representations of the gravity and topographic point observations stored within the database. A number of map projection grids are available. The programme `Binradii` uses a weighted average interpolation technique to assign values to undefined grid points after the main grid generation using programme `Grid.proj`. The programme `Grid.dump` provides a formatted listing of the gridded data. The formatted output consists of the coordinates of the centre of each grid square and one of the three gridded data fields. The programme `S2.matrix` provides a similar function but the formatted matrix of the gridded values produced is compatible with the Surface II grid input command '`MATRIX`'. The programme `S2.coast.con` writes out the database digitized coastline of the UK and Ireland in a form compatible with the Surface II coastline input command '`ROUTLINE`'. The programme `Image.proj` generates byte matrices from the data grids for input into the I²S image processing system. Finally, the programme `Fft.filter` filters the gridded data in the wave domain through the use of the fast fourier transform or FFT.

Object code compilation and external subroutine libraries

The documentation for each programme in the appendices B, C and D contains the required run command to execute the programme under the MTS operating system. The file '`-load`' should contain the object code generated from the source code listed. The compiler used to generate the object code is the IBM VS Fortran compiler, programme number 5748-F03.

The additional terms `*Nag`, `*Ghost80` and `*Ginof` in some of the run commands are required to call subroutines from the following external subroutine libraries:

`*Nag`, Numerical Algorithms Group subroutine library Mark 12, Numerical Algorithms Group Ltd., Oxford;

`*Ghost80`, Ghost80 graphical subroutine library Release 7, UKAEA, Culham labora-

tory;

*Ginof, Gino-f graphical subroutine library, CAD centre Ltd., Cambridge.

```

C**
C**  Programme Archive
C**  ~~~~~
C**
C**  Programme Archive generates a MTS source
C**  file of *Archive commands to restore
C**  or save the database files lying
C**  within a rectangular block of integer
C**  latitude and longitude values.
C**
C**  Programme Details
C**  ~~~~~
C**
C**  OS MTS
C**  Language Fortran 77
C**
C**  Author R.W.Woollett
C**  Date 30 th September 1987
C**
C**  Run Command
C**  ~~~~~
C**
C**  Run -load
C**
C*****C
C
C*  MAIN
C*  CHARACTER SFILE*7, BINAME*7, INDNAM*7
C
C*  LOGICAL LOGEX, OK
C
C*  INTEGER WLON, ELON, SLAT, NLAT
C
C*  PARAMETER (OK= .TRUE. )
C
C*  OPEN SOURCE FILE
C*  WRITE (6,10)
10  FORMAT (/, '&', 4X, 'Enter name of source file to be generated')
C*  READ (5,20) SFILE
20  FORMAT (A7)
C
C*  OPEN (UNIT=4,STATUS='NEW',FILE=SFILE,ACCESS='SEQUENTIAL',FORM=
1  'FORMATTED')
C
C*  INITIATE SOURCE COMMANDS
C*  WRITE (4,30)
30  FORMAT ('$Log on -Terminal', /, '$Set proute=dcumain', /,
1  '$Run *Archive')
C
C* 40 WRITE (6,50)
50  FORMAT (/, 5X, 'Do you wish to Save (0) or Restore (1) Data', /)
C
C*  READ (5,*) IOPT
C*  IF (IOPT .NE. 0 .AND. IOPT .NE. 1) GO TO 40
C
C*  ENTER GEOGRAPHICAL EXTENT OF SEARCH AREA

```

```

WRITE (6,60)
60  FORMAT (5X, 'Enter integer degree limits of region of interest', /
1  , '&', 4X, 'Wlon, Elon, Slat and Nlat')
C
C*  READ (5,*) WLON, ELON, SLAT, NLAT
C
C*  IF (SLAT .LT. 0 .OR. NLAT .LE. 0) THEN
C*  WRITE (6,70)
70  FORMAT (/, 5X, 'Error negative Latitude Input', /)
C*  CLOSE (UNIT=4,STATUS='KEEP')
C*  STOP
C*  END IF
C
C*  IF (WLON .LT. 0) WLON = WLON + 360
C*  IF (ELON .LT. 0 .OR. ELON .LT. WLON) ELON = ELON + 360
C
C*  WRITE (6,80) WLON, ELON, SLAT, NLAT
80  FORMAT (5X, 'Search Region Limits', /, 5X, 'Wlon = ', I3, /, 5X,
1  'Elon = ', I3, /, 5X, 'Slat = ', I3, /, 5X, 'Nlat = ', I3,
2  /)
C
C*  REDUCE MAXIMUM LIMITS
C*  ELON = ELON - 1
C*  NLAT = NLAT - 1
C*  IF (ELON .LT. WLON .OR. NLAT .LT. SLAT) THEN
C*  WRITE (6,90)
90  FORMAT (5X, 'Error Elon < Wlon and/or Nlat < Slat', /)
C*  STOP
C*  END IF
C
C*  DO 190 LON = WLON, ELON
C*  DO 180 LAT = SLAT, NLAT
C
C*  LSUB = LON
C*  IF (LSUB .GT. 359) LSUB = LSUB - 360
C
C*  CALL NAME(LAT, LSUB, BINAME, INDNAM)
C
C*  OPERATE ON DATA FILE
C*  INQUIRE (FILE=BINAME,EXIST=LOGEX)
C
C*  IF (IOPT .EQ. 0) THEN
C*  IF (LOGEX .EQV. OK) THEN
C
C*  WRITE (4,100) BINAME
100  FORMAT ('Save ', A7)
C*  ELSE
C*  WRITE (6,110) BINAME
110  FORMAT (5X, 'File ', A7, ' does not exist: Save cancelled')
C*  1
C
C*  END IF
C*  ELSE IF (IOPT .EQ. 1) THEN
C*  IF (LOGEX .NEQV. OK) THEN
C
C*  WRITE (4,120) BINAME

```

```

120      FORMAT ('Restore ', A7)
      ELSE
        WRITE (6,130) BINAME
130      FORMAT (5X, 'File ', A7, ' already on-line: Restore cancel
      iled')
C
      END IF
      END IF
C
C*   OPERATE ON INDEX FILE
      INQUIRE (FILE=INDNAM,EXIST=LOGEX)
C
      IF (IOPT.EQ. 0) THEN
        IF (LOGEX.EQV. OK) THEN
C
          WRITE (4,140) INDNAM
          FORMAT ('Save ', A7)
140          ELSE
            WRITE (6,150) INDNAM
            FORMAT (5X, 'File ', A7, ' does not exist: Save cancelled'
150          )
          1
C
          END IF
        ELSE IF (IOPT.EQ. 1) THEN
          IF (LOGEX.NEQV. OK) THEN
C
            WRITE (4,160) INDNAM
            FORMAT ('Restore ', A7)
160          ELSE
            WRITE (6,170) INDNAM
            FORMAT (5X, 'File ', A7, ' already exists: Restore cancell
170          iled')
          C
            END IF
          END IF
C
180  CONTINUE
190  CONTINUE
C
C*   FINALIZE SOURCE FILE INSTRUCTIONS
      WRITE (4,200)
200  FORMAT ('STOP')
      WRITE (4,210)
210  FORMAT ('$Log off', /, '$List -terminal *print*', /,
1      '$Display cost')
C
      CLOSE (UNIT=4,STATUS='KEEP')
C
      WRITE (6,220)
220  FORMAT (/, 5X, 'Archiving Source Complete', /)
C
      STOP
      END

```



```

C**
C**  Programme Binradii
C**  ~~~~~
C**
C**  Programme Binradii is designed to interpolate values for
C**  the undefined data grid points in the data grids after
C**  grid generation is performed by Grid.proj. The data grid
C**  is first read into Binradii and the data grid is checked
C**  for consistency. Holes within the input grid indicated by
C**  values of NGRID less than one are flagged on input. Binradii
C**  repairs these holes by taking a weighted average of the
C**  surrounding grid points from an area of around the hole
C**  specified by RADIUS. Radius is specified by the user or
C**  a default value of 10 grid intervals is used. The maximum
C**  number of holes that can be accommodated is 10,000.
C**
C**  Programme Details
C**  ~~~~~
C**
C**  OS MTS
C**  Language Fortran 77
C**
C**  Author R.W.Woollett 1986
C**  Modified from Grid.fix which is
C**  based on Binradii by G.D.Karner.
C**
C**  Run command
C**  ~~~~~
C**
C**  Run -load
C**
C** ~~~~~**C
C
C*  MAIN
C*  REAL FGRID(256,256), TGRID(256,256), BGRID(256,256),
C*  1 NGRID(256,256)
C
C*  INTEGER RADIUS, HOLES(2,10000)
C*  INTEGER IFFLAG(256,256), ITFLAG(256,256), IBFLAG(256,256)
C
C*  CHARACTER INFILE*7, OTFILE*7, FILE*7
C
C*  DATA NPTS, KOUNT, NBADF, NBADT, NBADB /0, 0, 0, 0, 0/
C
C*  FIRST SET DATA ARRAYS TO ZERO
C*  DO 10 I = 1, 256
C*    DO 10 J = 1, 256
C*      FGRID(I,J) = 0.0
C*      TGRID(I,J) = 0.0
C*      BGRID(I,J) = 0.0
C*      NGRID(I,J) = 0.0
C*  10 CONTINUE
C
C*  WRITE (6,20)
C*  20 FORMAT (5X, 'ENTER NAME OF GRIDDED INPUT FILE')
C*  READ (5,30) INFILE

```

```

30 FORMAT (A7)
WRITE (6,40)
40 FORMAT (5X, 'ENTER NAME OF GRIDDED OUTPUT FILE')
READ (5,50) OTFILE
50 FORMAT (A7)
C
C*  OPEN (UNIT=3,STATUS='OLD',FILE=INFILE,ACCESS='SEQUENTIAL',FORM=
C*  1 'UNFORMATTED')
C*  OPEN (UNIT=4,STATUS='NEW',FILE=OTFILE,ACCESS='SEQUENTIAL',FORM=
C*  1 'UNFORMATTED')
C
C*  READ INPUT HEADER RECORD AND DISPLAY ON SCREEN
C*  READ (UNIT=3) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
C*  WRITE (6,60) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
60 FORMAT (//, 5X, 'INPUT FILE:', A7, //, 5X, 'MINIMUM X VALUE' =
C*  1, F10.1, 'METRES', //, 5X, 'MAXIMUM X VALUE', F10.1,
C*  2 'METRES', //, 5X, 'MINIMUM Y VALUE', F10.1,
C*  3 'METRES', //, 5X, 'MAXIMUM Y VALUE', F10.1,
C*  4 'METRES', //, 5X, 'SAMPLING INTERVAL', F8.1,
C*  5 'METRES', //, 5X, 'ARRAY DIMENSIONS', //, 5X,
C*  6 'NX = ', I4, ' NY = ', I4, //)
C
C*  NPTS = NX * NY
C
C*  READ IN GRIDDED DATA
C*  DO 90 I = 1, NX
C*    DO 80 J = 1, NY
C
C*  READ (UNIT=3) X, Y, FGRID(I,J), TGRID(I,J), BGRID(I,J),
C*  1 NGRID(I,J), IFFLAG(I,J), ITFLAG(I,J), IBFLAG(I,J)
C*  IF (NGRID(I,J) .LT. 0.5) THEN
C*    KOUNT = KOUNT + 1
C*    IF (KOUNT .GT. 10000) THEN
C*      WRITE (6,70)
C*      70 FORMAT (5X, 'ARRAY HOLES OVERFLOWED-KOUNT>10,000', //, 5X,
C*      1 'PROGRAM TERMINATED')
C*      STOP
C*      END IF
C
C*  ASSIGN LOCATION TO ARRAY HOLES
C*  HOLES(1,KOUNT) = I
C*  HOLES(2,KOUNT) = J
C*  END IF
C
C*  80 CONTINUE
C*  90 CONTINUE
C
C*  DATA ARRAY READ IN AND HOLES FLAGGED.
C*  CLOSE (UNIT=3,STATUS='KEEP')
C
C*  WRITE (6,100) NPTS, KOUNT
C*  100 FORMAT (5X, 'NUMBER OF INPUT POINTS', //, 17, //, 5X,
C*  1 'NUMBER OF HOLES IN GRID', //, 17, //)
C
C*  IF (KOUNT .NE. 0) THEN
C*    NOW BEGIN TO REPAIR HOLES IN GRID

```

```

110 WRITE (6,110)
1   FORMAT (5X, 'ENTER INTERPOLATION RADIUS', //, 5X,
   'FOR DEFAULT VALUE ENTER 0', //)
   READ (5,*) NRDIUS
   IF (NRDIUS .EQ. 0) NRDIUS = 10
C
DO 160 LOOP = 1, KOUNT
   IX = HOLES(1,LOOP)
   IY = HOLES(2,LOOP)
C
   SUMF = 0.0
   SUMT = 0.0
   SUMB = 0.0
   NGOODF = 0
   NGOODT = 0
   NGOODB = 0
C
C*  AVERAGE OVER SQUARES RADIUS AWAY
DO 140 RADIUS = 1, NRDIUS
   IY1 = IY - RADIUS
   IF (IY1 .LT. 1) IY1 = 1
   IY2 = IY + RADIUS
   IF (IY2 .GT. NY) IY2 = NY
   IX1 = IX - RADIUS
   IF (IX1 .LT. 1) IX1 = 1
   IX2 = IX + RADIUS
   IF (IX2 .GT. NX) IX2 = NX
C
DO 130 J = IY1, IY2
DO 120 I = IX1, IX2
   IF (IFFLAG(I,J) .GT. 0) THEN
      SUMF = SUMF + FGRID(I,J)
      NGOODF = NGOODF + 1
   END IF
   IF (ITFLAG(I,J) .GT. 0) THEN
      SUMT = SUMT + TGRID(I,J)
      NGOODT = NGOODT + 1
   END IF
   IF (IBFLAG(I,J) .GT. 0) THEN
      SUMB = SUMB + BGRID(I,J)
      NGOODB = NGOODB + 1
   END IF
C
120   CONTINUE
130   CONTINUE
C
1   IF (NGOODF .GE. 8*RADIUS .AND. NGOODT .GE. 8*RADIUS .AND.
   NGOODB .GE. 8*RADIUS) GO TO 150
140   CONTINUE
C
C*  CALCULATE WEIGHTED AVERAGE IF DATA NOT ALREADY PRESENT
150   IF (IFFLAG(IX,IY) .EQ. 0) THEN
      IF (NGOODF .GT. 0) THEN
         FGRID(IX,IY) = SUMF / REAL(NGOODF)
         IFFLAG(IX,IY) = -1
      END IF

```

```

      END IF
      IF (ITFLAG(IX,IY) .EQ. 0) THEN
         IF (NGOODT .GT. 0) THEN
            TGRID(IX,IY) = SUMT / REAL(NGOODT)
            ITFLAG(IX,IY) = -1
         END IF
      END IF
      IF (IBFLAG(IX,IY) .EQ. 0) THEN
         IF (NGOODB .GT. 0) THEN
            BGRID(IX,IY) = SUMB / REAL(NGOODB)
            IBFLAG(IX,IY) = -1
         END IF
      END IF
C
160   CONTINUE
C
C*  SET DATA FREE AREAS TO ZERO
DO 180 I1 = 1, NX
DO 170 J1 = 1, NY
   IF (IFFLAG(I1,J1) .EQ. 0) THEN
      NBADF = NBADF + 1
      FGRID(I1,J1) = 0.0
   END IF
   IF (ITFLAG(I1,J1) .EQ. 0) THEN
      NBADT = NBADT + 1
      TGRID(I1,J1) = 0.0
   END IF
   IF (IBFLAG(I1,J1) .EQ. 0) THEN
      NBADB = NBADB + 1
      BGRID(I1,J1) = 0.0
   END IF
C
170   CONTINUE
180   CONTINUE
END IF
C
C*  WRITE HEADER RECORD TO OUTPUT FILE
WRITE (UNIT=4) OTFILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
C
C*  OUTPUT DATA GRID
DO 200 I = 1, NX
DO 190 J = 1, NY
   X = (REAL(I) - 0.5) * SAMP + XMIN
   Y = (REAL(J) - 0.5) * SAMP + YMIN
C
1   WRITE (UNIT=4) X, Y, FGRID(I,J), TGRID(I,J), BGRID(I,J),
   NGRID(I,J), IFFLAG(I,J), ITFLAG(I,J), IBFLAG(I,J)
C
190   CONTINUE
200   CONTINUE
C
CLOSE (UNIT=4,STATUS='KEEP')
C
C*  OUTPUT DATA DETAILS
WRITE (6,210) NPTS, KOUNT, NBADF, NBADT, NBADB

```

```

210 FORMAT (/, 5X, 'TOTAL NUMBER OF GRID POINTS   = ', 18, /, 5X,
1      'ORIGINAL NUMBER OF DATA HOLES = ', 18, /, 5X,
2      'REMAINING NUMBER OF DATA HOLES ', /, 5X,
3      'WITH RESPECT TO:-', /, 5X,
4      'FREE AIR GRAVITY               = ', 18, /, 5X,
5      'TOPOGRAPHY                    = ', 18, /, 5X,
6      'BOUGUER GRAVITY                = ', 18, //)
C
      STOP
      END

```

```

C**
C**  Programme C.Index
C**  ~~~~~
C**
C**  Programme C.Index is designed to
C**  update the contributor index Cntidx
C**  for all the files in a given lat.,
C**  lon. "rectangle". Programme C.Index
C**  is basically a simple driver routine
C**  to control the earlier programme
C**  Contr.Index1 now converted to the
C**  subroutine Cindex.
C**
C**  Programme Details
C**  ~~~~~
C**
C**  OS MTS
C**  Language Fortran 77
C**
C**  Author R.W.Woollett
C**  Date 24 th October 1987
C**
C**  Run Command
C**  ~~~~~
C**
C**  Run -load
C**  ~~~~~
C**
C**  ~~~~~
C**
C*  DEFINE VARIABLE TYPES
C*  CHARACTER BINAME*7, INDNAM*7
C
C*  LOGICAL LOGEXB, LOGEXI, OK
C
C*  INTEGER WLON, ELON, SLAT, NLAT
C
C*  PARAMETER (OK= .TRUE. )
C
C*  ENTER PARAMETERS
C*  WRITE (6,10)
10  FORMAT (/, 5X, 'Welcome to the GRVSYS contributor', /, 5X,
1   'Update System Programme', /)
C
C*  WRITE (6,20)
20  FORMAT (/, 5X, 'Enter integer degree limits of region to be', /,
1   '&', 4X, 'updated: wlon, elon, slat, nlat')
C
C*  READ (5,*) WLON, ELON, SLAT, NLAT
C
C*  IF (SLAT .LT. 0 .OR. NLAT .LT. 0) THEN
30  WRITE (6,30)
30  FORMAT (/, 5X, 'Error negative latitude input', /)
    STOP
    END IF
C
C*  IF (WLON .LT. 0) WLON = WLON + 360

```

```

    IF (ELON .LT. 0 .OR. ELON .LT. WLON) ELON = ELON + 360
C
C*  WRITE (6,40) WLON, ELON, SLAT, NLAT
40  FORMAT (/, 5X, 'Programme Update Region Limits', //, 5X,
1   'wlon = ', 13, /, 5X, 'elon = ', 13, /, 5X, 'slat = ', 13,
2   /, 5X, 'nlat = ', 13, //)
C
C*  DEDUCE MAXIMUM LIMITS
    ELON = ELON - 1
    NLAT = NLAT - 1
C
C*  IF (ELON .LT. WLON .OR. NLAT .LT. SLAT) THEN
    WRITE (6,50)
50  FORMAT (/, 5X, 'Error: Elon < Wlon and/or Nlat < Slat', /)
    STOP
    END IF
C
C*  UPDATE DATA FILES
    DO 110 LAT = SLAT, NLAT
    DO 100 LON = WLON, ELON
C
C*  LSUB = LON
    IF (LSUB .GT. 359) LSUB = LSUB - 360
C
C*  CALL NAME(LAT, LSUB, BINAME, INDNAM)
C
C*  DEDUCE IF FILES EXIST
    INQUIRE (FILE=BINAME, EXIST=LOGEXB)
    INQUIRE (FILE=INDNAM, EXIST=LOGEXI)
C
C*  IF ((LOGEXB .EQV. OK) .AND. (LOGEXI .EQV. OK)) THEN
    CALL CINDEX(BINAME, INDNAM)
    WRITE (6,60) BINAME, INDNAM
60  FORMAT (5X, 'Processing files ', A7, '/', A7)
    ELSE IF ((LOGEXB .NEQV. OK) .AND. (LOGEXI .NEQV. OK))
    THEN
1   WRITE (6,70) BINAME, INDNAM
70  FORMAT (5X, 'Files ', A7, '/', A7, ' are not available')
    ELSE IF ((LOGEXB .NEQV. OK) .AND. (LOGEXI .EQV. OK))
    THEN
1   WRITE (6,80) BINAME
80  FORMAT (5X, 'File ', A7, ' is not available')
    ELSE IF ((LOGEXB .EQV. OK) .AND. (LOGEXI .NEQV. OK))
    THEN
1   WRITE (6,90) INDNAM
90  FORMAT (5X, 'File ', A7, ' is not available')
    END IF
C
C* 100 CONTINUE
C* 110 CONTINUE
C
C*  WRITE (6,120)
120  FORMAT (/, 5X, 'Data File Update Complete', /)
C
C*  STOP
C*  END

```

```

C**
C** Programme Contr.del
C**
C**
C** Programme Contr.del is designed to retrieve all the data
C** in the data files supplied by a single contributor. After
C** each data record is retrieved the original data record is
C** erased from the data files to allow the data to be
C** after additional processing.
C**
C** Programme Details
C**
C**
C** OS MTS
C** Language Fortran 77
C**
C** Author R.W.Woollett 1986
C**
C** Run Command
C**
C**
C** Run -load
C**
C*****C
C
C* MAIN
C* CHARACTER PCONT(500)*8, FILES(300)*7
C* CHARACTER OTFILE*7, INDNAM*7
C* INTEGER*4 UNT, REG(2)
C* INTEGER*2 LEN
C
C* DIMENSION NUM1(500)
C
C* DATA UNT, REG /3, 1, 2/
C* DATA LEN /0/
C
C* OPEN CONTRIBUTOR INDEX.
C* OPEN (UNIT=3,STATUS='OLD',FILE='CNTIDX',ACCESS='DIRECT',FORM=
1  'FORMATTED',RECL=80,IOSTAT=J1)
C
C* IF (J1.NE. 0) THEN
C*   WRITE (6,10) J1
10  FORMAT (5X, 'ERROR OPENING FILE CNTIDX:IOSTAT=', I4, /, 5X,
1  'PROGRAM TERMINATED', //)
C*   STOP
C*   END IF
C
C* READ (UNIT=3,REC=500,FMT=20) NUM
20  FORMAT (30X, I3)
C*   WRITE (6,30) NUM
30  FORMAT (/, 5X, 'TOTAL NUMBER OF CONTRIBUTORS AT PRESENT=', I4, /)
C*   IF (NUM.GT. 500) THEN
C*     WRITE (6,40)
40  FORMAT (5X, 'MAX. NUMBER OF CONTRIBUTORS(=500) EXCEEDED ', /,
1  5X, 'SIZE OF ARRAYS PCONT,NUM1 MUST BE INCREASED', /, 5X,
2  'PROGRAM TERMINATES', //)

```

```

STOP
END IF
C
DO 60 K = 1, NUM
NREC = K * 1000
READ (UNIT=3,FMT=50,REC=NREC) PCONT(K), NUM1(K)
50  FORMAT (1X, A8, 2X, I3)
60  CONTINUE
C
70  WRITE (6,80)
80  FORMAT (5X, 'ENTER CONTRIBUTOR OF INTEREST', //)
C
DO 100 K = 1, NUM
WRITE (6,90) PCONT(K), K
90  FORMAT (5X, 'CONTRIBUTOR ', A8, 5X, 'ENTER ', I4)
100 CONTINUE
C
WRITE (6,110)
110 FORMAT (5X, 'ENTER -1 TO STOP PROGRAM OR', /, 5X,
1  'ENTER -2 TO LIST MENU AGAIN', /)
C
READ (5,*) ITEST0
IF (ITEST0.EQ. - 1) STOP
IF (ITEST0.EQ. - 2) GO TO 70
C
IF (NUM1(ITEST0).EQ. 0) THEN
WRITE (6,120) PCONT(ITEST0)
120  FORMAT (/, 5X, 'ALL DATA IN DATABASE FROM CONTRIBUTOR ', /, 5X,
1  A8, ' HAS BEEN ERASED', //)
C
STOP
END IF
C
C* CALL SUBROUTINE TO INTERROGATE CONTRIBUTOR INDEX
C* FOR FILE NAMES.
C* CALL READF(ITEST0, NUM1(ITEST0), FILES)
C
WRITE (6,130) PCONT(ITEST0)
130 FORMAT (5X, 'FILES CONTAINING DATA FROM ', /, 5X,
1  'CONTRIBUTOR ', A8, ' ARE: ', //)
C
DO 150 K = 1, NUM1(ITEST0)
WRITE (6,140) FILES(K)
140  FORMAT (5X, A7)
150 CONTINUE
C
CLOSE (UNIT=3,STATUS='KEEP')
C
WRITE (6,160) PCONT(ITEST0)
160 FORMAT (/, 5X, 'DO YOU WISH DATA FROM CONTRIBUTOR ', A8, /, 5X,
1  'TO BE WRITTEN TO A FILE YES(0) NO(1)', //)
C
READ (5,*) ITEST1
IF (ITEST1.NE. 0) THEN
WRITE (6,170)
170  FORMAT (/, 5X, 'DATA REMOVAL WITHOUT SAVE NOT ADMISSABLE', //)
C
STOP
ELSE IF (ITEST1.EQ. 0) THEN

```

```

180 WRITE (6,180)
1 FORMAT (/, 5X, 'ENTER NAME OF FILE TO WHICH DATA IS ', /, 5X,
    'TO BE WRITTEN ', /)
190 READ (5,190) OTFILE
190 FORMAT (A7)
1 OPEN (UNIT=7, STATUS='NEW', FILE=OTFILE, ACCESS='SEQUENTIAL', FORM=
    'FORMATTED')
C
200 WRITE (6,200)
200 FORMAT (/, 5X, 'ENTER OUTPUT FORMAT DESIRED ', /, 5X,
1 'FILENAME, LINE NUMBER, DATA (0) ', /, 5X,
2 'FILE FOR FURTHER PROCESSING (1) ', /)
2 READ (5,*) ITEST2
C
LIMIT = NUM1(ITEST0)
DO 220 K = 1, LIMIT
    IF (ITEST2 .EQ. 0) THEN
        WRITE (7,210) FILES(K)
210 FORMAT (/, 5X, 'FILE: ', A7, //)
        END IF
        CALL NAME2(FILES(K), INDNAM)
        CALL DATRET(FILES(K), INDNAM, PCONT(ITEST0), ITEST2)
220 CONTINUE
C
CLOSE (UNIT=7, STATUS='KEEP')
END IF
C
C* UPDATE CONTRIBUTOR INDEX
OPEN (UNIT=3, STATUS='OLD', FILE='CNTIDX', ACCESS='DIRECT', FORM=
1 'FORMATTED', RECL=80, IOSTAT=J2)
1 IF (J2 .NE. 0) THEN
    WRITE (6,230) J2
230 FORMAT (/, 5X, 'ERROR ON OPENING FILE CNTIDX FOR UPDATE', /, 5X,
1 'IOSTAT INTEGER =', I4, /)
    STOP
    END IF
C
IF (NUM1(ITEST0) .LE. 8) THEN
    NUMLIN = 1
ELSE IF (NUM1(ITEST0) .GT. 8) THEN
    NUMLIN = NUM1(ITEST0) / 8
    IF (NUM1(ITEST0) - (NUMLIN*8) .NE. 0) NUMLIN = NUMLIN + 1
END IF
C
C* DELETE FILES FROM INDEX
DO 240 K = 1, NUMLIN
    NREC = 1000 * ITEST0 + K
    CALL WRITE(REG, LEN, 2, NREC, UNT)
240 CONTINUE
C
NREC = ITEST0 * 1000
NUM1(ITEST0) = 0
WRITE (UNIT=3, FMT=250, REC=NREC) PCONT(ITEST0), NUM1(ITEST0)
250 FORMAT (1X, A8, 2X, I3)
CLOSE (UNIT=3, STATUS='KEEP')
C

```

STOP
END

```

C**
C** Programme Dbinwrite
C** ~~~~~
C**
C** Programme Dbinwrite is designed to write out the unformatted
C** database data files. To achieve this the programme first
C** opens the data file and reads and displays the file header
C** information. Then the data file index file is opened and
C** the interrogation of this file allows the data records in
C** the data file to be listed.
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77
C**
C** Author R.W.Woollett 1986
C**
C** Run command
C** ~~~~~
C**
C** Run -load 6= Output file
C** ~~~~~
C** ~~~~~**C
C
C* MAIN
C* CHARACTER BINAME*7, INDNAM*7, DATE*12
C* CHARACTER IDENT1*4, IDENT2*4, TCODE*1
C* CHARACTER VAR*4, CONT*4, ITC(10)*1
C
C* INTEGER FSTREC
C
C* ENTER DATA FILE NAME AND DETERMINE INDEX FILE NAME
C* CALL SCRND(BINAME)
C* CALL NAME2(BINAME, INDNAM)
C
C* OPEN DATA FILE AND READ AND DISPLAY HEADER INFORMATION.
C* OPEN (UNIT=3, STATUS='OLD', FILE=BINAME, ACCESS='DIRECT', FORM=
1  'UNFORMATTED', IOSTAT=J1, RECL=80)
C
C* IF (J1.NE. 0) THEN
C*   WRITE (6,10) J1
10  FORMAT (1X, 'ERROR OPENING UNIT 3 FOR DIRECT ACCESS, IOSTAT=',
1    14)
C*   GO TO 240
C* END IF
C
C* READ FILE HEADER RECORDS
C* READ (UNIT=3, REC=250) DATE
C* READ (UNIT=3, REC=500, IOSTAT=J2) IPOINT, ALAT, ALON, ATOP, AAGRV,
1  AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2, STERC2, RMSTOP,
2  RMSFRA, RMSBOU, RMSTER
C
C* IF (J2.NE. 0) THEN
C*   WRITE (6,20) J2

```

```

20  FORMAT (1X, 'ERROR READING FILE HEADER RECORD, IOSTAT=', 14)
C*   GO TO 240
C* END IF
C
C* WRITE (6,30) BINAME
30  FORMAT (2X, 'FILE:', A7)
C* WRITE (6,40)
40  FORMAT (2X, '~~~~~')
C* WRITE (6,50) DATE
50  FORMAT (2X, 'FILE CREATED: ', A12, '/')
C* WRITE (6,60)
60  FORMAT (2X, 'FILE STATISTICS')
C* WRITE (6,70)
70  FORMAT (2X, '~~~~~')
C* WRITE (6,80) IPOINT
80  FORMAT (2X, 'NUMBER OF RECORDS IN FILE=', I10)
C* WRITE (6,90)
90  FORMAT (2X, 'DATA FIELD', 12X, 'AVERAGE VALUE', 4X,
1    'RMS DEVIATION', 7X, 'UNITS')
C
C* WRITE (6,100) ALAT
100 FORMAT (2X, 'LATITUDE', 14X, F12.4, 25X, 'DEGREES')
C* WRITE (6,110) ALON
110 FORMAT (2X, 'LONGITUDE', 12X, F12.4, 25X, 'DEGREES')
C* WRITE (6,120) ATOP, RMSTOP
120 FORMAT (2X, 'TOPOGRAPHY', 12X, F12.2, 5X, F12.2, 8X, 'METRES')
C* WRITE (6,130) AAGRV
130 FORMAT (2X, 'ABSOLUTE GRAVITY', 6X, F12.2, 25X, 'MGAL')
C* WRITE (6,140) AFREEA, RMSFRA
140 FORMAT (2X, 'FREE AIR ANOMALY', 6X, F12.2, 5X, F12.2, 8X, 'MGAL')
C* WRITE (6,150) ABOUG, RMSBOU
150 FORMAT (2X, 'BOUGUER ANOMALY', 7X, F12.2, 5X, F12.2, 8X, 'MGAL')
C* WRITE (6,160) ATERRC, RMSTER
160 FORMAT (2X, 'TERRAIN CORRECTION', 4X, F12.2, 5X, F12.2, 8X,
1    'MGAL')
C* WRITE (6,170)
170 FORMAT (2X, 'LINE NUMBER*1000')
C
C* OPEN/READ INDEX AND READ DATA RECORDS FROM MAIN DATA FILE
C* WRITE DATA RECORDS TO OUTPUT FILE.
C* OPEN (UNIT=4, STATUS='OLD', FILE=INDNAM, ACCESS='SEQUENTIAL', FORM=
1  'UNFORMATTED', IOSTAT=J3)
C
C* IF (J3.NE. 0) THEN
C*   WRITE (6,180) INDNAM, J3
180  FORMAT (1X, 'ERROR OPENING FILE ', A7, ' ON UNIT 4, IOSTAT=', 14)
C*   GO TO 240
C* END IF
C
C* 190 READ (UNIT=4, END=230) ICODE1, FSTREC, LSTREC
C
C* IF (FSTREC.NE. 0) THEN
C*   DO 220 LNUM = FSTREC, LSTREC
C*     READ (UNIT=3, REC=LNUM, IOSTAT=J4) RLAT, RLON, IEAST, INORTH,
1     RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
2     (ITC(11), I1=1,10), VAR, CONT, IDENT1, IDENT2

```

```

C      IF (J4 .NE. 0) THEN
200      WRITE (6,200) BINAME, J4
        FORMAT (1X, 'ERROR ON DIR. ACCESS READ TO FILE ', A7,
1         'IOSTAT=', I4)
        GO TO 240
      END IF
C
      WRITE (6,210) LNUM, RLAT, RLON, IEAST, INORTH, RTOP, AGRV,
1      RFREEA, RBOUG, RTERRC, RDENSE, TCODE, (ITC(II),II=1,10), VAR,
2      CONT, IDENT1, IDENT2
C
210      FORMAT (2X, I11, 1X, F7.4, 1X, F8.4, 17, 17, F9.2, 1X, F8.1,
1      1X, F7.2, 1X, F7.2, 1X, F6.2, 1X, F7.1, A1, 1X, 10A1,
2      4A4)
C
220      CONTINUE
      END IF
C
      GO TO 190
230      CLOSE (UNIT=3,STATUS='KEEP')
      CLOSE (UNIT=4,STATUS='KEEP')
C
240      STOP
      END

```



```

C**
C** Programme Dbin.2
C** ~~~~~
C**
C** Programme Dbin.2 is the database generation routine. The
C** data to be input should be arranged into a sequential file.
C** The data in each record should be as follows:
C**
C** Ident1, Ident2, Rlat, Rlon, Ieast, Inorth, Rtop, Rdense,
C** Agrv, Rfreea, Tcode, Rterrc, Rboug, Var, Cont.
C**
C** Ident1 = Four character station identifier code
C** Ident2 = Four character additional station identifier code
C** Rlat = Decimal latitude of station.
C** Rlon = Decimal longitude of station.
C** Ieast = OSGB grid coordinate easting
C** Inorth = OSGB grid coordinate northing
C** Rtop = Station height in metres
C** Rdense = Bouguer correction density kg/m**3 (2700.0)
C** Agrv = Observed gravity in mGal
C** Rfreea = Free air gravity anomaly in mGal
C** Tcode = Terrain correction code
C** Rterrc = Terrain correction in mGal
C** Rboug = Bouguer gravity anomaly in mGal
C** Var = Additional character variable for extra information
C** Cont = Four character contributor identifier code
C**
C** Notes If Irish grid coordinates are used processing flag
C** ITC(2) should be set to 1. Also if the grid coordinates
C** are only accurate to decametres set ITC(1) to 1.
C**
C** Data input format given by format statement 40 in main programme.
C**
C** Input: When inputting new data make certain that if the files
C** for the region of the new data exist they are on—line
C** because the database will duplicate these files if they
C** are unavailable. The programme Archive will generate a
C** source file to de-archive blocks of data and index files.
C**
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77
C**
C** Author R.W.Woollett 1986
C**
C** Programme based on G.D.Karner's Landbin/Seabin
C** but considerably modified.
C**
C** Run command
C** ~~~~~
C**
C** Run -load 5 = Input file
C**

```

```

C*****C
C
C* MAIN
C* CHARACTER BINAME*7, IDENT1*4, IDENT2*4, TCODE*1, DATE*12
C* CHARACTER VAR*4, CONT*4, ITC(10)*1, ZERO*1, INDNAM*7
C
C LOGICAL LOGEX, LOGOP, OK
C
C INTEGER RECORD, FSTREC, KOUNT(0:99), GROUPN, RES
C
C PARAMETER (OK=.TRUE. )
C PARAMETER (ZERO='0')
C
C DATA IZERO /0/
C* MEASURE CPU TIME FOR PROCESSING
C CALL TIME(0)
C
C RECORD = 1
C* SET RMS VALUES OF TOPOGRAPHY, FREE AIR AND
C* BOUGUER ANOMALIES AND TERRAIN CORRECTIONS TO ZERO.
C RMSTOP = 0.0
C RMSFRA = 0.0
C RMSBOU = 0.0
C RMSTER = 0.0
C
C SET SUM OF SQUARES TO ZERO
C* STOP2 = 0.0
C* SFREA2 = 0.0
C* SBOUG2 = 0.0
C* STERC2 = 0.0
C
C SET PROCESSING FLAGS, ITC(1)=1 AS REQUIRED.
C* ITC(1) = '1'
C
C DO 10 I = 2, 10
C ITC(I) = ZERO
C 10 CONTINUE
C
C SET VALUES FOR ARRAY KOUNT
C* DO 20 K = 0, 99
C* KOUNT(K) = (K + 1) * 100000
C 20 CONTINUE
C
C ENTER DATA RECORDS
C* 30 READ (5,40,END=80) IDENT1, IDENT2, RLAT, RLO, IEAST, INORTH,
C* 1RTOP, RDENSE, AGRV, RFREEA, TCODE, RTERRC, RBOUG, VAR, CONT
C* 40 FORMAT (1X, A4, A4, 1X, F7.4, 1X, F8.4, I7, I7, F9.2, 1X, F7.1,
C* 1 1X, F8.1, 1X, F7.2, A1, 1X, F6.2, 1X, F7.2, A4, A4)
C
C CHECK FOR BAD DATA INPUT
C* IF (ABS(RLO)) .GT. 360.0) GO TO 100
C* IF (RLAT .LT. 0.0) GO TO 120
C
C IF (RLO .LT. 0.0) RLO = RLO + 360.0
C IF (RLO .EQ. 360.0) RLO = 0.0

```

```

C
C* DETERMINE NAME OF BIN TO HOLD RECORD
CALL NAMESQ(RLAT, RLO, BINAME, INDNAM)
C
C* DOES BIN EXIST. IF IT DOES IS IT OPEN OR CLOSED.
INQUIRE (FILE=BINAME, ERR=140, IOSTAT=J1, EXIST=LOGEX, OPENED=LOGOP)
C
IF (LOGEX .NEQV. OK) THEN
C
C* FILE DOES NOT EXIST
IF (RECORD .GT. 1) THEN
C* ANOTHER FILE IS ALREADY OPEN. WRITE SUMMARY HEADER RECORD
C* AND CLOSE OLD FILE AND INDEX. CALCULATE RMS OF TOP, FREE
C* AIR AND BOUGUER ANOMALIES AND TERRAIN CORRECTIONS.
IPOINT = IPOINT - 1
C
CALL RMSCAL(IPOINT, ATOP, STOP2, RMSTOP, RECORD)
CALL RMSCAL(IPOINT, AFREEA, SFREA2, RMSFRA, RECORD)
CALL RMSCAL(IPOINT, ABOUG, SBOUG2, RMSBOU, RECORD)
CALL RMSCAL(IPOINT, ATERRC, STERC2, RMSTER, RECORD)
C
1 WRITE (UNIT=3, REC=500, IOSTAT=J2, ERR=160) IPOINT, ALAT, ALON,
2 ATOP, AAGRV, AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2,
STERC2, RMSTOP, RMSFRA, RMSBOU, RMSTER
C
CLOSE (UNIT=3, ERR=180, IOSTAT=J3, STATUS='KEEP')
CLOSE (UNIT=4, STATUS='KEEP')
END IF
C
C* SET UP SUMMARY INFORMATION FOR NEW FILE.
IPOINT = 1
ALAT = RLAT
ALON = RLO
ATOP = RTOP
AAGRV = AGRV
AFREEA = RFREEA
ABOUG = RBOUG
ATERRC = RTERRC
C
STOP2 = ATOP * ATOP
SFREA2 = AFREEA * AFREEA
SBOUG2 = ABOUG * ABOUG
STERC2 = ATERRC * ATERRC
C
C* OPEN NEW BIN FOR DATA INPUT.
OPEN (UNIT=3, ERR=200, STATUS='NEW', FILE=BINAME, ACCESS='DIRECT',
1 FORM='UNFORMATTED', IOSTAT=J5, RECL=80)
1 OPEN (UNIT=4, STATUS='NEW', FILE=INDNAM, ACCESS='DIRECT', FORM=
'UNFORMATTED', RECL=20)
C
C* INITIATE NEW FILE WITH DATE
CALL TIME(5, 0, DATE)
WRITE (UNIT=3, REC=250) DATE
C
C* CALCULATE LINE NUMBER FOR RECORD WRITE.
ISYLO = INT(RLO*10.0)

```

```

ISYLO = INT(RLO*10.0)
LAT0 = INT(RLAT) * 10
LO0 = INT(RLO) * 10
CALL CODE(ISYLO, ISYLO, ICODE1)
CALL CODE(LO0, LAT0, ICODE0)
GROUPN = ICODE1 - ICODE0
LNUM = KOUNT(GROUPN)
C
1 WRITE (UNIT=3, REC=LNUM, IOSTAT=J4, ERR=220) RLAT, RLO, IEAST,
INORTH, RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
2 (ITC(1), I1=1, 10), VAR, CONT, IDENT1, IDENT2
C
C* WRITE OUT INDEX DATA
DO 50 N = 0, 99
ICODE = ICODE0 + N
LNUM1 = (N + 1) * 1000
IF (ICODE .EQ. ICODE1) THEN
1 WRITE (UNIT=4, REC=LNUM1) ICODE1, KOUNT(GROUPN),
KOUNT(GROUPN)
ELSE
WRITE (UNIT=4, REC=LNUM1) ICODE, IZERO, IZERO
END IF
50 CONTINUE
C
IPOINT = IPOINT + 1
RECORD = RECORD + 1
C
C* RETURN TO DATA READ
GO TO 30
ELSE IF (LOGOP .EQV. OK) THEN
C
C* FILE EXISTS AND IS OPEN. WRITE MORE DATA TO FILE.
CALL LINUM(RLAT, RLO, ICODE1, GROUPN, LNUM1, FSTREC, LSTREC,
1 RECORD)
IF (FSTREC .EQ. 0) THEN
FSTREC = KOUNT(GROUPN)
LSTREC = FSTREC
ELSE
LSTREC = LSTREC + 1
IF (LSTREC .GE. (KOUNT(GROUPN) + 99999)) THEN
60 WRITE (6, 60) ICODE1, RECORD
1 FORMAT (5X, 'LINE SPACE ALLOCATED FOR AREA ', I7, ' FULL', /
, 5X, 'RUN TERMINATED AT RECORD ', I8)
STOP
END IF
END IF
C
1 WRITE (UNIT=3, REC=LSTREC, IOSTAT=J4, ERR=220) RLAT, RLO, IEAST,
INORTH, RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
2 (ITC(1), I1=1, 10), VAR, CONT, IDENT1, IDENT2
C
C* UPDATE INDEX
WRITE (UNIT=4, REC=LNUM1) ICODE1, FSTREC, LSTREC
C
C* UPDATE FILE SUMMARY INFORMATION
CALL AVRAE(IPOINT, RLAT, ALAT)

```

```

CALL AVRAGE(IPOINT, RLON, ALON)
CALL AVRAGE(IPOINT, RTOP, ATOP)
CALL AVRAGE(IPOINT, AGRV, AAGRV)
CALL AVRAGE(IPOINT, RFREEA, AFREEA)
CALL AVRAGE(IPOINT, RBOUG, ABOUG)
CALL AVRAGE(IPOINT, RTERRC, ATERRC)

C
STOP2 = STOP2 + (RTOP*RTOP)
SFREA2 = SFREA2 + (RFREEA*RFREEA)
SBOUG2 = SBOUG2 + (RBOUG*RBOUG)
STERC2 = STERC2 + (RTERRC*RTERRC)

C
IPOINT = IPOINT + 1
RECORD = RECORD + 1

C*
RETURN TO READ.
GO TO 30
ELSE
C*
FILE EXISTS BUT IS CLOSED.
IF (RECORD .GT. 1) THEN
C*
WRITE SUMMARY TO OLD FILE.CLOSE OLD FILE.CALCULATE RMS
C*
VALUES FOR TOP.,FREE AIR AND BOUGUER ANOMALIES
C*
AND TERRAIN CORRECTION.
IPOINT = IPOINT - 1

C
CALL RMSCAL(IPOINT, ATOP, STOP2, RMSTOP, RECORD)
CALL RMSCAL(IPOINT, AFREEA, SFREA2, RMSFRA, RECORD)
CALL RMSCAL(IPOINT, ABOUG, SBOUG2, RMSBOU, RECORD)
CALL RMSCAL(IPOINT, ATERRC, STERC2, RMSTER, RECORD)

C
1 WRITE (UNIT=3,REC=500,IOSTAT=J2,ERR=160) IPOINT, ALAT, ALON,
2 ATOP, AAGRV, AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2,
STERC2, RMSTOP, RMSFRA, RMSBOU, RMSTER

C
CLOSE (UNIT=3,ERR=180,IOSTAT=J3,STATUS='KEEP')
CLOSE (UNIT=4,STATUS='KEEP')
END IF

C
C*
OPEN EXISTING DATA FILE AND INDEX.
OPEN (UNIT=3,ERR=200,STATUS='OLD',FILE=BINAME,ACCESS='DIRECT',
FORM='UNFORMATTED',IOSTAT=J5,RECL=80)
1 OPEN (UNIT=4,STATUS='OLD',FILE=INDNAM,ACCESS='DIRECT',FORM=
'UNFORMATTED',RECL=20)

C
C*
READ SUMMARY HEADER RECORD
READ (UNIT=3,REC=500,IOSTAT=J6,ERR=240) IPOINT, ALAT, ALON,
1 ATOP, AAGRV, AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2,
2 STERC2, RMSTOP, RMSFRA, RMSBOU, RMSTER

C
IPOINT = IPOINT + 1
CALL LINNUM(RLAT, RLON, ICODE1, GROUPN, LNUM1, FSTREC, LSTREC,
RECORD)
1 IF (FSTREC .EQ. 0) THEN
FSTREC = KOUNT(GROUPN)
LSTREC = FSTREC
ELSE

```

```

LSTREC = LSTREC + 1
IF (LSTREC .GE. (KOUNT(GROUPN) + 99999)) THEN
70 WRITE (6,70) ICODE1, RECORD
1 FORMAT (5X, 'SPACE ALLOCATED TO AREA ', 17, ' FULL ', /, 5X,
'RUN TERMINATED AT RECORD ', 18)
STOP
END IF
END IF

C
WRITE (UNIT=3,REC=LSTREC,IOSTAT=J4,ERR=220) RLAT, RLON, IEAST,
1 INORTH, RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
2 (ITC(1),I1=1,10), VAR, CONT, IDENT1, IDENT2

C
C*
UPDATE INDEX
WRITE (UNIT=4,REC=LNUM1) ICODE1, FSTREC, LSTREC

C
C*
UPDATE SUMMARY INFORMATION
CALL AVRAGE(IPOINT, RLAT, ALAT)
CALL AVRAGE(IPOINT, RLON, ALON)
CALL AVRAGE(IPOINT, RTOP, ATOP)
CALL AVRAGE(IPOINT, AGRV, AAGRV)
CALL AVRAGE(IPOINT, RFREEA, AFREEA)
CALL AVRAGE(IPOINT, RBOUG, ABOUG)
CALL AVRAGE(IPOINT, RTERRC, ATERRC)

C
STOP2 = STOP2 + (RTOP*RTOP)
SFREA2 = SFREA2 + (RFREEA*RFREEA)
SBOUG2 = SBOUG2 + (RBOUG*RBOUG)
STERC2 = STERC2 + (RTERRC*RTERRC)

C
IPOINT = IPOINT + 1
RECORD = RECORD + 1

C
C*
RETURN TO READ
GO TO 30
END IF

C
C*
CLOSE LAST FILE AND WRITE SUMMARY
80 IPOINT = IPOINT - 1

C
C
CALCULATE RMS VALUES
CALL RMSCAL(IPOINT, ATOP, STOP2, RMSTOP, RECORD)
CALL RMSCAL(IPOINT, AFREEA, SFREA2, RMSFRA, RECORD)
CALL RMSCAL(IPOINT, ABOUG, SBOUG2, RMSBOU, RECORD)
CALL RMSCAL(IPOINT, ATERRC, STERC2, RMSTER, RECORD)

C
WRITE (UNIT=3,REC=500,IOSTAT=J2,ERR=160) IPOINT, ALAT, ALON, ATOP,
1AAGRV, AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2, STERC2,
2RMSTOP, RMSFRA, RMSBOU, RMSTER

C
CLOSE (UNIT=3,ERR=180,IOSTAT=J3,STATUS='KEEP')
CLOSE (UNIT=4,STATUS='KEEP')

C
C*
DISPLAY NUMBER OF RECORDS PROCESSED
AND PROCESSING TIME
RECORD = RECORD - 1

```

```

      CALL TIME(1, 0, RES)
C
      WRITE (6,90) RECORD, RES
90  FORMAT (/, 5X, 'NUMBER OF RECORDS PROCESSED =', I8, /, 5X,
1    'CPU TIME REQUIRED      =', I8, ' MILLISECONDS', //)
C
C*   END PROGRAM IF NO ERRORS HAVE OCCURRED
      GO TO 260
C
C*   ERROR MESSAGES
100  WRITE (6,110) RECORD, RLO
110  FORMAT (1X, 'BAD INPUT LONGITUDE:RLO=', F8.4, 1X, 'RECORD=', I5)
      GO TO 260
120  WRITE (6,130) RLAT, RECORD
130  FORMAT (1X, 'BAD INPUT LATITUDE:RLAT=', F8.4, 1X, 'RECORD=', I5)
      GO TO 260
140  WRITE (6,150) BINAME, J1
150  FORMAT (1X, 'ERROR ON INQUIRE TO FILE ', A7, 1X, 'IOSTAT INT=',
1    I4)
      GO TO 260
160  WRITE (6,170) J2
170  FORMAT (1X, 'ERROR ON SUMMARY WRITE TO UNIT 3,IOSTAT INT=', I4)
      GO TO 260
180  WRITE (6,190) J3
190  FORMAT (1X, 'ERROR ON CLOSING UNIT 3,IOSTAT INT=', I4)
      GO TO 260
200  WRITE (6,210) BINAME, J5
210  FORMAT (1X, 'ERROR ON OPENING FILE ', A7, 1X, 'IOSTAT INT=', I4)
      GO TO 260
220  WRITE (6,230) J4
230  FORMAT (1X, 'ERROR ON DATA WRITE TO UNIT 3,IOSTAT INT=', I4)
      GO TO 260
240  WRITE (6,250) J6
250  FORMAT (1X, 'ERROR ON READ TO UNIT 3,IOSTAT INT=', I4)
C
260  STOP
      END

```

```

C**
C** Programme Fft.Filter
C** ~~~~~
C**
C** Programme Fft.Filter is designed to allow
C** the regular grid output of Grid.proj and
C** Binradii to be modified by a variety of
C** frequency domain filters.
C**
C** At present two filters are available
C** a gaussian low pass filter and an
C** upward continuation filter.
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + *Nag
C**
C** Author R.W.Woollett
C** Date 10 th June 1987
C**
C** Run Command
C** ~~~~~
C**
C** Run -load+*nag
C** ~~~~~
C** *****C
C
C* MAIN
C* DEFINE ARRAY SPACE AND MAIN VARIABLES
C* REAL*8 DATAR(50000), DATAI(50000), DWORK(1000)
C* REAL*4 RFREEA(50000), TOPO(50000), BOUG(50000)
C
C* INTEGER*4 ND(2)
C
C* DEFINE COMMON
C* COMMON /FAA/ RFREEA
C* COMMON /TOP/ TOPO
C* COMMON /BG/ BOUG
C* COMMON /RCOMP/ DATAR
C* COMMON /ICOMP/ DATAI
C* COMMON /AREA/ XMIN, XMAX, YMIN, YMAX, SAMP
C
C* DATA LWORK, NDIM, IFAIL /1000, 2, 0/
C
C* CLEAN ARRAY SPACE
C* DO 10 I = 1, 50000
C
C* RFREEA(I) = 0.0
C* TOPO(I) = 0.0
C* BOUG(I) = 0.0
C* DATAR(I) = 0.0
C* DATAI(I) = 0.0
C
C* 10 CONTINUE
C
C
C DO 20 I = 1, LWORK
C
C DWORK(I) = 0.0
C
C 20 CONTINUE
C
C* INPUT DATA GRIDS
C* CALL INPUT(NX, NY, NPTS)
C
C* CHOOSE DATA TYPE FOR MODIFICATION
C* 30 WRITE (6,40)
C* 40 FORMAT (/, 5X, 'Enter data type to be filtered', //, 5X,
C* 1 'Free Air Gravity = 1', //, 5X,
C* 2 'Topography = 2', //, 5X,
C* 3 'Bouguer Gravity = 3', //)
C
C READ (5,*) ITYPE
C IF (ITYPE .LT. 1 .OR. ITYPE .GT. 3) THEN
C WRITE (6,50)
C 50 FORMAT (/, 5X, 'Data type incorrectly specified', //)
C GO TO 30
C END IF
C
C* PREPARE DATA FOR FFT
C* IF (ITYPE .EQ. 1) THEN
C* DO 60 I = 1, NPTS
C* DATAR(I) = DBLE(RFREEA(I))
C* 60 CONTINUE
C* ELSE IF (ITYPE .EQ. 2) THEN
C* DO 70 I = 1, NPTS
C* DATAR(I) = DBLE(TOPO(I))
C* 70 CONTINUE
C* ELSE IF (ITYPE .EQ. 3) THEN
C* DO 80 I = 1, NPTS
C* DATAR(I) = DBLE(BOUG(I))
C* 80 CONTINUE
C* END IF
C
C* TAPER DATA IF DESIRED
C* WRITE (6,90)
C* 90 FORMAT (/, 5X, 'Do you wish to taper array', //, 5X, ' Yes=0 No=1',
C* 1 //)
C
C READ (5,*) ITEST
C IF (ITEST .EQ. 0) THEN
C WRITE (6,100)
C 100 FORMAT (/, 5X, 'Enter desired taper lengths LX and LY', //)
C READ (5,*) LX, LY
C
C CALL TAPER(DATAR, NX, NY, LX, LY)
C END IF
C
C* PAD DATA WITH ZEROES
C* CALL PAD(DATAR, DATAI, NX, NY, IXTOT, IYTOT)
C

```

```

C*   ENTER DESIRED MODIFICATION OPTION
      WRITE (6,110)
110  FORMAT (/, 5X, 'Enter desired modification option', /, 5X,
1      'Gaussian Low Pass Filter      =1', /, 5X,
2      'Upward Continuation          =2', /)
C
      READ (5,*) IMOD
C
C*   FOURIER TRANSFORM DATA ARRAY
      ND(1) = IXTOT
      ND(2) = IYTOT
      N = ND(1) * ND(2)
      CALL C06FJF(NDIM, ND, N, DATAR, DATAI, DWORK, LWORK, IFAIL)
C
C*   FILTER FREQUENCY DOMAIN DATA
      CALL FILTER(ND(1), ND(2), IMOD)
C
C*   INVERSE FOURIER TRANSFORM
      CALL C06GCF(DATAI, N, IFAIL)
      CALL C06FJF(NDIM, ND, N, DATAR, DATAI, DWORK, LWORK, IFAIL)
      CALL C06GCF(DATAI, N, IFAIL)
C
C*   RETURN DATA TO ORIGINAL ARRAY DE-PADDING DATA
      IXSTR = NX / 2 + 1
      IYSTR = NY / 2 + 1
C
      IF (ITYPE .EQ. 1) THEN
        DO 130 I = 1, NX
          DO 120 J = 1, NY
            IPOS = (J - 1) * NX + I
            IPOSNW = IXSTR + (I - 1) + IXTOT * ((IYSTR + J) - 2)
            RFREEA(IPOS) = SNGL(DATAR(IPOSNW))
120      CONTINUE
130      CONTINUE
      ELSE IF (ITYPE .EQ. 2) THEN
        DO 150 I = 1, NX
          DO 140 J = 1, NY
            IPOS = (J - 1) * NX + I
            IPOSNW = IXSTR + (I - 1) + IXTOT * ((IYSTR + J) - 2)
            TOPO(IPOS) = SNGL(DATAR(IPOSNW))
140      CONTINUE
150      CONTINUE
      ELSE IF (ITYPE .EQ. 3) THEN
        DO 170 I = 1, NX
          DO 160 J = 1, NY
            IPOS = (J - 1) * NX + I
            IPOSNW = IXSTR + (I - 1) + IXTOT * ((IYSTR + J) - 2)
            BOUG(IPOS) = SNGL(DATAR(IPOSNW))
160      CONTINUE
170      CONTINUE
      END IF
C
C*   OUTPUT DATA GRIDS
      CALL OUTPUT(NX, NY, NPTS)
C
      STOP

```

END

```

C**
C**  Programme Grid.dump
C**  ~~~~~
C**
C**  Programme Grid.dump outputs the unformatted data
C**  grid files created by Grid.proj and Binradii in
C**  a simple formatted sequential dump.
C**
C**  Programme Details
C**  ~~~~~
C**
C**  OS MTS
C**  Language Fortran 77
C**
C**  Author R.W.Woollett
C**  Date 2 nd October 1987
C**
C**  Run Command
C**  ~~~~~
C**
C**  Run -load
C**  ~~~~~
C**
C**  ~~~~~
C**
C**  MAIN
C**  CHARACTER INFILE*7, OTFILE*7, FILE*7
C
C**  REAL FGRID(256,256), TGRID(256,256), BGRID(256,256), NGRID
C
C**  INTEGER IFFLAG, ITFLAG, IBFLAG
C
C**  WRITE (6,10)
10 FORMAT ('&', 4X, 'ENTER NAME OF INPUT FILE ')
C**  READ (5,20) INFILE
20 FORMAT (A7)
C**  WRITE (6,30)
30 FORMAT ('&', 4X, 'ENTER NAME OF OUTPUT FILE ')
C**  READ (5,40) OTFILE
40 FORMAT (A7)
C
C**  OPEN FILES
C**  OPEN (UNIT=3, FILE=INFILE, STATUS='OLD', ACCESS='SEQUENTIAL', FORM=
1 'UNFORMATTED')
C**  OPEN (UNIT=4, FILE=OTFILE, STATUS='NEW', ACCESS='SEQUENTIAL', FORM=
1 'FORMATTED')
C
C**  READ HEADER DATA ON INPUT FILE
C**  READ (UNIT=3) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
C
C**  X RANGE = XMAX - XMIN
C**  Y RANGE = YMAX - YMIN
C
C**  WRITE (6,50) FILE, XMIN, XMAX, YMIN, YMAX, X RANGE, Y RANGE, SAMP,
1 NX, NY
50 FORMAT (//, 5X, 'INPUT FILE:', A7, //, 5X, 'MINIMUM X VALUE
1= ', F10.1, ' METRES', //, 5X, 'MAXIMUM X VALUE = ', F10.1,

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```

2 ' METRES', //, 5X, 'MINIMUM Y VALUE = ', F10.1,
3 ' METRES', //, 5X, 'MAXIMUM Y VALUE = ', F10.1,
4 ' METRES', //, 5X, 'TOTAL X RANGE = ', F10.1,
5 ' METRES', //, 5X, 'TOTAL Y RANGE = ', F10.1,
6 ' METRES', //, 5X, 'SAMPLING INTERVAL = ', F8.1,
7 ' METRES', //, 5X, 'ARRAY DIMENSIONS', //, 5X, 'NX = ', I4,
8 2X, 'NY = ', I4, //)
C
C**  ENTER DATA FIELD TO BE OUTPUT
C**  WRITE (6,60)
60 FORMAT (//, 5X, 'ENTER DATA FIELD REQUIRED', //, 5X,
1 'FREE AIR GRAVITY = 1', //, 5X,
2 'TOPOGRAPHY = 2', //, 5X,
3 'BOUGUER GRAVITY = 3', //)
C
C**  READ (5,*) ITYPE
C
C**  READ IN / WRITE OUT DATA
C**  DO 90 I = 1, NX
C**  DO 80 J = 1, NY
C
C**  READ (UNIT=3) X, Y, FGRID(I,J), TGRID(I,J), BGRID(I,J), NGRID,
1 IFFLAG, ITFLAG, IBFLAG
C
C**  IF (ITYPE .EQ. 1) THEN
C**  WRITE (4,70) Y, X, FGRID(I,J)
C**  ELSE IF (ITYPE .EQ. 2) THEN
C**  WRITE (4,70) Y, X, TGRID(I,J)
C**  ELSE IF (ITYPE .EQ. 3) THEN
C**  WRITE (4,70) Y, X, BGRID(I,J)
C**  END IF
C
C**  70 FORMAT (5X, F10.1, 2X, F10.1, 2X, F7.2)
C
C**  80 CONTINUE
C**  90 CONTINUE
C
C**  CLOSE (UNIT=3, STATUS='KEEP')
C**  CLOSE (UNIT=4, STATUS='KEEP')
C
C**  STOP
C**  END

```

```

C**
C** Programme Grid.proj
C** ~~~~~
C**
C** Programme Grid.proj is designed to
C** generate a regular data grid from the
C** database data files using one of a number
C** of geographical projections.
C**
C** At present three projections are available
C** for gridding:
C**
C** 1) Ordnance survey transverse mercator;
C** 2) Lambert conformal projection;
C** 3) Irish national grid.
C**
C** In all cases the programme asks for a grid
C** area, retrieves the data from this area,
C** transforms the data to grid coordinates
C** in the desired system and then grids the
C** data. If the subroutine FEED is used with
C** either national grid system the extra data
C** must be of the same grid type as the main
C** grid being generated.
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + MTS Subroutines
C**
C** Author R.W. Woollett
C** Date 6/01/88 (Modified for Irish grid)
C**
C** Run Command
C** ~~~~~
C**
C** Option 1 OS Projection
C**
C** Run -Load 7 = Output
C**
C** Option 2 Lambert Conformal Projection
C**
C** Run -Load 2 = Lamcon.dat 7 = Output
C**
C** Input on unit 2
C**
C** Line 1 OLAT,OLON,SLAT1,SLAT2,CSFACT
C** Line 2 EQRAD,ECC
C**
C** OLAT = Latitude of origin of projection
C** OLON = Longitude of origin of projection
C** SLAT1 = Latitude of standard parallel 1
C** SLAT2 = Latitude of standard parallel 2
C** CSFACT = Central scale factor (1.0)
C** EQRAD = Equatorial radius of spheroid (m)

```

```

C** ECC = Eccentricity of spheroid
C**
C** Nota bene OLON should bisect longitudinal
C** range of WLOK, ELON for XLEFT = XRIGHT
C**
C** Option 3 Irish grid projection
C**
C** Run Command
C** ~~~~~
C**
C** Run -load 7= Output file
C**
C** ~~~~~**C
C
C* MAIN ROUTINE
C* IMPLICIT DOUBLE PRECISION(A - H,O - Z)
C* DOUBLE PRECISION NLAT
C* REAL RWLOK, RELON, RSLAT, RNLAT, FGRID(256,256), TGRID(256,256),
C* 1 BGRID(256,256), NGRID(256,256), RXMIN, RXMAX, RYMIN, RYMAX,
C* 2 RSAMP, RPCNT
C* INTEGER IFFLAG(256,256), ITFLAG(256,256), IBFLAG(256,256)
C* CHARACTER OFILE*7
C
C* ASSIGN DATA TO COMMON BLOCKS
C* COMMON /GRIDS/ FGRID, TGRID, BGRID, NGRID
C* COMMON /FLAGS/ IFFLAG, ITFLAG, IBFLAG
C* COMMON /GRDDAT/ RXMIN, RXMAX, RYMIN, RYMAX, RSAMP, IPROJ
C
C* SET UP COMMON FOR LAMBERT PROJECTION
C* COMMON /MAPC01/ OLAT, OLON, SLAT1, SLAT2, CSFACT
C* COMMON /MAPC02/ CLAT1, CLON1, CLAT2, CLON2, AZIM
C* COMMON /SPHCON/ EQRAD, ECC
C
C* DATA IHOLE, ITOTAL /0, 0/
C
C* ZERO DATA ARRAYS
C* DO 20 I = 1, 256
C* DO 10 J = 1, 256
C
C* FGRID(I,J) = 0.0
C* TGRID(I,J) = 0.0
C* BGRID(I,J) = 0.0
C* NGRID(I,J) = 0.0
C
C* IFFLAG(I,J) = 0
C* ITFLAG(I,J) = 0
C* IBFLAG(I,J) = 0
C
C 10 CONTINUE
C 20 CONTINUE
C
C* ASK USER TO ENTER PROJECTION TYPE AND SET UP ROUTINE
C* FOR DATA SEARCH AND GRIDDING.
C* CALL SETUP(WLOK, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX, SAMP,
C* 1 IPROJ)

```



```

C
C* CALL CONVRT TO DETERMINE SEARCH PARAMETERS ETC.
C* TO SINGLE PRECISION.
C* CALL CONVRT(WLON, ELON, SLAT, NLAT, RWLON, RELON, RSLAT, RNLAT,
1 XMIN, XMAX, YMIN, YMAX, SAMP)
C
C* RETRIEVE AND GRID DATA
C* CALL DATART(RWLON, RELON, RSLAT, RNLAT)
C* CALL DATAVG(IHOLE, ITOTAL, NX, NY)
C
C* ENTER ADDITIONAL DATA SETS
C* WRITE (6,30)
30 FORMAT (/, 5X, 'DO YOU WISH TO ENTER ANY EXTRA', /, '&', 4X,
1 'DATA SETS ? YES(1) NO(0)')
C
C* READ (5,*) IEXTRA
C* IF (IEXTRA .EQ. 1) THEN
C
C* CALL FEED
C
C* END IF
C
C* DETERMINE QUALITY OF GRID
C* RPCNT = (REAL(IHOLE)/REAL(ITOTAL)) * 100.0
C* WRITE (6,40) ITOTAL, IHOLE, RPCNT
40 FORMAT (/, 5X, 'NUMBER OF GRID POINTS = ', I8, /, 5X,
1 'NUMBER OF GRID HOLES = ', I8, /, 5X,
2 'PERCENTAGE OF HOLES = ', F5.1, /)
C
C* OUTPUT DATA GRID
C* WRITE (6,50)
50 FORMAT (/, 5X, 'ENTER NAME OF OUTPUT FILE', /)
C* READ (5,60) OFILE
60 FORMAT (A7)
C
C* OPEN (UNIT=8, FILE=OFILE, STATUS='NEW', ACCESS='SEQUENTIAL', FORM=
1 'UNFORMATTED')
C
C* WRITE (UNIT=8) OFILE, RXMIN, RXMAX, RYMIN, RYMAX, RSAMP, NX, NY
C
C* CALL DDUMP(NX, NY)
C
C* CLOSE (UNIT=8, STATUS='KEEP')
C
C* STOP
C* END

```

```

C**
C**  Programme Ibinwrite
C**  ~~~~~
C**
C**  Programme Ibinwrite is designed to list an unformatted
C**  index file whose name is entered using the subroutine
C**  SCRND in a formatted form.
C**
C**  Programme Details
C**  ~~~~~
C**
C**  OS MTS
C**  Language Fortran 77
C**
C**  Author R.W.Woollett 1986
C**
C**  Run Command
C**  ~~~~~
C**
C**  Run -load 6 = Output file
C**
C** ~~~~~C
C
C*
C*  MAIN
C*  CHARACTER INDNAM*7
C*  INTEGER FSTREC
C
C*  INPUT FILE TO BE WRITTEN
C*  CALL SCRND(INDNAM)
C
C*  WRITE HEADER INFORMATION TO OUTPUT FILE
C*  WRITE (6,10) INDNAM
10  FORMAT (10X, 'FILE:', A7)
C*  WRITE (6,20)
20  FORMAT (10X, '~~~~~'//)
C*  WRITE (6,30)
30  FORMAT (5X, 'BOX CODE', 7X, 'FIRST RECORD', 7X, 'LAST RECORD')
C*  WRITE (6,40)
40  FORMAT (5X, '~~~~~', 7X, '~~~~~', 7X, '~~~~~'//)
C
C*  OPEN (UNIT=3,STATUS='OLD',FILE=INDNAM,ACCESS='SEQUENTIAL',FORM=
1  'UNFORMATTED',IOSTAT=J1)
C
C*  IF (J1.NE.0) THEN
C*    WRITE (6,50) INDNAM, J1
50  FORMAT (1X, 'ERROR OPENING FILE ', A7, ' IOSTAT=', I4)
C*    WRITE (6,60)
60  FORMAT (1X, 'RUN TERMINATED')
C*    GO TO 100
C*  END IF
C
C*  READ/WRITE DATA
C*  READ (UNIT=3,END=90) ICODE1, FSTREC, LSTREC
70  WRITE (6,80) ICODE1, FSTREC, LSTREC
80  FORMAT (6X, I7, 9X, I10, 8X, I10)
C*  GO TO 70

```

```

C
90 CLOSE (UNIT=3,STATUS='KEEP')
100 STOP
END

```

```

C**
C**
C** Programme Image.proj
C** ~~~~~
C**
C** Programme Image.proj is designed to create and
C** enhance computer images from the gridded data files
C** produced by Grid.proj and Binradii. A coastline of the
C** British Isles may be superimposed on the images using
C** the OS, Lambert conformal and Irish grid projections.
C**
C** The gridded data files may be enhanced by several
C** digital image processing techniques:
C**
C** Grey scale modification
C** 1) Linear interpolation
C** 2) Clipped linear scale
C** 3) Power scale
C** Image sharpening
C** 4) Digital laplacian
C** 5) Image differentiation
C** Image smoothing
C** 6) Neighbourhood averaging
C** Artificial effects
C** 7) Artificial illumination of digital terrain model
C**
C** Histogram modification is available on the
C** I2S system and is, therefore, not included.
C**
C** The programme structure is similar to G.D.Karner's
C** BINIMAGE. However, The imaging algorithm's are taken
C** from 'Digital image processing' by Gonzalez
C** and Wintz (1977) except for the digital Laplacian
C** which is taken from 'Digital picture processing' by
C** Rosenfeld and Kak (1976) and the artificial illumination
C** algorithm which came from Horn and Bachman (1978).
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77
C**
C** Author R.W.Woollett
C** Date 1986 Modified Jan. 1988
C**
C** Run Command
C** ~~~~~
C**
C** General: Run -Load
C**
C** Lambert conformal projection option
C**
C** Run -Load 2 = Lamdat
C**

```

```

C** Input on unit 2
C**
C** Line 1 OLAT, OLON, SLAT1, SLAT2, CSFACT
C** Line 2 EQRAD, ECC
C**
C** OLAT = Latitude of origin of projection
C** OLON = Longitude of origin of projection
C** SLAT1 = Latitude of standard parallel 1
C** SLAT2 = Latitude of standard parallel 2
C** CSFACT = Central scale factor (1.0)
C** EQRAD = Equatorial radius of spheroid (M)
C** ECC = Eccentricity of spheroid
C** ~~~~~**C
C
C* MAIN
C* DIMENSION DATA(202500)
C
C* REAL*8 OLAT, OLON, SLAT1, SLAT2, CSFACT, CLAT1, CLON1, CLAT2,
1 CLON2, AZIM, EQRAD, ECC
C
C* CHARACTER INFILE*7, FILE*7, OTFILE*7
C* INTEGER BAD
C
C* COMMON /MAPCO1/ OLAT, OLON, SLAT1, SLAT2, CSFACT
C* COMMON /MAPCO2/ CLAT1, CLON1, CLAT2, CLON2, AZIM
C* COMMON /SPHCON/ EQRAD, ECC
C
C* BAD = 0
C* NPOINT = 0
C* WRITE (6,10)
10 FORMAT (5X, 'ENTER NAME OF GRIDDED DATA FILE', /)
C* READ (5,20) INFILE
20 FORMAT (A7)
C* OPEN (UNIT=3, FILE=INFILE, STATUS='OLD', ACCESS='SEQUENTIAL', FORM=
1 'UNFORMATTED')
C* WRITE (6,30)
30 FORMAT (5X, 'ENTER NAME OF OUTPUT FILE ', /)
C* READ (5,40) OTFILE
40 FORMAT (A7)
C* OPEN (UNIT=4, STATUS='NEW', FILE=OTFILE, ACCESS='SEQUENTIAL', FORM=
1 'FORMATTED')
C
C* READ FILE HEADER RECORD DATA AND DISPLAY
C* READ (UNIT=3) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
C* WRITE (6,50) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
50 FORMAT (/, 5X, 'GRID FILE:', A7, //, 5X, 'MINIMUM X VALUE
1 =', F10.1, ' METRES', /, 5X, 'MAXIMUM X VALUE', F10.1,
2 ' METRES', /, 5X, 'MINIMUM Y VALUE', F10.1,
3 ' METRES', /, 5X, 'MAXIMUM Y VALUE', F10.1,
4 ' METRES', /, 5X, 'SAMPLING INTERVAL', F8.1,
5 ' METRES', /, 5X,
6 'ARRAY DIMENSIONS', ' ', /, /, 5X,
7 'NX = ', I4, ' NY = ', I4, //)
C
C* IF (NX*NY .GT. 202500) THEN

```

```

        WRITE (6,60)
60    FORMAT (5X, 'INSUFFICIENT ARRAY SPACE (>202500 POINTS)', /)
        STOP
        END IF
C
        WRITE (6,70)
70    FORMAT (5X, 'DATA TYPE TO BE DISPLAYED ', //, 5X,
1      'FREE AIR GRAVITY      =1', //, 5X,
2      'TOPOGRAPHY           =2', //, 5X,
3      'BOUGUER GRAVITY       =3', //, 5X,
4      'FREE AIR GRAVITY(SEA)/ =4', //, 5X,
5      'BOUGUER GRAVITY(LAND) =4', //, 5X,
6      'COASTLINE+MARKER GRID =5', //)
C
        READ (5,*) ITYPE
        IF (ITYPE.NE. 5) THEN
C
C*      READ IN GRIDDED DATA
        DO 90 I = 1, NX
            DO 80 J = 1, NY
C
                READ (UNIT=3) X, Y, FGRID, TGRID, BGRID, NGRID, IFFLAG,
1              ITFLAG, IBFLAG
C
                NPOINT = NPOINT + 1
                IF (ITYPE.EQ. 1) THEN
                    IF (IFFLAG.NE. 0) THEN
                        VALUE = FGRID
                    ELSE
                        VALUE = 32767.0
                        BAD = BAD + 1
                    END IF
                ELSE IF (ITYPE.EQ. 2) THEN
                    IF (ITFLAG.NE. 0) THEN
                        VALUE = TGRID
                    ELSE
                        VALUE = 32767.0
                        BAD = BAD + 1
                    END IF
                ELSE IF (ITYPE.EQ. 3) THEN
                    IF (IBFLAG.NE. 0) THEN
                        VALUE = BGRID
                    ELSE
                        VALUE = 32767.0
                        BAD = BAD + 1
                    END IF
                ELSE IF (ITYPE.EQ. 4) THEN
                    IF (TGRID.LT. 0.0) THEN
                        IF (IFFLAG.NE. 0) THEN
                            VALUE = FGRID
                        ELSE
                            VALUE = 32767.0
                            BAD = BAD + 1
                        END IF
                    ELSE IF (TGRID.GE. 0.0) THEN
                        IF (IBFLAG.NE. 0) THEN
                            VALUE = BGRID
                        ELSE
                            VALUE = 32767.0
                            BAD = BAD + 1
                        END IF
                    END IF
                ELSE IF (TGRID.GE. 0.0) THEN
                    IF (IBFLAG.NE. 0) THEN
                        VALUE = BGRID
                    ELSE
                        VALUE = 32767.0
                        BAD = BAD + 1
                    END IF
                END IF
            END DO
        END DO

```

```

        VALUE = BGRID
        ELSE
            VALUE = 32767.0
            BAD = BAD + 1
        END IF
    END IF
END IF
C
        DATA((J - 1)*NX + 1) = VALUE
C
80    CONTINUE
90    CONTINUE
C
        CLOSE (UNIT=3,STATUS='KEEP')
        NGOOD = NPOINT - BAD
        WRITE (6,100) NPOINT, NGOOD, BAD
100    FORMAT (5X, 'TOTAL NUMBER OF SAMPLED POINTS =', 18, //, 5X,
1      'TOTAL NUMBER OF GOOD POINTS   =', 18, //, 5X,
2      'TOTAL NUMBER OF BAD POINTS    =', 18, //)
C
C*      ENTER IMAGE OPTION
        WRITE (6,110)
110    FORMAT (5X, 'ENTER DATA ENHANCEMENT METHOD: ', //, 5X,
1      'GREY SCALE MODIFICATION      =1', //, 5X,
2      'LINEAR GREY SCALE              =2', //, 5X,
3      'CLIPPED LINEAR SCALE           =3', //, 5X,
4      'POWER SCALE GREY LEVEL         =4', //, 5X,
5      'IMAGE SHARPENING               =5', //, 5X,
6      'LAPLACIAN REMOVAL              =6', //, 5X,
7      'IMAGE DERIVATION               =7', //, 5X,
8      'IMAGE SMOOTHING                =8', //, 5X,
9      'NEIGHBOURHOOD AVERAGING        =9', //, 5X,
*      'ADDITIONAL TECHNIQUES          =10', //, 5X,
1     'ARTIFICIAL ILLUMINATION         =11', //)
C
        READ (5,*) IHANCE
C
C*      CALL ENHANCEMENT ROUTINE
        CALL IMAGE(DATA, NX, NY, IHANCE, SAMP)
        WRITE (6,120) IHANCE
120    FORMAT (/, 5X, 'CONVERTING IMAGE OPTION ', 12, ' TO BYTE MATRIX'
1      , //)
C
        CALL CONVRT(DATA, NX, NY, IHANCE)
C
        ELSE IF (ITYPE.EQ. 5) THEN
C
C*      PLOT COASTLINE+MARKER GRID
        CLOSE (UNIT=3,STATUS='KEEP')
        WRITE (6,130)
130    FORMAT (/, 5X, 'DO YOU WISH TO ENTER NEW ARRAY DIMENSIONS ', /,
1      5X, ' YES (0) NO (1)', //)
        READ (5,*) ITEST
        IF (ITEST.EQ. 0) THEN
            WRITE (6,140)
140    FORMAT (5X, 'ENTER X,Y ARRAY DIMENSIONS', /)

```

```
      READ (5,*) NX, NY  
      END IF  
      CALL CSTPIX(DATA, NX, NY, XMIN, XMAX, YMIN, YMAX, INDIC, SAMP)  
      CALL CONVRT(DATA, NX, NY, INDIC)  
      END IF  
      STOP  
      END
```

C


```

C      CALL PROJECT(RLAT1, RLO1, SWAZ, HWIDTH, CRNLAT(1), CRNLON(1))
C      CALL PROJECT(RLAT1, RLO1, NWAZ, HWIDTH, CRNLAT(2), CRNLON(2))
C      CALL PROJECT(RLAT2, RLO2, NEAZ, HWIDTH, CRNLAT(3), CRNLON(3))
C      CALL PROJECT(RLAT2, RLO2, SEAZ, HWIDTH, CRNLAT(4), CRNLON(4))

C*     CALCULATE POSITION OF POLE FOR OBLIQUE PROJECTION
RADLN1 = RLO1 / RAD
RADLT1 = RLAT1 / RAD
RADLN2 = RLO2 / RAD
RADLT2 = RLAT2 / RAD
CALL POLDET(RADLN1, RADLT1, RADLN2, RADLT2, PIE, RADPLN, RADPLT)
LAMDA0 = RADPLN + PIE / 2D0

C
C*     CONVERT ENDS OF PROFILE TO OBLIQUE PROJECTION
C*     UV SPACE
CALL UVCALC(RADLN1, RADLT1, RADPLT, LAMDA0, UW, VW)
CALL UVCALC(RADLN2, RADLT2, RADPLT, LAMDA0, UE, VE)
WRITE (8,70) UW, UE, VW, VE
70 FORMAT (/ , 5X, 'PROFILE DATA' , / , 5X,
1      'U SPACE (ALONG PROFILE)' , / , 5X, 'U WEST=' , F10.4,
2      2X, 'U EAST=' , F10.4, / , 5X, 'V SPACE (PERP. TO PROFILE)' ,
3      / , 5X, 'V WEST=' , F10.4, 2X, 'V EAST=' , F10.4, /)

C
C*     RETRIEVE DATA FOR GEODESIC/WINDOW REGION
IF (DABS(RLO1 - RLO2) .LT. 0.2D0 .OR. (RLAT1 .EQ. 0.0 .AND.
1      RLAT2 .EQ. 0.0)) THEN

C
C*     RETRIEVE DATA FROM RECTANGLE
MAXLAT = CRNLAT(1)
MINLAT = CRNLAT(1)
MAXLON = CRNLON(1)
MINLON = CRNLON(1)

C
DO 80 K = 1, 4
IF (CRNLAT(K) .GT. MAXLAT) THEN
MAXLAT = CRNLAT(K)
END IF
IF (CRNLAT(K) .LT. MINLAT) THEN
MINLAT = CRNLAT(K)
END IF
IF (CRNLON(K) .GT. MAXLON) THEN
MAXLON = CRNLON(K)
END IF
IF (CRNLON(K) .LT. MINLON) THEN
MINLON = CRNLON(K)
END IF
80 CONTINUE

C
CALL CRECET(MINLON, MAXLON, MINLAT, MAXLAT, HWIDTH, U, DATA,
1      RADPLT, LAMDA0, UE, UW, KOUNT1, KOUNT2)

C
ELSE

C
C*     ANGLED GEODESIC BEGIN COMPLEX DATA RETRIEVAL
IF (CRNLON(1) .GT. CRNLON(2)) THEN

LIMITW = CRNLON(1)
ELSE
LIMITW = CRNLON(2)
END IF
IF (CRNLON(3) .LT. CRNLON(4)) THEN
LIMITE = CRNLON(3)
ELSE
LIMITE = CRNLON(4)
END IF

C
C*     RE EVALUATE LIMITS TO NEAREST 0.05 DEGREES (INWARDS)
LIMITW = DBLE(REAL(INT(LIMITW*10.0D0))/10.0) + 0.05D0
LIMITE = DBLE(REAL(INT(LIMITE*10.0D0))/10.0) - 0.05D0
IF (LIMITE .LT. LIMITW) LIMITE = LIMITW

C
C*     TRACE GEODESICS BETWEEN LIMIT WEST AND LIMIT EAST
CALL GDSTRC(CRNLAT(2), CRNLON(2), CRNLAT(3), CRNLON(3), LIMITW,
1      LIMITE, GLATN, GLONN, NUMN)
CALL GDSTRC(RLAT1, RLO1, RLAT2, RLO2, LIMITW, LIMITE, GLATM,
1      GLONM, NUMM)
CALL GDSTRC(CRNLAT(1), CRNLON(1), CRNLAT(4), CRNLON(4), LIMITW,
1      LIMITE, GLATS, GLONS, NUMS)

C
C*     EXPAND STRIPS TO ACCOUNT FOR ANGLE OF GEODESIC
DO 90 K = 1, NUMN
CALL EXPAND(GLATN(K), GLATM(K), GLATS(K), HWIDTH)
90 CONTINUE

C
C*     RETRIEVE DATA FOR N-S STRIPS CROSSING GEODESIC
DO 100 K = 1, NUMN
CALL STPRET(GLONM(K), GLATS(K), GLATN(K), HWIDTH, U, DATA,
1      RADPLT, LAMDA0, UE, UW, KOUNT1, KOUNT2)
100 CONTINUE

C
C*     RETRIEVE DATA AROUND END SECTIONS OF GEODESIC NOT
INCLUDED IN STRIP RETRIEVAL
CALL ENDRET(CRNLAT, CRNLON, GLATN(1), GLATS(1), GLONM(1),
1      GLATN(NUMN), GLATS(NUMN), GLONM(NUMN), HWIDTH, U, DATA,
2      RADPLT, LAMDA0, UE, UW, KOUNT1, KOUNT2)

C
END IF

C
WRITE (6,110) KOUNT2, KOUNT1
110 FORMAT (/ , 5X, 'DATA POINT STATISTICS' , / , 5X,
1      'TOTAL POINTS SAMPLED=' , I5, / , 5X, 'POINTS IN PROFILE' =',
2      I5, /)

C
CLOSE (UNIT=8, STATUS='KEEP')

C
C*     AFTER RETRIEIVING DATA AND CONVERTING TO U,V SPACE
C*     BEGIN PLOTTING PROFILES.
WRITE (6,120)
120 FORMAT (/ , 5X, 'ENTER DESIRED DATA FIELD(S)' , / , 5X,
1      'FOR PROFILE(S)' , / , 5X,
2      'FREE AIR GRAVITY' (1) , / , 5X,
3      'TOPOGRAPHY' (2) , / , 5X,

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      4      'BOUQUER GRAVITY      (3)  ', /, 5X,
      5      'MULTIPLY OF ALL 3 FIELDS      (4)  ', /)

C
      READ (5,*) ITEST0
      WRITE (6,130) ITEST0
130  FORMAT (/, 5X, 'PLOTING OF OPTION ', 12, ' BEGINS      ', /)

C
C*  INITIALISE GINO-F GRAPHICS PACKAGE
      CALL GINO
      CALL PLTSYS
      CALL UNITS(25,4)
      CALL DEVPA(30.0, 30.0, 0)
      CALL MOVTO2(0.0, 0.0)
      CALL CHASIZ(.15, .2)

C
      WRITE (6,140)
140  FORMAT (/, 5X, 'ENTER MAIN TITLE OF PROFILE      ', /)
      READ (5,150) ITITLE
150  FORMAT (40A1)
      IF (ITEST0 .NE. 4) THEN
         CALL MOVTO2(1.0, 8.0)
      ELSE
         CALL MOVTO2(1.0, 9.0)
      END IF
      CALL CHAA1(ITITLE, 40)

C
C*  ENTER OPTIONAL PROFILE LENGTH
      WRITE (6,160)
160  FORMAT (/, 5X, 'ENTER DESIRED LENGTH OF PROFILE ', /, 5X,
1      ' UNITS=INCHES MAX. LENGTH=30.0 ', /)
      READ (5,*) XEXT

C
      IF (ITEST0 .NE. 4) THEN
         WRITE (6,170)
170  FORMAT (/, 5X, 'ENTER DESIRED HEIGHT OF PROFILE', /, 5X,
1      ' UNITS=INCHES MAX. HEIGHT=5.0 ', /)
         READ (5,*) YEXT
         CALL GRF(1.5, 2.0, XEXT, YEXT, ITEST0, U, DATA, UE, UW, RLAT1,
1      RLON1, RLAT2, RLON2, WAZ, EAZ, KOUNT1, 0)
      ELSE
         CALL GRF(1.5, 1.10, XEXT, 1.50, 3, U, DATA, UE, UW, RLAT1,
1      RLON1, RLAT2, RLON2, WAZ, EAZ, KOUNT1, 0)
         CALL GRF(0.0, 2.55, XEXT, 1.50, 2, U, DATA, UE, UW, RLAT1,
1      RLON1, RLAT2, RLON2, WAZ, EAZ, KOUNT1, 1)
         CALL GRF(0.0, 2.55, XEXT, 1.50, 1, U, DATA, UE, UW, RLAT1,
1      RLON1, RLAT2, RLON2, WAZ, EAZ, KOUNT1, 1)
      END IF

C
      CALL GINEND

C
      STOP
      END

```



```

C**
C** Programme Line.del
C** ~~~~~
C**
C** Programme Line.del is designed to allow a user to delete
C** a line within a data file. The deletion is complex because of
C** the following requirements:
C**
C** 1) the update of the index file;
C** 2) the update of the data file header record;
C** 3) the complex data file structure.
C**
C** Lines are deleted by overwriting records of length zero.
C** After deletion lines within data record subregion line
C** ranges may require renumbering.
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + MTS subroutines
C**
C** Author R.W.Woollett
C** Date March 1986
C**
C** Run Command
C** ~~~~~
C**
C** Run -load
C** ~~~~~
C** .....C
C
C MAIN
C CHARACTER BNAME*7, INDNAM*7
C CHARACTER IDENT1*4, IDENT2*4, TCODE*1
C CHARACTER VAR*4, CONT*4, ITC(10)*1
C
C INTEGER*4 FSTREC, UNT, REG(2), GROUPN
C INTEGER*2 LEN
C
C DATA UNT, INCR, REG /3, 1, 1, 2/
C DATA LEN /0/
C
C WRITE (6,10)
10 FORMAT (/ , 5X, 'ENTER NAME OF FILE CONTAINING LINE ', / , 5X,
1 'TO BE DELETED ', /)
C READ (5,20) BNAME
20 FORMAT (A7)
C CALL NAME2(BNAME, INDNAM)
C
C OPEN (UNIT=3, STATUS='OLD', FILE=BNAME, ACCESS='DIRECT', FORM=
1 'UNFORMATTED', RECL=80, IOSTAT=J1)
C IF (J1 .NE. 0) THEN
C WRITE (6,30) J1
30 FORMAT (5X, 'ERROR ON OPENING DATAFILE:IOSTAT=', I4, / , 5X,
1 'PROGRAM TERMINATES ', /)
C
C STOP
C END IF
C
C OPEN (UNIT=4, STATUS='OLD', FILE=INDNAM, ACCESS='DIRECT', FORM=
1 'UNFORMATTED', RECL=20, IOSTAT=J2)
C IF (J2 .NE. 0) THEN
C WRITE (6,40) J2
40 FORMAT (5X, 'ERROR OPENING INDEX FILE:IOSTAT=', I4, / , 5X,
1 'PROGRAM TERMINATES ', /)
C
C STOP
C END IF
C
C WRITE (6,50)
50 FORMAT (5X, 'ENTER INTERNAL LINE NUMBER OF LINE TO ', / , 5X,
1 'BE DELETED (EG.LINE NUMBER*1000) ', /)
C READ (5,*) LNUM
C
C READ (UNIT=3, REC=LNUM) RLAT, RLON, IEAST, INORTH, RTOP, AGRV,
1 RFREEA, RBOUG, RTERRC, RDENSE, TCODE, (ITC(II), II=1,10), VAR,
2 CONT, IDENT1, IDENT2
C WRITE (6,60) LNUM
60 FORMAT (/ , 5X, 'LINE ', I11, /)
C WRITE (6,70) RLAT, RLON, IEAST, INORTH, RTOP, AGRV, RFREEA, RBOUG,
1 RTERRC, RDENSE, TCODE, (ITC(II), II=1,10), VAR, CONT, IDENT1,
2 IDENT2
70 FORMAT (2X, F7.4, 1X, F8.4, 17, 17, F9.2, 1X, F8.1, 1X, F7.2, 1X,
1 F7.2, 1X, F6.2, 1X, F7.1, A1, 1X, 10A1, 4A4)
C
C READ APPROPRIATE INDEX RECORD
C ISYLAT = INT(RLAT*10.0)
C ISYLON = INT(RLON*10.0)
C LAT0 = INT(RLAT) * 10
C LON0 = INT(RLON) * 10
C CALL CODE(ISYLON, ISYLAT, ICODE1)
C CALL CODE(LON0, LAT0, ICODE0)
C GROUPN = ICODE1 - ICODE0
C LNUMI = (GROUPN + 1) * 1000
C
C READ (UNIT=4, REC=LNUMI) ICODE, FSTREC, LSTREC
C
C IF (ICODE1 .NE. ICODE) THEN
C WRITE (6,80) ICODE1, ICODE
80 FORMAT (5X, 'ERROR ON ACCESSING INDEX ICODE1.NE.ICODE', / , 5X,
1 'ICODE1=', I7, 5X, 'ICODE=', I7, /)
C
C STOP
C END IF
C
C WRITE (6,90) ICODE1, FSTREC, LNUM, LSTREC
90 FORMAT (/ , 5X, 'DATA FILE DETAILS FOR SUBREGION ', I7, / , 5X,
1 'FIRST RECORD =', I11, / , 5X,
2 'LINE TO BE DELETED =', I11, / , 5X,
3 'LAST RECORD =', I11, /)
C
C IF (LNUM .LT. FSTREC .OR. LNUM .GT. LSTREC) THEN
C WRITE (6,100) LNUM
100 FORMAT (/ , 5X, 'ERROR LINE NUMBER ', I11, ' OUTSIDE ', / , 5X,
1 'LINE RANGE FOR GIVEN SUBREGION ', /)

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      STOP
      END IF
C
110 WRITE (6,120) LNUM
120 FORMAT (5X, 'DO YOU STILL WISH TO DELETE LINE ', I11, '/', 5X,
1      YES(0) NO(-1)
      READ (5,*) ITEST0
      IF (ITEST0.NE. 0 .AND. ITEST0.NE. - 1) GO TO 110
      IF (ITEST0.EQ. - 1) STOP
C
C* READ AND UPDATE FILE HEADER BEFORE LINE DELETION
      READ (UNIT=3,REC=500,Iostat=J3) IPOINT, ALAT, ALON, ATOP, AAGRV,
1      AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2, STERC2, RMSTOP,
2      RMSFRA, RMSBOU, RMSTER
C
      IF (J3.NE. 0) THEN
        WRITE (6,130) J3
130   FORMAT (5X, 'ERROR ON DIRECT HEADER READ TO UNIT 3:Iostat=', I4)
        STOP
        END IF
C
C* UPDATE AVERAGES+RMS VALUES
      RPOINT = REAL(IPOINT)
      ALAT = (ALAT*RPOINT - RLAT) / (RPOINT - 1.0)
      ALON = (ALON*RPOINT - RLON) / (RPOINT - 1.0)
      ATOP = (ATOP*RPOINT - RTOP) / (RPOINT - 1.0)
      AAGRV = (AAGRV*RPOINT - AGRV) / (RPOINT - 1.0)
      AFREEA = (AFREEA*RPOINT - RFREEA) / (RPOINT - 1.0)
      ABOUG = (ABOUG*RPOINT - RBOUG) / (RPOINT - 1.0)
      ATERRC = (ATERRC*RPOINT - RTERRC) / (RPOINT - 1.0)
C
      IPOINT = IPOINT - 1
      STOP2 = STOP2 - (RTOP*RTOP)
      SFREA2 = SFREA2 - (RFREEA*RFREEA)
      SBOUG2 = SBOUG2 - (RBOUG*RBOUG)
      STERC2 = STERC2 - (RTERRC*RTERRC)
C
      CALL RMSCAL(IPOINT, ATOP, STOP2, RMSTOP)
      CALL RMSCAL(IPOINT, AFREEA, SFREA2, RMSFRA)
      CALL RMSCAL(IPOINT, ABOUG, SBOUG2, RMSBOU)
      CALL RMSCAL(IPOINT, ATERRC, STERC2, RMSTER)
C
      WRITE (UNIT=3,REC=500) IPOINT, ALAT, ALON, ATOP, AAGRV, AFREEA,
1      ABOUG, ATERRC, STOP2, SFREA2, SBOUG2, STERC2, RMSTOP,
2      RMSFRA, RMSBOU, RMSTER
C
C* DELETE LINE FROM FILE+UPDATE INDEX FILE
      IF (FSTREC.EQ. LSTREC) THEN
        CALL WRITE(REG, LEN, 2, LNUM, UNT)
        FSTREC = 0
        LSTREC = 0
      ELSE IF (LSTREC.GT. FSTREC) THEN
        CALL WRITE(REG, LEN, 2, LNUM, UNT)
        IF (LNUM.NE. LSTREC) THEN
          NEXTL = LNUM + 1
          CALL RENUMB(UNT, NEXTL, LSTREC, LNUM, INCR, 130, 150, 170,

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1      190, 210, 230, 250)
      END IF
      LSTREC = LSTREC - 1
      END IF
C
      WRITE (UNIT=4,REC=LNUM1) ICODE, FSTREC, LSTREC
C
C* IF ARRIVE HERE NO ERRORS DETECTED-GO TO END
      GO TO 280
C
C* ERRORS
140 WRITE (6,150)
150 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 4')
      GO TO 280
160 WRITE (6,170)
170 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 8')
      GO TO 280
180 WRITE (6,190)
190 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 12')
      GO TO 280
200 WRITE (6,210)
210 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 16')
      GO TO 280
220 WRITE (6,230)
230 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 20')
      GO TO 280
240 WRITE (6,250)
250 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 24')
      GO TO 280
260 WRITE (6,270)
270 FORMAT (5X, 'RENUMB:ERROR RETURN CODE 28')
280 STOP
      END

```



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      NCOAST = NCOAST + 1
      END IF
C
      NPTS = 0
C
      END IF
C
      ELSE IF (OLDPOS .NEQV. .TRUE. ) THEN
        NPTS = NPTS + 1
        XPOS(NPTS) = X / 1000.000
        YPOS(NPTS) = Y / 1000.000
      END IF
C
      OLDPOS = .TRUE.
C
      ELSE
C
        IF (OLDPOS .EQV. .TRUE. ) THEN
          IF (NPTS .GT. 1) THEN
80          WRITE (8,80) NPTS, IZERO
             FORMAT (2I4)
C
             DO 100 I = 1, NPTS
               WRITE (8,90) XPOS(I), YPOS(I)
               FORMAT (2(2X,F9.4))
90          CONTINUE
100
C
             NCOAST = NCOAST + 1
             END IF
C
             NPTS = 0
C
             END IF
C
             OLDPOS = .FALSE.
C
             END IF
C
             OLDNUM = SNUM
C
             GO TO 40
C
110      DLAT = DBLE(RLAT)
          DLON = DBLE(RLON)
          IF (DLON .GT. 180.000) DLON = DLON - 360.000
C
          IF (IPROJ .EQ. 1) THEN
            CALL LLTOGR(DLAT, DLON, X, Y)
          ELSE IF (IPROJ .EQ. 2) THEN
            CALL EELLGR(DLAT, DLON, X, Y)
          END IF
C
          IF (X .GT. XMIN .AND. X .LT. XMAX .AND. Y .GT. YMIN .AND. Y .LT.
1          YMAX) THEN
C
            IF (OLDPOS .EQV. .TRUE. ) THEN

```

```

          IF (SNUM .EQ. OLDNUM) THEN
            NPTS = NPTS + 1
            XPOS(NPTS) = X / 1000.000
            YPOS(NPTS) = Y / 1000.000
          END IF
C
          IF (NPTS .GT. 1) THEN
            WRITE (8,120) NPTS, IZERO
            FORMAT (2I4)
120
            DO 140 I = 1, NPTS
              WRITE (8,130) XPOS(I), YPOS(I)
              FORMAT (2(2X,F9.4))
130
140            CONTINUE
C
            ELSE
C
              NCOAST = NCOAST - 1
C
              END IF
C
              WRITE (6,150) NCOAST
              FORMAT (/ , 5X, 'Number of coastlines = ', I3, /)
150
            ELSE IF (OLDPOS .NEQV. .TRUE. ) THEN
              NCOAST = NCOAST - 1
              WRITE (6,160) NCOAST
              FORMAT (/ , 5X, 'Number of coastlines = ', I3, /)
160
            END IF
C
            ELSE
C
              IF (OLDPOS .EQV. .TRUE. ) THEN
                IF (NPTS .GT. 1) THEN
                  WRITE (8,170) NPTS, IZERO
                  FORMAT (2I4)
170
                  DO 190 I = 1, NPTS
                    WRITE (8,180) XPOS(I), YPOS(I)
                    FORMAT (2(2X,F9.4))
180
190                  CONTINUE
C
                  ELSE
C
                    NCOAST = NCOAST - 1
C
                    END IF
C
                    WRITE (6,200) NCOAST
                    FORMAT (/ , 5X, 'Number of coastlines = ', I3, /)
200
                ELSE IF (OLDPOS .NEQV. .TRUE. ) THEN
                  NCOAST = NCOAST - 1
                  WRITE (6,210) NCOAST
                  FORMAT (/ , 5X, 'Number of coastlines = ', I3, /)
210

```

```
C      END IF
C      END IF
C      CLOSE (UNIT=4, STATUS='KEEP')
C      STOP
C      END
```



```

C**
C** Appendix B: Subroutine library
C** ~~~~~
C**
C** This subroutine library contains all of the subroutines
C** referred to in the programmes listed in Appendix B.
C** Where different subroutines with the same name occur in
C** two or more programmes there is a comment at the head of
C** each subroutine specifying the main programme or programmes
C** which call the subroutine.

```

```

C** ~~~~~**C
C**
C**

```

```

C** SUBROUTINE AVRAGE(N, RVALUE, AMEAN)
C** ~~~~~
C**
C** Subroutine AVRAGE calculates the average value of each data
C** field of interest in each data file.
C**
C**

```

```

C** DOUBLE PRECISION DPOINT, DVALUE, DMEAN, DMEAN1

```

```

C
C   RPOINT = REAL(N)
C   DPOINT = DBLE(RPOINT)
C   DVALUE = DBLE(RVALUE)
C   DMEAN = DBLE(AMEAN)
C
C   DMEAN1 = (DMEAN*(DPOINT - 1D0) + DVALUE) / DPOINT
C   DMEAN = DMEAN1
C   AMEAN = SNGL(DMEAN)
C   RETURN
C   END

```

```

C**
C** SUBROUTINE AVRAGM(IPOINT, RVALUE, AVG)
C** ~~~~~
C**

```

```

C** Subroutine AVRAGM recalculates the average of each data field
C** after the removal of one record from the data file.
C**
C**

```

```

C** Note IPOINT is reduced by one before calling AVRAGM.
C**

```

```

C** DOUBLE PRECISION DPOINT, DVALUE, DAVG

```

```

C
C   DPOINT = DFLOAT(IPOINT)
C   DVALUE = DBLE(RVALUE)
C   DAVG = DBLE(AVG)

```

```

C
C   DAVG = (DAVG*(DPOINT + 1D0) - DVALUE) / DPOINT
C   AVG = SNGL(DAVG)

```

```

C
C   RETURN
C   END

```

```

C**

```

```

C** SUBROUTINE AZDIST(RLAT1, ROLON1, RLAT2, ROLON2, A, AZB, DIST)
C** ~~~~~
C**

```

```

C** Subroutine AZDIST calculates the azimuth of a geodesic
C** line assuming a spherical Earth at both ends of the
C** geodesic.
C**

```

```

C** DOUBLE PRECISION RLAT1, RLAT2, ROLON1, ROLON2
C** DOUBLE PRECISION RAD, RADIUS, CLAT1, CLAT2, C, BETA, ALPHA
C** DOUBLE PRECISION SC, CC, SBETA, CBETA, SALPHA, CALPHA, CGAMMA
C** DOUBLE PRECISION GAMMA, SGAMMA, CA, SA, A, CB, SB, B, AZB
C** DOUBLE PRECISION RATIOA, RATIOB, RATIOC, PIE, DIST

```

```

C
C   DATA RAD, RADIUS /57.295779513D0, 6371.0D0/

```

```

C
C   PIE = 4D0 * DATAN(1D0)
C   IF (ROLON1 .GT. 180.0) ROLON1 = ROLON1 - 360.0D0
C   IF (ROLON2 .GT. 180.0) ROLON2 = ROLON2 - 360.0D0

```

```

C
C   IF (ROLON1 .EQ. ROLON2) THEN

```

```

C
C*   GEODESIC NORTH-SOUTH:SPECIAL CASE
C*   ANGLES BOTH ZERO
C*   IF (RLAT1 .LT. RLAT2) THEN
C*     A = 0.0D0
C*     AZB = 0.0D0
C*     ADEG = 0.0
C*     BDEG = 180.0
C*     AZBDEG = 0.0
C*   ELSE IF (RLAT1 .GT. RLAT2) THEN

```

```

C
C*   UPDATE WRITTEN OUTPUT ADEG ETC. BUT LEAVE INTERNAL
C*   A, AZB VALUES AS ABOVE.
C*   A = 0.0D0
C*   AZB = 0.0D0
C*   ADEG = 180.0
C*   BDEG = 0.0
C*   AZBDEG = 180.0
C*   END IF

```

```

C
C   DIST = DABS(RLAT2 - RLAT1) * PIE * RADIUS / 180D0
C   ELSE

```

```

C
C*   CALCULATE CO-LATITUDES
C*   CLAT1 = 90.0D0-RLAT1
C*   CLAT2 = 90.0D0-RLAT2

```

```

C
C*   CALCULATE ANGLES OF SPHERICAL TRIANGLE IN RADIANS
C*   C = (ROLON2 - ROLON1) / RAD
C*   BETA = CLAT1 / RAD
C*   ALPHA = CLAT2 / RAD

```

```

C
C   SC = DSIN(C)
C   CC = DCOS(C)

```

```

      SBETA = DSIN(BETA)
      CBETA = DCOS(BETA)
      SALPHA = DSIN(ALPHA)
      CALPHA = DCOS(ALPHA)
C
      CGAMMA = (CALPHA*CBETA + SALPHA*SBETA*CC)
      GAMMA = DACOS(CGAMMA)
      SGAMMA = DSIN(GAMMA)
C
C*  CALCULATE ANGLES BETWEEN GEODESIC LINE AND MERIDIANS
      CA = (CALPHA - CBETA*CGAMMA) / (SBETA*SGAMMA)
      CB = (CBETA - CGAMMA*CALPHA) / (SALPHA*SGAMMA)
C
      A = DACOS(CA)
      SA = DSIN(A)
      B = DACOS(CB)
      SB = DSIN(B)
C
C*  CALCULATE AZIMUTH AT EASTERN END OF GEODESIC
      AZB = PIE - B
C
C*  CONVERT ANGLES TO DEGREES FOR OUTPUT
      ADEG = A * RAD
      BDEG = B * RAD
      AZBDEG = AZB * RAD
C
      DIST = GAMMA * RADIUS
      END IF
C
      WRITE (8,10) RLAT1, RLON1, RLAT2, RLON2, ADEG, BDEG, AZBDEG, DIST
10  FORMAT (/ , 5X, 'PROFILE DATA OUTPUT FILE' , / , 5X,
1      '~~~~~' , / , 5X,
2      'WESTERN END OF PROFILE:GEODESIC' , / , 5X, 'LAT.=' ,
3      F8.4, 2X, 'LON.=' , F8.4, / , 5X,
4      'EASTERN END OF PROFILE:GEODESIC' , / , 5X, 'LAT.=' ,
5      F8.4, 2X, 'LON.=' , F8.4, / , 5X,
6      'AZIMUTH AT WESTERN END' , AZ=' , F8.4, / , 5X,
7      'ANGLE AT EASTERN END' , B=' , F8.4, / , 5X,
8      'AZIMUTH AT EASTERN END' , AZB=' , F8.4, / , 5X,
9      'LENGTH OF GEODESIC' (KM)=' , F10.3, //)
C
      IF (RLON1 .NE. RLON2) THEN
C
C*  CALCULATE SPHERICAL TRIANGLE SINE RATIOS
      RATIOA = SALPHA / SA
      RATIOB = SBETA / SB
      RATIOC = SGAMMA / SC
C
      IF (ABS(RATIOA - RATIOB) .GT. 1.0E-3 .OR. ABS(RATIOB - RATIOC)
1      .GT. 1.0E-3) THEN
10  WRITE (6,20) RATIOA, RATIOB, RATIOC
20  FORMAT (5X, 'ERROR:SINE RATIOS FOR SPHERICAL TRIANGLE' , //,
1      7X, 'RATIO A=' , F7.4, / , 7X, 'RATIO B=' , F7.4, / , 7X,
2      'RATIO C=' , F7.4, /)
      END IF
      END IF

```

```

C  RETURN
END
C**
C**  SUBROUTINE BOXRET(RLON, RLAT, HWIDTH, U, DATA, RADPLT, LAMDA0, UE,
1      UW, KOUNT1, KOUNT2)
C**  ~~~~~
C**
C**  Subroutine BOXRET retrieves all data from the 0.1 degrees
C**  by 0.1 degrees box containing RLAT and RLON. After retrieval
C**  each station coordinate pair is converted to uv space and tested
C**  to see if it lies in the window about the geodesic. If it does
C**  the data for the given station is stored in array DATA
C**  and its distance along the u axis is recorded in array U.
C**
C**  CHARACTER IDENT1*4, IDENT2*4, TCODE*1
C**  CHARACTER VAR*4, CONT*4, ITC(10)
C**  INTEGER FSTREC, GROUPN
C**  DOUBLE PRECISION RADPLT, LAMDA0, UE, UW, RADLT, RADLN
C**  DOUBLE PRECISION RAD, DLAT, DLON, UPOS, VPOS, HWIDTH, TEMP
C**  REAL U(2000), DATA(3,2000)
C
      DATA RAD /57.295779513D0/
C
      ISIGN = 0
      IF (UW .GT. UE) THEN
C*  EXCHANGE UW FOR UE AND VICE VERSA
          ISIGN = 1
          TEMP = UW
          UW = UE
          UE = TEMP
          WRITE (8,10) UW, UE
10  FORMAT (/ , 5X, 'AFTER EXCHANGE' , / , 5X,
1      'UW=' , F10.4, 2X, 'UV=' , F10.4, /)
      END IF
C
      ISYLON = INT(RLON*10.0)
      ISYLAT = INT(RLAT*10.0)
      LON0 = INT(RLON) * 10
      LAT0 = INT(RLAT) * 10
      CALL CODE(ISYLON, ISYLAT, ICODE1)
      CALL CODE(LON0, LAT0, ICODE0)
      GROUPN = ICODE1 - ICODE0
      LNUM1 = (GROUPN + 1) * 1000
C
C*  READ INDEX DATA
      READ (UNIT=4,REC=LNUM1) ICODE, FSTREC, LSTREC
      IF (ICODE .NE. ICODE1) THEN
20  WRITE (6,20) ICODE, ICODE1
20  FORMAT (/ , 5X, 'ERROR ON INDEX READ:BOXRET' , / , 5X,
1      7X, 'PREDICTED ICODE1' , / , 17, / , 5X,
2      'READ ICODE' , / , 17, /)
      STOP
      END IF

```



```

C      IF (FSTREC .NE. 0) THEN
        DO 60 LNUM = FSTREC, LSTREC
          KOUNT2 = KOUNT2 + 1
          READ (UNIT=3,REC=LNUM,IOSTAT=J1) XLAT, XLON, IEAST, INORTH,
1          RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
2          (ITC(11),I=1,10), VAR, CONT, IDENT1, IDENT2
C
          IF (J1 .NE. 0) THEN
            WRITE (6,30) J1
30          FORMAT ('/, 5X, 'ERROR ON DATA READ:BOXRET-IOSTAT=', I4)
            STOP
          END IF
C
          IF (XLON .GT. 180.0) XLON = XLON - 360.0
          DLAT = DBLE(XLAT)
          DLON = DBLE(XLON)
          RADLN = DLON / RAD
          RADLT = DLAT / RAD
C
          CONVERT TO UV SPACE
          CALL UVCALC(RADLN, RADLT, RADPLT, LAMDA0, UPOS, VPOS)
C
          TEST FOR DATA IN WINDOW
          IF (DABS(VPOS) .LE. HWIDTH) THEN
            IF (UPOS .GE. UW .AND. UPOS .LE. UE) THEN
              KOUNT1 = KOUNT1 + 1
              IF (KOUNT1 .GE. 2000) THEN
                WRITE (6,40)
40          FORMAT ('/, 5X, 'ARRAY U(2000) AND ARRAY DATA(3,2000)',
2          ' ', 5X, 'OVERFLOWED PROGRAM TERMINATES',
              STOP
            END IF
            IF (ISIGN .EQ. 0) THEN
              U(KOUNT1) = SNGL(UPOS - UW)
            ELSE IF (ISIGN .EQ. 1) THEN
              U(KOUNT1) = SNGL(UE - UPOS)
            END IF
C
            DATA(1,KOUNT1) = RFREEA
            DATA(2,KOUNT1) = RTOP
            DATA(3,KOUNT1) = RBOUG
C
            WRITE (8,50) XLAT, XLON, UPOS, VPOS, U(KOUNT1),
1            DATA(1,KOUNT1), DATA(2,KOUNT1), DATA(3,KOUNT1)
50          FORMAT (2X, F8.4, 1X, F8.4, 1X, F10.4, 1X, F10.4, 1X,
1            F10.4, 1X, F7.2, 1X, F9.2, 1X, F7.2)
          END IF
        END IF
C
60      CONTINUE
      END IF
C
      RETURN
      END

```

```

C**
C**      SUBROUTINE CINDEX(BINAME, INDNAM)
C**
C**      ~~~~~
C**      Subroutine CINDEX is a modification of Contr.Index1 and
C**      allows a series of files specified in main to be updated
C**      with respect to the contributor file Cntidx.
C**
C**      This sub-section searches each data file for the
C**      component contributors.
C**
C**      Programme updated to enable contributor deletion by
C**      the routines Contr.del and Contr.del1.
C**
C**      CHARACTER BINAME*7, INDNAM*7, NAME4(50)*4, FCONTM(50)*8
C**      CHARACTER IDENT1*4, IDENT2*4, TCODE*1, NAMEB(50)*8, ZERO4*4
C**      CHARACTER VAR*4, CONT*4, ITC(10)*1, ZERO8*8, STARS*4
C
C      INTEGER FSTREC, RECORD
C
C      PARAMETER (ZERO8='00000000')
C      PARAMETER (ZERO4='0000')
C      PARAMETER (STARS='****')
C
C      INITIALIZE DATA VARIABLES
C      RECORD = 1
C      I = 1
C      DO 10 K = 1, 50
C        NAME4(K) = ZERO4
C        NAME8(K) = ZERO8
10      CONTINUE
C
C      OPEN DATA FILE
C**      OPEN (UNIT=3,STATUS='OLD',FILE=BINAME,ACCESS='DIRECT',FORM=
1      'UNFORMATTED',IOSTAT=J1,RECL=80)
C
C      IF (J1 .NE. 0) THEN
        WRITE (6,20) J1
20      FORMAT (1X, 'ERROR OPENING UNIT 3 FOR DIRECT ACCESS,IOSTAT=',
1      I4)
        STOP
      END IF
C
C      OPEN/READ INDEX AND READ DATA RECORDS FROM MAIN DATA FILE
C**      WRITE DATA RECORDS TO OUTPUT FILE.
C**      OPEN (UNIT=4,STATUS='OLD',FILE=INDNAM,ACCESS='SEQUENTIAL',FORM=
1      'UNFORMATTED',IOSTAT=J2)
C
C      IF (J2 .NE. 0) THEN
        WRITE (6,30) INDNAM, J2
30      FORMAT (1X, 'ERROR OPENING FILE ', A7, ' ON UNIT 4,IOSTAT=', I4)
        STOP
      END IF
C
40      READ (UNIT=4,END=120) ICODE1, FSTREC, LSTREC

```

```

C      IF (FSTREC .NE. 0) THEN
        DO 110 LNUM = FSTREC, LSTREC
          READ (UNIT=3, REC=LNUM, IOSTAT=J3) RLAT, RLON, IEAST, INORTH,
            1      RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
            2      (ITC(11), I1=1, 10), VAR, CONT, IDENT1, IDENT2
C      IF (J3 .NE. 0) THEN
        WRITE (6, 50) BINAME, J3
        50  FORMAT (1X, 'ERROR ON DIR. ACCESS READ TO FILE ', A7,
            1      ' IOSTAT=', I4)
        STOP
        END IF
C      IF (RECORD .EQ. 1) THEN
        IF (VAR .EQ. 'MGU') THEN
          NAME8(I) = VAR // CONT
        ELSE IF (CONT .EQ. 'MGU') THEN
          NAME8(I) = CONT // IDENT1
        ELSE
          NAME4(I) = CONT
        END IF
        I = I + 1
        RECORD = RECORD + 1
        ELSE IF (RECORD .GT. 1) THEN
          IF (I .GT. 50) THEN
            60  WRITE (8, 60)
            1      FORMAT (5X, 'MORE THAN 50 CONTRIBUTORS TO FILE ', //
                5X, 'ARRAY FCONTM OVERLOADED:PROGRAM STOPS', //)
            STOP
            END IF
C      N = I - 1
        IF (VAR .EQ. 'MGU') THEN
          NAME8(I) = VAR // CONT
          DO 70 K = 1, N
            IF (NAME8(K) .EQ. NAME8(I)) THEN
              NAME8(I) = ZERO8
              GO TO 100
            END IF
            70  CONTINUE
            I = I + 1
          ELSE IF (CONT .EQ. 'MGU') THEN
            NAME8(I) = CONT // IDENT1
            DO 80 K = 1, N
              IF (NAME8(K) .EQ. NAME8(I)) THEN
                NAME8(I) = ZERO8
                GO TO 100
              END IF
              80  CONTINUE
              I = I + 1
            ELSE
              NAME4(I) = CONT
              DO 90 K = 1, N
                IF (NAME4(K) .EQ. NAME4(I)) THEN
                  NAME4(I) = ZERO4

```

```

              GO TO 100
            END IF
            90  CONTINUE
            I = I + 1
          END IF
          RECORD = RECORD + 1
          END IF
C      110 CONTINUE
        END IF
C      GO TO 40
C      EXIT LOOP
        120 I = I - 1
        L = 1
C      DO 130 K = 1, I
        IF (NAME4(K) .NE. '0000') THEN
          FCONTM(L) = NAME4(K) // STARS
          L = L + 1
        END IF
        IF (NAME8(K) .NE. '00000000') THEN
          FCONTM(L) = NAME8(K)
          L = L + 1
        END IF
C      130 CONTINUE
        L = L - 1
C      CLOSE (UNIT=3, STATUS='KEEP')
        CLOSE (UNIT=4, STATUS='KEEP')
C      CALL INDEXING ROUTINE CONIDX.
        CALL CONIDX(BINAME, FCONTM, L)
C      RETURN
        END
C**
C** SUBROUTINE CODE(I, J, ICODE)
C** ~~~~~
C** Main programmes: Contr.del, Dbin.2, Liner and Line.del.
C** Subroutine CODE encodes the symbolic
C** integers ISYLAT and ISYLON etc., for the
C** left bottom corner of a 1 degree by 1 degree
C** bin to form an identifier for the bin.
C**
        ILAT = INT((REAL(J))/10.0)
        ILON = INT((REAL(I))/10.0)
        JLAT = J - (10*ILAT)
        JLON = I - (10*ILON)
C      CREATE CODE
        ICODE = JLAT + (JLON*10) + (ILAT*100) + (ILON*10000)

```

```

C      RETURN
C      END

C**
C**
C**      SUBROUTINE CONIDX(BINAME, FCONTS, L)
C**      ~~~~~
C**
C**      Subroutine CONIDX writes and maintains/updates a contributor
C**      index file Cntidx. The complicated update procedures are
C**      carried out by a further subroutine called UPDATE.
C**
C**      CHARACTER FCONTS(L)*8, PCONT(500)*8, BINAME*7
C**
C**      Array FCONTS holds the contributors to file BINAME.
C**      Array PCONT will later hold all those contributors
C**      presently held in the file Cntidx. Note the programme
C**      at present can hold 500 different contributors.
C**
C**      INTEGER ONE
C**      LOGICAL LOGEX, OK
C**      DIMENSION NUM1(500)
C
C
C      PARAMETER (OK=.TRUE., )
C      PARAMETER (ONE=1)
C
C*      DETERMINE WHETHER CONTRIBUTOR INDEX EXISTS OR NOT.
C      INQUIRE (FILE='CNTIDX',ERR=160,IOSTAT=J1,EXIST=LOGEX)
C
C      IF (LOGEX .NEQV. OK) THEN
C          WRITE (6,10)
C10      FORMAT (1X, 'FILE CNTIDX DOES NOT EXIST')
C
C*      OPEN FILE AND ENTER INITIAL INFORMATION
C      OPEN (UNIT=3,ERR=180,STATUS='NEW',FILE='CNTIDX',ACCESS='DIRECT',
C1      FORM='FORMATTED',IOSTAT=J2,RECL=80)
C
C      WRITE (UNIT=3,FMT=20,REC=500,IOSTAT=J3,ERR=200) L
C20      FORMAT (1X, 'TOTAL NUMBER OF CONTRIBUTORS=', 13)
C
C      DO 50 K = 1, L
C          NREC = K * 1000
C          NREC1 = NREC + 1
C          WRITE (UNIT=3,REC=NREC,FMT=30,IOSTAT=J4,ERR=220) FCONTS(K),
C1          ONE
C30      FORMAT (1X, A8, 2X, 13)
C          WRITE (UNIT=3,REC=NREC1,FMT=40,IOSTAT=J5,ERR=240) BINAME
C40      FORMAT (3X, A7)
C50      CONTINUE
C
C      CLOSE (UNIT=3,ERR=260,IOSTAT=J6,STATUS='KEEP')
C
C      ELSE
C*      FILE EXISTS BUT IS CLOSED
C      OPEN (UNIT=3,FILE='CNTIDX',ERR=280,STATUS='OLD',ACCESS='DIRECT',

```

```

1      FORM='FORMATTED',IOSTAT=J7,RECL=80)
C*      READ HEADER RECORD TO CNTIDX
C      READ (UNIT=3,REC=500,FMT=60,IOSTAT=J8,ERR=300) NUM
C60      FORMAT (30X, 13)
C      WRITE (6,70) NUM
C70      FORMAT (1X, 'NUMBER OF CONTRIBUTORS ON OPENING CNTIDX=', 13)
C
C      IF (NUM .GT. 500) THEN
C          WRITE (6,80) NUM
C80      FORMAT (1X, 'ERROR,NUMBER OF CONTRIBUTORS TOO LARGE,NUM=', 13)
C          WRITE (6,90)
C90      FORMAT (1X, 'ARRAYS PCONT,NUM1 ONLY HOLD 500 ELEMENTS')
C          WRITE (6,100)
C100     FORMAT (1X, 'SEE ARRAY BOUNDS AT HEAD OF SUB. CONIDX')
C          GO TO 360
C      END IF
C
C*      READ ALL CONTRIBUTORS IN INDEX INTO ARRAY
C      DO 130 L1 = 1, NUM
C          NREC = L1 * 1000
C          READ (UNIT=3,REC=NREC,FMT=30,IOSTAT=J8,ERR=300) PCONT(L1),
C1          NUM1(L1)
C
C      IF (NUM1(L1) .GE. 300) THEN
C          WRITE (6,110) NUM1(L1)
C110     FORMAT (1X, 'ERROR NO. OF FILES EXCEEDS BOUND OF 300,NUM1=',
C1          13)
C          WRITE (6,120)
C120     FORMAT (1X, 'ARRAY ''FILE'' MUST BE ENLARGED,SEE SUB. UPDATE
C1          1')
C          GO TO 360
C      END IF
C130     CONTINUE
C
C*      Test each contributor to see if contributor already in index.
C*      If contributor not in index add new contributor to index.
C*      If contributor in index but new data file not in index add
C*      new data file to index. Use subroutine Update for latter
C*      operation. Set variable to allow for increase NUM with new
C*      contributors.
C      NEWNUM = NUM
C
C      DO 150 L2 = 1, L
C          INDIC = 1
C          DO 140 L3 = 1, NUM
C              IF (PCONT(L3) .EQ. FCONTS(L2)) THEN
C*              CONTRIBUTOR ALREADY IN INDEX. CHECK IF DATA FILE IN INDEX.
C                  CALL UPDATE(BINAME, L3, NUM1(L3), PCONT(L3))
C                  INDIC = 2
C              END IF
C140             CONTINUE
C
C          IF (INDIC .EQ. 1) THEN
C*          CONTRIBUTOR NOT IN INDEX. ADD NEW CONTRIBUTOR TO INDEX.
C              NEWNUM = NEWNUM + 1
C              NREC = NEWNUM * 1000

```

```

      WRITE (UNIT=3,REC=NREC,FMT=30,IOSTAT=J9,ERR=320) FCONTS(L2),
1      ONE
      NREC1 = NEWNUM * 1000 + 1
      WRITE (UNIT=3,REC=NREC1,FMT=40,ERR=320,IOSTAT=J9) BINAME
      END IF
C
150  CONTINUE
C*  IF NO. OF CONTRIBUTORS HAS INCREASED CHANGE HEADER RECORD
      IF (NEWNUM.GT. NUM) THEN
        WRITE (UNIT=3,REC=500,FMT=20,IOSTAT=J10,ERR=340) NEWNUM
      END IF
C
      CLOSE (UNIT=3,IOSTAT=J6,ERR=260,STATUS='KEEP')
      END IF
C
      IF RUN SUCCESSFUL RETURN
      GO TO 370
C*  ERROR MESSAGES
C
160  WRITE (6,170) J1
170  FORMAT (1X, 'ERROR OCCURRING ON INQUIRE,IOSTAT INT=', I4)
      GO TO 360
180  WRITE (6,190) J2
190  FORMAT (1X, 'ERROR ON OPENING NEW CNTIDX FILE,IOSTAT INT=', I4)
      GO TO 360
200  WRITE (6,210) J3
210  FORMAT (1X, 'ERROR ON INITIAL HEADER WRITE TO CNTIDX,IOSTAT=', I4)
      GO TO 360
220  WRITE (6,230) J4
230  FORMAT (1X, 'ERROR ON INITIAL DATA WRITE TO CNTIDX,IOSTAT=', I4)
      GO TO 360
240  WRITE (6,250) J5
250  FORMAT (1X, 'ERROR ON INITIAL FILENAME WRITE TO CNTIDX,IOSTAT=',
1      I4)
      GO TO 360
260  WRITE (6,270) J6
270  FORMAT (1X, 'ERROR ON CLOSING CNTIDX ON UNIT 3,IOSTAT=', I4)
      GO TO 360
280  WRITE (6,290) J7
290  FORMAT (1X, 'ERROR ON REOPENING CNTIDX ON UNIT 3,IOSTAT=', I4)
      GO TO 360
300  WRITE (6,310) J8
310  FORMAT (1X, 'ERROR ON READ TO CNTIDX ON UNIT 3,IOSTAT=', I4)
      GO TO 360
320  WRITE (6,330) J9
330  FORMAT (1X, 'ERROR ON WRITING NEW CONTRIBUTOR INFORMATION', 1X,
1      'TO CNTIDX,IOSTAT=', I4)
      GO TO 360
340  WRITE (6,350) J10
350  FORMAT (1X, 'ERROR ON UPDATING NO. OF CONTRIBUTORS,IOSTAT=', I4)
360  STOP
370  RETURN
      END
C**
C**
      SUBROUTINE CONVRT(WLON, ELON, SLAT, NLAT, RWLON, RELON, RSLAT,
1      RNLAT, XMIN, XMAX, YMIN, YMAX, SAMP)

```

```

C**
C**
C**  Main programme: Grid.proj
C**
C**  Simple subroutine to convert DOUBLE PRECISION
C**  projection constants to database REALS.
C**
C**
      DOUBLE PRECISION WLON, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX,
1      SAMP
C
      COMMON /GRDDAT/ RXMIN, RXMAX, RYMIN, RYMAX, RSAMP, IPROJ
C
      RWLON = SNGL(WLON)
      RELON = SNGL(ELON)
      RSLAT = SNGL(SLAT)
      RNLAT = SNGL(NLAT)
C
      RXMIN = SNGL(XMIN)
      RXMAX = SNGL(XMAX)
      RYMIN = SNGL(YMIN)
      RYMAX = SNGL(YMAX)
C
      RSAMP = SNGL(SAMP)
C
      RETURN
      END
C**
C**
      SUBROUTINE CONVRT(DATA, IXRANG, IYRANG, IHANCE)
C**
C**
C**  Main programme: Image.proj
C**
C**  Subroutine CONVRT is basically a simple subroutine to
C**  convert data to a byte form for entry into the I2S image
C**  processing system.
C**
C**  Complicated by variable size output of image.
C**  E.g. (IXRANG, IYRANG) or (IXRANG-2, IYRANG-2)
C**  depending on enhancement option and by the I2S
C**  system requiring the input record length to be
C**  an even number of bytes.
C**
      DIMENSION DATA(IXRANG,IYRANG)
      INTEGER*2 INTG2(450)
      CHARACTER OUTPUT*450, TEMP*900
C
      EQUIVALENCE (INTG2,TEMP)
C
      SET INTG2 TO ZERO
      DO 10 K = 1, 450
        INTG2(K) = 0
      10 CONTINUE
C
      DETERMINE ARRAY PARAMETERS

```



```

C*   SET CONSTANTS FOR ARRAY DEFINITION
    EXX = XMAX - XMIN
    EXY = YMAX - YMIN
    XRANG = REAL(IXRANG)
    YRANG = REAL(IYRANG)

C
    WRITE (6,40)
40  FORMAT (/, 5X, 'IF YOU WISH TO CREATE COASTLINE', /, 5X,
1    'IMAGE ENTER (0)', /)
    READ (5,*) ITEST1

C
    IF (ITEST1 .EQ. 0) THEN

C
        WRITE (6,50)
50  FORMAT (/, 5X, 'ENTER DESIRED FORM OF PROJECTION', /, 5X,
1    '0.S. TRANSVERSE MERCATOR = 1', /, 5X,
2    'LAMBERT CONFORMAL = 2', /, 5X,
3    'IRISH GRID TRANSVERSE MERCATOR = 3', /)

C
        READ (5,*) IPROJ

C
        IF LAMBERT CONFORMAL PROJECTION READ IN
        ADDITIONAL PROJECTION DATA
        IF (IPROJ .EQ. 2) THEN
            READ (2,*) OLAT, OLON, SLAT1, SLAT2, CSFACT
            READ (2,*) EQRAD, ECC
        END IF

C
        OPEN (UNIT=7, STATUS='OLD', FILE='COASTUF', ACCESS='SEQUENTIAL',
1          FORM='UNFORMATTED', IOSTAT=J1)
        IF (J1 .NE. 0) THEN
            WRITE (6,60) J1
60      FORMAT (5X, 'ERROR OPENING FILE COASTUF, IOSTAT=', I4, /)
            STOP
        END IF

C
        SEARCH FILE FOR DATA POINTS ON MAP
70      READ (UNIT=7, END=80) SNUM, RLAT, RLON

C
        CONVERT TO GRID COORDINATES
        CALL PPREP(RLAT, RLON, GRN, GRE, IPROJ)
        IF (GRE .GT. XMIN .AND. GRE .LT. XMAX .AND. GRN .GT. YMIN .AND.
1          GRN .LT. YMAX) THEN
            IX = INT(((GRE - XMIN)/EXX)*XRANG) + 1
            IY = INT(((GRN - YMIN)/EXY)*YRANG) + 1

C
            IF (IX .GE. 1 .AND. IX .LE. IXRANG .AND. IY .GE. 1 .AND. IY
1            .LE. IYRANG) THEN
                DATA(IX,IY) = 255.0
            END IF

C
            GO TO 70

C
80      CLOSE (UNIT=7, STATUS='KEEP')
        END IF

```

```

C
    WRITE (6,90)
90  FORMAT (/, 5X, 'IF YOU WISH TO HAVE A MARKER GRID', /, 5X,
1    'SUPERIMPOSED ON THE IMAGE ENTER (0)', /)
    READ (5,*) ITEST2

C
    IF (ITEST2 .EQ. 0) THEN
        LN1 = XMIN / 100000
        LN1 = LN1 * 100000
        IF (REAL(LN1) .LE. XMIN) LN1 = LN1 + 100000
        LN2 = XMAX / 100000
        LN2 = LN2 * 100000
        IF (REAL(LN2) .GE. XMAX) LN2 = LN2 - 100000
        LT1 = YMIN / 100000
        LT1 = LT1 * 100000
        IF (REAL(LT1) .LE. YMIN) LT1 = LT1 + 100000
        LT2 = YMAX / 100000
        LT2 = LT2 * 100000
        IF (REAL(LT2) .GE. YMAX) LT2 = LT2 - 100000

C
        DO 130 K = LN1, LN2, 100000
        DO 120 L = LT1, LT2, 100000
            IX = INT(((REAL(K) - XMIN)/EXX)*XRANG) + 1
            IY = INT(((REAL(L) - YMIN)/EXY)*YRANG) + 1

C
            DEFINE MARKER CROSSES
            DO 100 K1 = IX - 3, IX + 3
                IF (K1 .GE. 1 .AND. K1 .LE. IXRANG .AND. IY .GE. 1 .AND.
1              IY .LE. IYRANG) THEN
                    DATA(K1,IY) = 255.0
                END IF
            CONTINUE

C
            DO 110 L1 = IY - 3, IY + 3
                IF (L1 .GE. 1 .AND. L1 .LE. IYRANG .AND. IX .GE. 1 .AND.
1              IX .LE. IXRANG) THEN
                    DATA(IX,L1) = 255.0
                END IF
            CONTINUE

C
            CONTINUE
        CONTINUE

C
    END IF

C
    RETURN
    END

C**
C**
C** SUBROUTINE DATART(WLON, ELON, SLAT, NLAT)
C**
C** ~~~~~
C** Subroutine DATART retrieves all data within area specified
C** by input. Search area rectangle defined by min., max. lat. and
C** lon.. Data held in database data files.
C**

```

```

C** Data retrieved from data files for an area equal in
C** size or just larger than the user specified area. All data
C** is tested to check it lies within the area before being
C** gridded.
C**
C** REAL NLAT
C** INTEGER RES
C
C* INITIALIZE CPU TIME COUNT
CALL TIME(0)
C
C IF (WLOD .LT. 0.0) WLOD = WLOD + 360.0
C IF (ELOD .LE. 0.0) ELOD = ELOD + 360.0
C
C IF (NLAT .LT. 0.0 .OR. SLAT .LT. 0.0) THEN
  WRITE (6,10)
10  FORMAT (1X, 'NEGATIVE LATITUDE INVALID:PROGRAM TERMINATED')
  STOP
END IF
C
C IF (WLOD .GT. ELOD) THEN
  CALL MRETRV(WLOD, 360.0, SLAT, NLAT, 1)
  CALL MRETRV(0.0, ELOD, SLAT, NLAT, 2)
ELSE
  CALL MRETRV(WLOD, ELOD, SLAT, NLAT, 0)
END IF
C
C* FINISH CPU TIME COUNT AND PRINT RESULTS
CALL TIME(1, 0, RES)
WRITE (6,20) RES
20  FORMAT (5X, ' CPU TIME COUNT FOR DATA RETRIEVAL AND ', /, 5X,
1    ' PRELIMINARY GRIDDING = ', 18, ' MILLISECONDS', /)
C
C RETURN
END
C**
C** SUBROUTINE DATAVG(IHOLE, ITOTAL, NX, NY)
C**
C** Subroutine DATAVG calculates the size of the main grid
C** array and calculates average value for each grid square.
C**
C** N.B. The calculation of array dimensions
C** is difficult and checks must be made.
C**
C** REAL FGRID(256,256), TGRID(256,256), BGRID(256,256),
1  NGRID(256,256)
C
C COMMON /GRIDS/ FGRID, TGRID, BGRID, NGRID
C COMMON /GRDDAT/ XMIN, XMAX, YMIN, YMAX, SAMP, IPROJ
C
C DATA IEDGE /0/

```

```

C* DETERMINE ARRAY DIMENSIONS
IF (AMOD(XMAX,SAMP) .EQ. 0.0 .AND. AMOD(XMIN,SAMP) .EQ. 0.0)
1  THEN
  NX = NINT((XMAX/SAMP) - (XMIN/SAMP))
ELSE
  NX = INT((XMAX/SAMP) - (XMIN/SAMP)) + 1
END IF
C
IF (AMOD(YMAX,SAMP) .EQ. 0.0 .AND. AMOD(YMIN,SAMP) .EQ. 0.0)
1  THEN
  NY = NINT((YMAX/SAMP) - (YMIN/SAMP))
ELSE
  NY = INT((YMAX/SAMP) - (YMIN/SAMP)) + 1
END IF
C
C* DETERMINE TOTAL NUMBER OF GRID POINTS
ITOTAL = NX * NY
C
C* CALCULATE AVERAGE FOR EACH GRID POINT
DO 20 I = 1, NX
  DO 10 J = 1, NY
    C
    IF (NGRID(I,J) .GT. 0.0) THEN
      FGRID(I,J) = FGRID(I,J) / NGRID(I,J)
      TGRID(I,J) = TGRID(I,J) / NGRID(I,J)
      BGRID(I,J) = BGRID(I,J) / NGRID(I,J)
    ELSE
      IHOLE = IHOLE + 1
    END IF
    C
    IF (I .EQ. NX .OR. J .EQ. NY) THEN
      IF (NGRID(I,J) .LT. 1.0) THEN
        IEDGE = IEDGE + 1
      END IF
    END IF
  10 CONTINUE
20 CONTINUE
C
C* TEST PERCENTAGE OF OUTSIDE EDGES WITH NO DATA
INUM = NX + NY - 1
PCENT = (REAL(IEEDGE)/REAL(INUM)) * 100.0
IF (PCENT .GT. 50.0) THEN
  WRITE (6,30) IEDGE, INUM, PCENT
30  FORMAT (//, 5X, 'ARRAY DIMENSIONS POSSIBLY SUSPECT', //, 5X,
1    'NUMBER OF GOOD POINTS ALONG OUTSIDE EDGE = ', 13, /, 5X,
2    'TOTAL NUMBER OF POINTS ALONG OUTSIDE EDGE = ', 13, /,
3    5X, 'PERCENTAGE HOLES = ', F5.1, //)
END IF
C
C RETURN
END
C**
C** SUBROUTINE DATRET(BINAME, INDNAM, PCONT, ITEST0)

```

```

C** Subroutine Datret retrieves all the data from file BINAME
C** supplied by contributor PCONT. Two output modes are available:
C** 1) Filename, line number and data output;
C** 2) Data output in formatted style for plotting
C** on a geographical projection using Contr.plot.
C**
C** This version of DATRET also simultaneously deletes
C** the retrieved data from the files.
C
CHARACTER BINAME*7, INDNAM*7, PCONT*8
CHARACTER IDENT1*4, IDENT2*4, TCODE*1, STARS*4
CHARACTER VAR*4, CONT*4, ITC(10)*1, NAME8*8

C
INTEGER FSTREC

C
PARAMETER (STARS='****')

C
OPEN DATA FILE
OPEN (UNIT=3, STATUS='OLD', FILE=BINAME, ACCESS='DIRECT', FORM=
1 'UNFORMATTED', IOSTAT=J1, RECL=80)

C
IF (J1 .NE. 0) THEN
WRITE (6,10) J1
10 FORMAT (1X, 'ERROR OPENING UNIT 3 FOR DIRECT ACCESS, IOSTAT=',
1 I4)
GO TO 90
END IF

C
OPEN/READ INDEX AND READ DATA RECORDS FROM MAIN DATA FILE
C
WRITE DATA RECORDS TO OUTPUT FILE.
OPEN (UNIT=4, STATUS='OLD', FILE=INDNAM, ACCESS='SEQUENTIAL', FORM=
1 'UNFORMATTED', IOSTAT=J2)

C
IF (J2 .NE. 0) THEN
WRITE (6,20) INDNAM, J2
20 FORMAT (1X, 'ERROR OPENING FILE ', A7, ' ON UNIT 4, IOSTAT=', I4)
GO TO 90
END IF

C
30 READ (UNIT=4, END=80) ICODE1, FSTREC, LSTREC

C
IF (FSTREC .NE. 0) THEN
C
SUBROUTINE LINDEL CHANGES LINE RANGE THEREFORE
C
USE DUMMY LINE NUMBER LNSB (LINE NO. SUB.)
LNSB = FSTREC
DO 70 LNUM = FSTREC, LSTREC
READ (UNIT=3, REC=LNSB, IOSTAT=J3) RLAT, RLON, IEAST, INORTH,
1 RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE, TCODE,
2 (ITC(11), I1=1,10), VAR, CONT, IDENT1, IDENT2

C
IF (J3 .NE. 0) THEN
WRITE (6,40) BINAME, J3
40 FORMAT (1X, 'ERROR ON DIR. ACCESS READ TO FILE ', A7,

```

```

1 IOSTAT=', I4)
GO TO 90
END IF

C
FORM CONTRIBUTOR IDENTIFIER
C*
IF (VAR .EQ. 'MGU') THEN
NAME8 = VAR // CONT
ELSE IF (CONT .EQ. 'MGU ') THEN
NAME8 = CONT // IDENT1
ELSE
NAME8 = CONT // STARS
END IF

C
IF (NAME8 .EQ. PCONT) THEN
IF (ITEST0 .EQ. 0) THEN
WRITE (7,50) LNSB, RLAT, RLON, IEAST, INORTH, RTOP, AGRV,
1 RFREEA, RBOUG, RTERRC, RDENSE, TCODE, (ITC(11), I1=1,10),
2 VAR, CONT, IDENT1, IDENT2

C
50 FORMAT (2X, I11, 1X, F7.4, 1X, F8.4, I7, I7, F9.2, 1X,
1 F8.1, 1X, F7.2, 1X, F7.2, 1X, F6.2, 1X, F7.1, A1,
2 1X, 10A1, 4A4)
ELSE IF (ITEST0 .EQ. 1) THEN
WRITE (7,60) RLAT, RLON, IEAST, INORTH, RTOP, AGRV,
1 RFREEA, RBOUG, RTERRC, RDENSE, TCODE, (ITC(11), I1=1,10),
2 VAR, CONT, IDENT1, IDENT2
60 FORMAT (2X, F7.4, 1X, F8.4, I7, I7, F9.2, 1X, F8.1, 1X,
1 F7.2, 1X, F7.2, 1X, F6.2, 1X, F7.1, A1, 1X, 10A1,
2 4A4)
END IF

C
DELETE LINE FROM FILE
C*
CALL LINDEL(LNSB, BINAME, INDNAM)

C
LINDEL REARRANGES LINE NUMBERS THEREFORE
C*
RETARD LNSB
LNSB = LNSB - 1
END IF
LNSB = LNSB + 1

C
70 CONTINUE
END IF

C
GO TO 30
80 CLOSE (UNIT=3, STATUS='KEEP')
CLOSE (UNIT=4, STATUS='KEEP')

C
90 RETURN
END

C**
C** SUBROUTINE DDUMP(NX, NY)
C**
C** Subroutine DDUMP outputs data grids in an unformatted
C** file assigned to unit 8.

```



```

C** REAL FGRID(256,256), TGRID(256,256), BGRID(256,256),
1   NGRID(256,256)
C   INTEGER IFFLAG(256,256), ITFLAG(256,256), IBFLAG(256,256)
C   COMMON /GRIDS/ FGRID, TGRID, BGRID, NGRID
COMMON /FLAGS/ IFFLAG, ITFLAG, IBFLAG
COMMON /GRDDAT/ XMIN, XMAX, YMIN, YMAX, SAMP, IPROJ
C   OUTPUT DATA GRID
C* DO 20 I = 1, NX
DO 10 J = 1, NY
C     X = (REAL(I) - 0.5) * SAMP + XMIN
Y = (REAL(J) - 0.5) * SAMP + YMIN
C     WRITE (UNIT=8) X, Y, FGRID(I,J), TGRID(I,J), BGRID(I,J),
1       NGRID(I,J), IFFLAG(I,J), ITFLAG(I,J), IBFLAG(I,J)
C   10 CONTINUE
20 CONTINUE
C   RETURN
END
C**
C** SUBROUTINE EEGRLL ( GREAST, GRNRTH, ALAT, ALON )
*
*--T Subroutine EEGRLL ( GREAST, GRNRTH, ALAT, ALON )
*--A M.J.Smith 22-Mar-86
*--L Fortran 77
*--OS MTS
*--D+
*
* MODIFIED FOR IRISH GRID AUGUST 1986
*
* This is a modified transverse mercator, central meridian
8W00.00, Lat. origin 53N30.00.
*
* False origin set to 200000m west and 250000m south of true
origin to ensure positive grid coordinates.
*
* Scale at central meridian is 1.000035
*
* Returns the latitude and longitude ( ALAT, ALON ) in degrees of
a point given its grid reference ( GREAST, GRNRTH ) in metres.

```

```

* Angles returned are positive east of Greenwich and north
of the equator.
*
* If the grid reference is given to the nearest metre, the lat/long
will be accurate to +/-0.0000089 degrees, 0.0005 minutes or
0.035 seconds.
*
* Uses formulae given in Snyder, J.P., (1982), " Map projections
used by the U.S. Geological Survey ", Geological Survey bulletin
1532, page 68.
*
* The UK national grid is a modified UTM projection with a false
origin at ( 0m, 0m ) and a true origin ( 400000m, 100000m ) at
49N, 2W.
*
* Double precision used throughout.
*-D-
* IMPLICIT DOUBLE PRECISION (A-H, O-Z)
LOGICAL INITC
*
* earth constants ( Airy's 1849 spheroid )
*
PARAMETER ( EQRAD = 6377563.4D0 )
PARAMETER ( POLRAD = 6356256.9D0 )
PARAMETER ( FLAT = 1. / 299.32 )
*
* other constants
*
PARAMETER ( PI = 3.14159265358979D0 )
PARAMETER ( DEGRAD = .1745329251994329D-01 )
*
* Initialise INITC. This ensures that constant initialisation
is only carried out once, on the first call to this routine.
*
DATA INITC / .TRUE. /
*
* now start the calculations
*
IF ( INITC ) THEN
*
OLAT = 53.5D0
CMLON = -8.0D0
SCALE = 1.000035
*
CLON = CMLON * DEGRAD
CLAT = OLAT * DEGRAD
*
FLT = 1.0D0 - POLRAD / EQRAD
ECC = DSQRT( 2.0D0 * FLT - FLT**2 )
ECC2 = ECC**2
ECC4 = ECC**4
ECC6 = ECC**6
*
TERM1 = 1.0D0 - ( ECC2 / 4.0D0 ) - ( 3.0D0 * ECC4 / 64.0D0 ) -
% ( 5.0D0 * ECC6 / 256.0D0 )

```

```

      TERM2 = ( 3.0D0 * ECC2 / 8.0D0 ) + ( 3.0D0 * ECC4 / 32.0D0 ) +
%      45.0D0 * ECC6 / 1024.0D0 )
      TERM3 = ( 15.0D0 * ECC4 / 256.0D0 ) + ( 45.0D0 * ECC6 /
%      1024.0D0 )
      TERM4 = ( 35.0D0 * ECC6 / 3072.0D0 )

      calculate distance along central meridian from
      equator to latitude origin.

      EQBDIS = EQRAD * ( { TERM1 * CLAT } -
%      { TERM2 * DSIN( CLAT * 2.0D0 ) } +
%      { TERM3 * DSIN( CLAT * 4.0D0 ) } -
%      { TERM4 * DSIN( CLAT * 6.0D0 ) } )

      calculate e1
      SRE2 = DSQRT( 1.0D0 - ECC2 )
      E1 = ( 1.0D0 - SRE2 ) / ( 1.0D0 + SRE2 )

      INITC = .FALSE.

      ENDIF

      TRUEGE = GREAST - 200000.0D0
      TRUEGN = GRNRTH - 250000.0D0

      calculate EQDIS
      EQDIS = EQBDIS + TRUEGN / SCALE

      calculate MU
      XMU = EQDIS / ( EQRAD * ( 1.0D0 - ECC2 / 4.0D0 -
%      3.0D0 * ECC4 / 64.0D0 - 5.0D0 * ECC6 / 256.0D0 ) )

      calculate footpoint latitude, PHI1
      PHIT1 = ( 3.0D0 * E1 / 2.0D0 ) - ( 27.0D0 * E1**3 / 32.0D0 )
      PHIT2 = ( 21.0D0 * E1**2 / 16.0D0 ) - ( 55.0D0 * E1**4 / 32.0D0 )
      PHIT3 = ( 151.0D0 * E1**3 / 96.0D0 )

      PHI1 = XMU + PHIT1 * DSIN( 2.0D0 * XMU ) +
%      PHIT2 * DSIN( 4.0D0 * XMU ) +
%      PHIT3 * DSIN( 6.0D0 * XMU )
      PLAT = PHI1

      other constants
      EPRIM2 = ECC2 / ( 1.0D0 - ECC2 )
      RCURVE = EQRAD / DSQRT( 1.0D0 - ECC2 * DSIN( PLAT )**2 )
      TSQLT1 = DTAN( PLAT )**2
      TSQLT2 = TSQLT1**2
      ECSSQ1 = EPRIM2 * DCOS( PLAT )**2
      ECSSQ2 = ECSSQ1**2

      R1 = EQRAD * ( 1.0D0 - ECC2 ) /

```

```

%      DSQRT( ( 1.0D0 - ECC2 * DSIN( PLAT ) )**3 )
      DIST1 = TRUEGE / ( RCURVE * SCALE )
      DIST2 = DIST1**2
      DIST3 = DIST1**3
      DIST4 = DIST1**4
      DIST5 = DIST1**5
      DIST6 = DIST1**6

      latitude...

      ALATT1 = 5.0D0 + ( 3.0D0 * TSQLT1 ) + ( 10.0D0 * ECSSQ1 ) -
%      ( 4.0D0 * ECSSQ2 ) - ( 9.0D0 * EPRIM2 )
      ALATT2 = 61.0D0 + ( 90.0D0 * TSQLT1 ) + ( 298.0D0 * ECSSQ1 ) +
%      ( 45.0D0 * TSQLT2 ) - ( 252.0D0 * EPRIM2 ) -
%      ( 3.0D0 * ECSSQ2 )

      ALAT = PHI1 - ( RCURVE * TAN( PHI1 ) / R1 ) *
%      ( DIST2 / 2.0D0 - ALATT1 * DIST4 / 24.0D0 +
%      ALATT2 * DIST6 / 720.0D0 )

      longitude...

      ALAMB1 = 1.0D0 + 2.0D0 * TSQLT1 + ECSSQ1
      ALAMB2 = 5.0D0 - ( 2.0D0 * ECSSQ1 ) + ( 28.0D0 * TSQLT1 ) -
%      ( 3.0D0 * ECSSQ2 ) + ( 8.0D0 * EPRIM2 ) +
%      ( 24.0D0 * TSQLT2 )

      ALON = CLON + ( DIST1 - ( ALAMB1 * DIST3 / 6.0D0 ) +
%      ( ALAMB2 * DIST5 / 120.0D0 ) ) / DCOS( PLAT )

      ALAT = ALAT / DEGRAD
      ALON = ALON / DEGRAD

      END

C**
C**
      SUBROUTINE EELLGR ( ALAT, ALON, GREAST, GRNRTH )
      *
      *      Subroutine EELLGR ( ALAT, ALON, GREAST, GRNRTH )
      *
      *      M.J.Smith      22-Mar-86
      *
      *      Fortran 77
      *
      *      MTS
      *
      *      -D+
      *
      *
      *      MODIFIED FOR IRISH GRID      Sept. 1987
      *
      *      This is a modified transverse mercator, central meridian
      *      8W00.00, Lat. origin 53N30.00
      *
      *      False origin set to 200000m west and 250000m south of true

```

```

*   origin to ensure grid coordinates.
*
*   Scale at central meridian is 1.000035
*
*-----
*
*   This routine converts the latitude-longitude coordinate
*   pair ( ALAT, ALON ) into its equivalent grid reference
*   ( GREAST, GRNRTH ). The angles are in degrees, and the
*   grid references are returned in metres.
*
*   To obtain a grid reference to +/-1m, the angles ALAT, ALON
*   must be known to 0.0000089 degrees, 0.0005 minutes or
*   0.03 seconds.
*
*   All calculations are in double precision.
*
*-----
*
*   The UK National Grid is based on a transverse mercator
*   projection with its true origin at 49N, 2W and a coordinate
*   origin at 400000m west and 100000m south of the true origin.
*   All values are multiplied by a scale factor 0.9996 to
*   minimise scale distortion over the area of the UK.
*
*   The calculations use Airy's (1849) spheroid and are based
*   on formulae given in Snyder, J.P., (1982), " Map projections
*   used by the U.S. Geological Survey ", Geological Survey
*   bulletin 1532, page 68.
*
*-D-
*
*   IMPLICIT DOUBLE PRECISION (A-H, O-Z)
*   LOGICAL INITC
*
*   SAVE
*
*   earth constants ( Airy's 1849 spheroid )
*
*   PARAMETER ( EQRAD = 6377563.4D0 )
*   PARAMETER ( POLRAD = 6356256.9D0 )
*   PARAMETER ( FLAT = 1. / 299.32 )
*
*   other constants
*
*   PARAMETER ( PI = 3.14159265358979D0 )
*   PARAMETER ( DEGRAD = .1745329251994329D-01 )
*
*   Initialise INITC.
*
*   This will ensure that constant initialisation will only
*   occur the first time that the routine is used.
*
*   DATA INITC / .TRUE. /
*
*   Set up projection constants

```

```

*   IF ( INITC ) THEN
*
*   OLAT, CMLON is the coordinate origin of the UK
*               national grid.
*   SCALE      is a scaling factor applied to minimise
*               distortion over the map area.
*
*   OLAT = 53.5D0
*   CMLON = -8.0D0
*   SCALE = 1.000035D0
*
*   now start the calculations
*
*   CLON = CMLON * DEGRAD
*   CLAT = OLAT * DEGRAD
*
*   FLT = 1.0D0 - POLRAD / EQRAD
*   ECC = DSQRT( 2 * FLT - FLT**2 )
*   ECC2 = ECC**2
*   ECC4 = ECC**4
*   ECC6 = ECC**6
*
*   EPRIM2 = ECC2 / ( 1.0D0 - ECC2 )
*
*   TERM1 = 1.0D0 - ( ECC2 / 4.0D0 ) - ( 3.0D0 * ECC4 / 64.0D0 ) -
*   %   { 5.0D0 * ECC6 / 256.0D0 }
*   TERM2 = { 3.0D0 * ECC2 / 8.0D0 } + ( 3.0D0 * ECC4 / 32.0D0 ) +
*   %   { 45.0D0 * ECC6 / 1024.0D0 }
*   TERM3 = { 15.0D0 * ECC4 / 256.0D0 } +
*   %   { 45.0D0 * ECC6 / 1024.0D0 }
*   TERM4 = { 35.0D0 * ECC6 / 3072.0D0 }
*
*   calculate distance along central meridian from
*   equator to latitude origin.
*
*   EQBDIS = EQRAD * ( ( TERM1 * CLAT ) -
*   %   { TERM2 * DSIN( CLAT * 2.0D0 ) } ) +
*   %   { TERM3 * DSIN( CLAT * 4.0D0 ) } -
*   %   { TERM4 * DSIN( CLAT * 6.0D0 ) } )
*
*   INITC = .FALSE.
*
*   ENDIF
*
*   Convert input lat/long to radians
*
*   PLAT = ALAT * DEGRAD
*   PLON = ALON * DEGRAD
*
*   these constants have no meaning outside of Snyder.
*
*   RCURVE = EQRAD / DSQRT ( 1.0D0 - ECC2 * DSIN( PLAT )**2 )
*   TSQLT1 = DTAN( PLAT )**2
*   TSQLT2 = TSQLT1**2
*   ECSSQ1 = EPRIM2 * DCOS( PLAT )**2
*   ECSSQ2 = ECSSQ1**2

```

```

      CDIFF1 = DCOS ( PLAT ) * ( PLON - CLON )
      CDIFF2 = CDIFF1**2
      CDIFF3 = CDIFF1**3
      CDIFF4 = CDIFF1**4
      CDIFF5 = CDIFF1**5
      CDIFF6 = CDIFF1**6

      calculate distance from equator to coordinate latitude
      EQDIS = EORAD * ( ( TERM1 * PLAT ) -
      % ( TERM2 * DSIN( PLAT * 2. ) ) +
      % ( TERM3 * DSIN( PLAT * 4. ) ) -
      % ( TERM4 * DSIN( PLAT * 6. ) ) )

      calculate easting GREAST
      XTERM1 = 1. - TSQLT1 + ECSSQ1
      XTERM2 = 5. - ( 18. * TSQLT1 ) + TSQLT2 + ( 72. * ECSSQ1 ) -
      % ( 58. * EPRIM2 )

      GREAST = SCALE * RCURVE * ( CDIFF1 + ( XTERM1 * CDIFF3 / 6. ) +
      % ( XTERM2 * CDIFF5 / 120. ) ) + 200000.

      calculate northing GRNRTH
      YTERM1 = 5. - TSQLT1 + ( 9. * ECSSQ1 ) + ( 4. * ECSSQ2 )
      YTERM2 = 61. - ( 58. * TSQLT1 ) + TSQLT2 + ( 600. * ECSSQ1 ) -
      % ( 330. * EPRIM2 )

      GRNRTH = SCALE * ( ( EQDIS - EQBDIS ) +
      % ( RCURVE * TAN ( PLAT ) * ( ( CDIFF2 / 2. ) +
      % ( YTERM1 * CDIFF4 / 24. ) +
      % ( YTERM2 * CDIFF6 / 720. ) ) ) ) + 250000.

      calculate scale along parallel at PLAT, PLON
      (Distortion from true scale of 1.0 )
      SCALEP = SCALE * ( 1. + ( 1. + ( EPRIM2 * DCOS( PLAT )**2 ) ) *
      % ( XCOORD - 400000. )**2 / ( 2. * SCALE**2 * RCURVE**2 ) ) )

      END
C**
C**
SUBROUTINE ENDRET(CRNLAT, CRNLON, GLATN1, GLATS1, GLON1, GLATNN,
1 GLATSN, GLONN, HWIDTH, U, DATA, RADPLT, LAMDA0, UE, UW,
2 KOUNT1, KOUNT2)
C**
C**
C** Subroutine ENDRET calculates the boundaries of the two
C** rectangles at each end of the geodesic designed
C** to cover all parts of the geodesic excluding
C** the area covered by the strip retrieval.
C**
      DOUBLE PRECISION CRNLAT(4), CRNLON(4)
      DOUBLE PRECISION GLATN1, GLATS1, GLON1

```

```

      DOUBLE PRECISION GLATNN, GLATSN, GLONN
      DOUBLE PRECISION RADPLT, LAMDA0, UE, UW
      DOUBLE PRECISION HWIDTH
      REAL NLAT, U(2000), DATA(3,2000)

C
C* CALCULATE BOUNDING POINTS FOR WESTERN END
      ELON = REAL(GLON1) - 0.1
      IF (GLATN1 .GT. CRNLAT(2)) THEN
        NLAT = GLATN1
      ELSE
        NLAT = CRNLAT(2)
      END IF
      IF (CRNLON(1) .LT. CRNLON(2)) THEN
        WLON = CRNLON(1)
      ELSE
        WLON = CRNLON(2)
      END IF
      IF (GLATS1 .LT. CRNLAT(1)) THEN
        SLAT = GLATS1
      ELSE
        SLAT = CRNLAT(1)
      END IF

C
      CALL CRECET(WLON, ELON, SLAT, NLAT, HWIDTH, U, DATA, RADPLT,
1 LAMDA0, UE, UW, KOUNT1, KOUNT2)

C
      WLON = REAL(GLONN) + 0.1
      IF (GLATNN .GT. CRNLAT(3)) THEN
        NLAT = GLATNN
      ELSE
        NLAT = CRNLAT(3)
      END IF
      IF (CRNLON(3) .GT. CRNLON(4)) THEN
        ELON = CRNLON(3)
      ELSE
        ELON = CRNLON(4)
      END IF
      IF (GLATSN .LT. CRNLAT(4)) THEN
        SLAT = GLATSN
      ELSE
        SLAT = CRNLAT(4)
      END IF

C
      CALL CRECET(WLON, ELON, SLAT, NLAT, HWIDTH, U, DATA, RADPLT,
1 LAMDA0, UE, UW, KOUNT1, KOUNT2)

C
      RETURN
      END

C**
C**
C** SUBROUTINE EXPAND(GLATN, GLATM, GLATS, HW)
C**
C**
C** Subroutine EXPAND extends north-south strips at both extremes.
C** The expansion is dependent upon the azimuth of the geodesic.
C** The azimuth is determined by difference in GLATN, GLATM etc..

```

```

C** Assume geodesic is a straight line for 0.1 degree section.
C**
C**
C** DOUBLE PRECISION GLATN, GLATM, GLATS, HW
C** DOUBLE PRECISION RAD, RADIUS, PIE, ALPHA
C** DOUBLE PRECISION DELTAD, DELTAH, TEMP
C
C DATA RAD, RADIUS /57.295779513D0, 6371.0D0/
C
C PIE = 4D0 * DATAN(1D0)
C
C DETERMINE N-S EXTENT OF HALF STRIP IN KM
C DELTAD = ((GLATN - GLATM) + (GLATM - GLATS)) / 2D0
C DELTAD = DELTAD * RADIUS / RAD
C
C ALPHA = DACOS(HW/DELTAD)
C DELTAH = 0.05D0 / DTAN(PIE/2D0-ALPHA)
C GLATN = GLATN + DABS(DELTAD)
C GLATS = GLATS - DABS(DELTAD)
C
C RETURN
C END
C**
C**
C** SUBROUTINE FEED
C** ~~~~~
C**
C** Subroutine FEED allows data from additional
C** data files to be read into the main gridding
C** procedure. The format of these input files should
C** be as follows.
C**
C** Sequential free format
C** RLAT, RLON, DATA FIELD (1 data field only)
C**
C** RLAT, RLON maybe replaced by GRNTH, GREAST.
C** Note only use additional OS Grid data for OS
C** Grids and additional Irish grid data for Irish
C** grids. The programme cannot convert data from
C** one grid to the other at present.
C**
C**
C** REAL FGRID(256,256), TGRID(256,256), BGRID(256,256),
C** 1 NGRID(256,256)
C
C INTEGER IFFLAG(256,256), ITFLAG(256,256), IBFLAG(256,256)
C
C CHARACTER INFILE*7, ITC2*1
C
C COMMON /GRIDS/ FGRID, TGRID, BGRID, NGRID
C COMMON /FLAGS/ IFFLAG, ITFLAG, IBFLAG
C COMMON /GRDOAT/ XMIN, XMAX, YMIN, YMAX, SAMP, IPROJ
C
C SET UNUSED ARGUMENTS TO BLANK (SEE TRANS)
C IEAST = 9999999
C INORTH = 9999999

```

```

C
C* IDENTIFY NEW DATA FILE
C 10 WRITE (6,20)
C 20 FORMAT ('/, '&', 4X, 'ENTER NAME OF INPUT DATA FILE')
C READ (5,30) INFILE
C 30 FORMAT (A7)
C
C OPEN (UNIT=1, FILE=INFILE, STATUS='OLD', ACCESS='SEQUENTIAL', FORM=
C 1 'FORMATTED')
C
C WRITE (6,40)
C 40 FORMAT ('/, 5X, 'ENTER TYPE OF FILE FORMAT', //, 5X,
C 1 'LATITUDE, LONGITUDE, DATA FIELD =1', //, 5X,
C 2 'OS GRID REF. :NORTH, EAST, DATA FIELD =2', //, '&', 4X,
C 3 'IRISH GRID REF. :NORTH, EAST, DATA FIELD =3')
C
C READ (5,*) IFORM
C
C IF (IFORM .NE. 3) THEN
C ITC2 = '0'
C ELSE IF (IFORM .EQ. 3) THEN
C ITC2 = '1'
C END IF
C
C WRITE (6,50)
C 50 FORMAT ('/, 5X, 'ENTER DATA FIELD TYPE ', //, 5X,
C 1 'FREE AIR GRAVITY =1', //, 5X, 'TOPOGRAPHY =2', //,
C 2 '&', 4X, 'BOUGUER GRAVITY =3')
C
C READ (5,*) ITYPE
C
C INPUT DATA IN END TERMINATED LOOP
C 60 READ (1,*, END=70) U, V, DATA
C
C IF (IFORM .EQ. 1) THEN
C
C CALL TRANS(U, V, IEAST, INORTH, X, Y, IPROJ, ITC2)
C
C ELSE
C
C X = V
C Y = U
C
C END IF
C
C ADD EXTRA DATA TO GRID
C IF ((X .GT. XMIN .AND. X .LT. XMAX) .AND. (Y .GT. YMIN .AND. Y .
C 1 LT. YMAX)) THEN
C
C IX = INT((X - XMIN)/SAMP) + 1
C IY = INT((Y - YMIN)/SAMP) + 1
C
C IF (ITYPE .EQ. 1) THEN
C
C IF (NGRID(IX,IY) .GT. 0.5 .AND. IFFLAG(IX,IY) .EQ. 1)
C 1 THEN

```

```

      IFFLAG(IX,IY) = INT(NGRID(IX,IY))
      END IF
C
      FGRID(IX,IY) = (FGRID(IX,IY)*REAL(IFFLAG(IX,IY)) + DATA) / (
1      REAL(IFFLAG(IX,IY)) + 1.0)
      IFFLAG(IX,IY) = IFFLAG(IX,IY) + 1
C
      ELSE IF (ITYPE .EQ. 2) THEN
C
      IF (NGRID(IX,IY) .GT. 0.5 .AND. ITFLAG(IX,IY) .EQ. 1)
1      THEN
C
      ITFLAG(IX,IY) = INT(NGRID(IX,IY))
C
      END IF
C
      TGRID(IX,IY) = (TGRID(IX,IY)*REAL(ITFLAG(IX,IY)) + DATA) / (
1      REAL(ITFLAG(IX,IY)) + 1.0)
      ITFLAG(IX,IY) = ITFLAG(IX,IY) + 1
C
      ELSE IF (ITYPE .EQ. 3) THEN
C
      IF (NGRID(IX,IY) .GT. 0.5 .AND. IBFLAG(IX,IY) .EQ. 1)
1      THEN
C
      IBFLAG(IX,IY) = INT(NGRID(IX,IY))
C
      END IF
C
      BGRID(IX,IY) = (BGRID(IX,IY)*REAL(IBFLAG(IX,IY)) + DATA) / (
1      REAL(IBFLAG(IX,IY)) + 1.0)
      IBFLAG(IX,IY) = IBFLAG(IX,IY) + 1
C
      END IF
C
      END IF
C
      LOOP TO READ
      GO TO 60
C
      AT END OF FILE EXIT LOOP
70 CLOSE (UNIT=1,STATUS='KEEP')
C
      ENTER NEW INPUT FILE ?
      WRITE (6,80)
80 FORMAT (/, 5X, 'DO YOU WISH TO ENTER ANOTHER ', /, '&', 4X,
1      'INPUT FILE ? YES(1) NO(0) ')
      READ (5,*) INEW
C
      IF (INEW .EQ. 1) GO TO 10
C
      RETURN
      END
C**
C**

```

```

SUBROUTINE FILTER(NX, NY, IMOD)
C**
C**
C** Subroutine Filter is the main frequency domain
C** modification routine which will allow a
C** variety of frequency domain filters to be applied.
C**
C**
      REAL*8 DATAR(50000), DATAI(50000)
      REAL*8 DNX, DNY, PIE, DSAMP, DK, DKSQ, ZLVL
C
C* DEFINE COMMON
      COMMON /RCOMP/ DATAR
      COMMON /ICOMP/ DATAI
      COMMON /AREA/ XMIN, XMAX, YMIN, YMAX, SAMP
C
C* DEFINE REPETITELY USED VARIABLES
      DNX = DFLOAT(NX)
      DNY = DFLOAT(NY)
      DSAMP = DBLE(SAMP)
      PIE = 4.0D0 * ATAN(1.0D0)
C
      IF (IMOD .EQ. 1) THEN
C
      C* SET UP LOW PASS FILTER
      CALL GLPSET(DSAMP, DK)
      DKSQ = DK * DK
C
      ELSE IF (IMOD .EQ. 2) THEN
C
      C* ENTER CONTINUATION DISTANCE
      WRITE (6,10)
10  FORMAT (/, 5X, 'Enter continuation distance (Metres)', /, 5X,
1      'Note: Z axis positive downwards', /)
      READ (5,*) ZLVL
C
      END IF
C
      C* MODIFY FFT DATA WITH APPROPRIATE FILTER
      DO 40 KX = 1, NX / 2 + 1
      KXN = KX - 1
      DO 20 KY = 1, NY / 2 + 1
      KYN = KY - 1
C
      IF (IMOD .EQ. 1) THEN
      CALL GLP(KX, KY, KXN, KYN, NX, NY, DNX, DNY, DKSQ, DSAMP)
      ELSE IF (IMOD .EQ. 2) THEN
      CALL UPCONT(KX, KY, KXN, KYN, NX, NY, DNX, DNY, ZLVL, DSAMP)
      END IF
C
20  CONTINUE
      DO 30 KY = NY / 2 + 2, NY
      KYN = NY - (KY - 1)
C
      IF (IMOD .EQ. 1) THEN
      CALL GLP(KX, KY, KXN, KYN, NX, NY, DNX, DNY, DKSQ, DSAMP)

```

```

        ELSE IF (IMOD.EQ. 2) THEN
          CALL UPCONT(KX, KY, KXN, KYN, NX, NY, DNX, DNY, ZLVL, DSAMP)
        END IF
C
30  CONTINUE
40  CONTINUE
C
      DO 70 KX = NX / 2 + 2, NX
        KXN = NX - (KX - 1)
        DO 50 KY = 1, NY / 2 + 1
          KYN = KY - 1
C
          IF (IMOD.EQ. 1) THEN
            CALL GLP(KX, KY, KXN, KYN, NX, NY, DNX, DNY, DKSQ, DSAMP)
          ELSE IF (IMOD.EQ. 2) THEN
            CALL UPCONT(KX, KY, KXN, KYN, NX, NY, DNX, DNY, ZLVL, DSAMP)
          END IF
C
50  CONTINUE
      DO 60 KY = NY / 2 + 2, NY
        KYN = NY - (KY - 1)
C
        IF (IMOD.EQ. 1) THEN
          CALL GLP(KX, KY, KXN, KYN, NX, NY, DNX, DNY, DKSQ, DSAMP)
        ELSE IF (IMOD.EQ. 2) THEN
          CALL UPCONT(KX, KY, KXN, KYN, NX, NY, DNX, DNY, ZLVL, DSAMP)
        END IF
C
60  CONTINUE
70  CONTINUE
C
      WRITE (6,80)
80  FORMAT (/, 5X, 'Frequency Domain Modification Complete', /)
C
      RETURN
      END
C**
C**
      DOUBLE PRECISION FUNCTION FRM ( ECC, PLAT )
      *
      *-T Double precision function FRM ( ECC, PLAT )
      *
      *-A M.J.Smith      August 1986
      *
      *-D+
      *
      *-D- Used in ALBEE and ALBEEI
      *
      *
      * IMPLICIT DOUBLE PRECISION ( A-H, O-Z )
      *
      * ECC2 = ECC**2
      *
      * FRM = COS( PLAT ) / SORT( 1.0D0 - ECC2 * SIN( PLAT )**2 )
      *
      *
      END
C**

```

```

C**
      DOUBLE PRECISION FUNCTION FT ( ECC, PLAT )
      *
      *-T Double precision function FT ( ECC, PLAT )
      *
      *-A M.J.Smith      August 1986
      *
      *-D+
      *
      *-D- Used to calculate Tn in LAMCE and LAMCEI
      *
      *
      * IMPLICIT DOUBLE PRECISION ( A-H, O-Z )
      *
      * PARAMETER ( PI = 3.14159265358979312D0 )
      * PARAMETER ( DEGRAD = 0.174532925199432946D-01 )
      *
      * T1 = TAN( PI / 4.0D0 - PLAT / 2.0D0 )
      * T2 = ( 1.0D0 - ECC * SIN( PLAT ) ) / ( 1.0D0 + ECC * SIN( PLAT ) )
      *
      * FT = T1 / SQRT( T2**ECC )
      *
      *
      END
C**
C**
      SUBROUTINE GDSTRC(RLAT1, RLO1, RLAT2, RLO2, LIMITW, LIMITE,
1      GLAT, GLON, K)
C**
      *
C**
      * Subroutine GDSTRC traces out the spherical geodesic between
C**
      * RLAT1, RLO1 and RLAT2, RLO2 in the range LIMITW to LIMITE (Long.)
C**
      * in 0.1 degrees of longitude intervals.
C**
      *
      * IMPLICIT DOUBLEPRECISION(D)
      * DOUBLE PRECISION RLAT1, RLO1, RLAT2, RLO2, RAD
      * DOUBLE PRECISION LIMITE, LIMITW, GLON(1000), GLAT(1000)
      * DOUBLE PRECISION RADLT1, RADLN1, RADLT2, RADLN2, RADGLN
C
      DATA RAD /57.295779513D0/
C
      RADLT1 = RLAT1 / RAD
      RADLN1 = RLO1 / RAD
      RADLT2 = RLAT2 / RAD
      RADLN2 = RLO2 / RAD
C
      *
C*
      * EVALUATE CONSTANTS IN TRACING FORMULA
      * DCNST1 = (DTAN(RADLT2)*DCOS(RADLN1) - DTAN(RADLT1)*DCOS(RADLN2)) /
      * 1 DSIN(RADLN2 - RADLN1)
      * DCNST2 = (DTAN(RADLT2)*DSIN(RADLN1) - DTAN(RADLT1)*DSIN(RADLN2)) /
      * 1 DSIN(RADLN2 - RADLN1)
C
      *
      * K = 1
      * GLON(K) = LIMITW
      * RADGLN = GLON(K) / RAD
C
      *
      * 10 GLAT(K) = DATAN(DCNST1*DSIN(RADGLN) - DCNST2*DCOS(RADGLN))

```

```

      GLAT(K) = GLAT(K) * RAD
      IF (DABS(GLON(K) - LIMITE) .LT. 0.09D0) GO TO 20
      K = K + 1
      GLON(K) = GLON(K - 1) + 0.1D0
      RADGLN = GLON(K) / RAD
      GO TO 10
C
20 RETURN
END
C**
C**
C** SUBROUTINE GLP(KX, KY, KXN, KYN, NX, NY, DNX, DNY, DKSQ, DSAMP)
C** ~~~~~
C** Subroutine GLP performs the Gaussian Low Pass filtering
C** driven by Filter. Note that for this application K is
C** the inverse of wavelength without the 2*pi scaling
C** factor. This is due to the approach of Mesko.
C**
C**
C** REAL*8 DATAR(50000), DATAI(50000)
C** REAL*8 DNX, DNY, DKX, DKY, DSAMP, DKSQ, DKZSQ, FILT
C
COMMON /RCOMP/ DATAR
COMMON /ICOMP/ DATAI
C
C* DEDUCE POSITION OF DATA ELEMENT IN MAIN ARRAY
IPOS = (KY - 1) * NX + KX
C
C* CALCULATE WAVENUMBER IN M-1
DKX = DFLOAT(KXN)
DKY = DFLOAT(KYN)
C
DKZSQ = (DKX/(DNX*DSAMP)) ** 2 + (DKY/(DNY*DSAMP)) ** 2
C
C* EVALUATE FILTER COEFFICIENTS
FILT = EXP(-1.0D0*(DKSQ*DKZSQ))
C
DATAR(IPOS) = DATAR(IPOS) * FILT
DATAI(IPOS) = DATAI(IPOS) * FILT
C
RETURN
END
C**
C**
C** SUBROUTINE GLPSET(DSAMP, DK)
C** ~~~~~
C** Subroutine GLPSET (Gaussian Low Pass Filter set up)
C** is designed to define the parameter K in
C**
C**
C** S(fr) = exp(-((k*fr)**2))
C**
C** In Fft.Filter K is represented by DK. The value
C** of K is set using a cut off frequency fc at which
C** frequency the filter gain is -3dB. However aliasing

```

```

C** becomes troublesome if DK/DSAMP < 4. Therefore the
C** user specified cut off frequency must be checked
C** before filtering.
C**
C** Additional details of Low Pass Filter design can be
C** found in Mesko:Digital Filtering: Applications in
C** Geophysical Exploration for Oil
C**
C**
C** IMPLICIT REAL*8(A - H,O - Z)
C
C* ENTER CUT OFF FREQUENCY
10 WRITE (6,20)
20 FORMAT (/, 5X, 'Enter cut off frequency in Km', /)
C
READ (5,*) WAVEKM
WAVEM = WAVEKM * 1000.0
FC = 1.0D0 / WAVEM
C
C* CALCULATE PARAMETER DK
DK = 0.588D0 / FC
C
C* CALCULATE DIMENSIONLESS CONSTANT DK PRIME
DKPR = DK / DSAMP
C
C* CHECK FOR ALIASING
IF (DKPR .LT. 4.0D0) THEN
  WRITE (6,30) DKPR
30 FORMAT (/, 5X, 'Value of K prime < 4 : K'' = ', F8.4, /, 5X,
1 'Errors may occur due to aliasing', /, 5X,
2 'Please increase cut off wavelength', /)
C
GO TO 10
END IF
C
WRITE (6,40) DKPR
40 FORMAT (/, 5X, 'Parameter K'' = ', F8.4, /)
C
RETURN
END
C**
C**
C** SUBROUTINE GRF(XORGN, YORGN, XEXT, YEXT, ITEST0, U, DATA, UE, UW,
1 DLAT1, DLON1, DLAT2, DLON2, WAZ, EAZ, KOUNT1, INDIC)
C** ~~~~~
C** Subroutine GRF is the plotting subroutine to draw the gravity and
C** topography profiles. Automatic scaling fits any profile to XEXT,
C** YEXT the actual length of the axes.
C**
C**
C** XORGN, YORGN = x, y origin for Gnof coordinates
C** XEXT, YEXT = Length of x, y axes in inches
C** ITEST0 = Profile option indicator
C** U = Array holding x positions of data
C** DATA = Array holding values of data fields
C** KOUNT1 = Number of elements in arrays U and DATA

```



```

C**
C**
      DIMENSION U(2000), DATA(3,2000)
      DOUBLE PRECISION DLAT1, DLON1, DLAT2, DLON2, UE, UW, WAZ, EAZ, RAD
      CHARACTER LINE1*7, LINE2*7, LINE3*10, LINE4*20
      CHARACTER LINE5*38, LINE6*29, LINE7*32, LINE8*18
      CHARACTER LINE9*12, LINE10*17

C
C*
C*
      SET VALUES TO CHARACTER STRINGS:*. IS THE GINO
      CHARACTER STRING TERMINATING ESCAPE CHARACTER
      PARAMETER (LINE1='LAT.=*.*')
      PARAMETER (LINE2='LON.=*.*')
      PARAMETER (LINE3='AZIMUTH=*.*')
      PARAMETER (LINE4='D*LISTANCE *U(KM)*.*')
      PARAMETER (LINE5='F*LREE *UA*LIR *UA*LNOMALY M*UG*LAL*.*')
      PARAMETER (LINE6=' T*LOPOGRAPHY *UM*LETRES*.*')
      PARAMETER (LINE7='B*LOUGUER *UA*LNOMALY M*UG*LAL*.*')
      PARAMETER (LINE8='FREE AIR GRAVITY*.*')
      PARAMETER (LINE9='TOPOGRAPHY*.*')
      PARAMETER (LINE10='BOUGUER GRAVITY*.*')

C
      DATA RAD /57.295779513D0/

C
C*
      SET CHARACTER SIZE
      WD = .1
      HT = .1
      CALL CHASIZ(WD, HT)

C
C*
      SHIFT GINO ORIGIN
      CALL SHIFT2(XORGN, YORGN)
      CALL MOVTO2(0.0, 0.0)

C
C*
      CALCULATE X AND Y SCALE FACTORS
      XDIST = SNGL(DABS(UE - UW))
      YMAX = DATA(ITEST0,1)
      YMIN = DATA(ITEST0,1)
      DO 10 K = 1, KOUNT1
        IF (DATA(ITEST0,K) .GT. YMAX) THEN
          YMAX = DATA(ITEST0,K)
        END IF
        IF (DATA(ITEST0,K) .LT. YMIN) THEN
          YMIN = DATA(ITEST0,K)
        END IF
      10 CONTINUE

C
      YDIST = YMAX - YMIN
      XSCALE = XEXT / XDIST
      YSCALE = YEXT / YDIST

C
C*
      CALCULATE SCALING UNITS
      IF (YDIST .LE. 10.0) THEN
        LY = 1
      ELSE IF (YDIST .GT. 10.0 .AND. YDIST .LE. 100.0) THEN
        LY = 10
      ELSE IF (YDIST .GT. 100.0 .AND. YDIST .LE. 500.0) THEN
        LY = 50
      ELSE IF (YDIST .GT. 500.0 .AND. YDIST .LE. 1000.0) THEN
        LY = 100
      ELSE
        LY = 500
      END IF

C
      IF (XDIST .LE. 10.0) THEN
        LX = 1
      ELSE IF (XDIST .GT. 10.0 .AND. XDIST .LE. 100.0) THEN
        LX = 10
      ELSE IF (XDIST .GT. 100.0 .AND. XDIST .LE. 500.0) THEN
        LX = 50
      ELSE IF (XDIST .GT. 500.0 .AND. XDIST .LE. 1000.0) THEN
        LX = 100
      ELSE
        LX = 250
      END IF

C
      LYMIN = YMIN / LY
      LYMIN = LYMIN * LY
      IF (REAL(LYMIN) .LE. YMIN) LYMIN = LYMIN + LY
      LYMAX = YMAX / LY
      LYMAX = LYMAX * LY
      IF (REAL(LYMAX) .GE. YMAX) LYMAX = LYMAX - LY
      LXMAX = XDIST / LX
      LXMAX = LXMAX * LX
      IF (REAL(LXMAX) .GE. XDIST) LXMAX = LXMAX - LX

C
C*
      DRAW AND ANNOTATE AXES
      CALL LINTO2(0.0, YEXT)
      IF (YMAX*YMIN .LE. 0.0) THEN
        YAXIS = (0.0 - YMIN) * YSCALE
      ELSE
        YAXIS = 0.0
      END IF
      CALL MOVTO2(0.0, YAXIS)
      CALL LINTO2(XEXT, YAXIS)

C
      CALL MOVTO2(0.0, 0.0)
      XPOS = WD * (-7.0)
      DO 20 K = LYMIN, LYMAX, LY
        Y = (REAL(K) - YMIN) * YSCALE
        CALL MOVTO2(XPOS, Y)
        CALL CHAINT(K, 6)
        CALL MOVTO2(-0.05, Y)
        CALL LINTO2(0.0, Y)
      20 CONTINUE

C
      CALL MOVTO2(0.0, 0.0)
      YPOS = HT * (-2.0)
      IF (LX .LE. LXMAX) THEN
        DO 30 K = LX, LXMAX, LX
          X = REAL(K) * XSCALE
          XPOS = X - 2.0 * WD
          CALL MOVTO2(XPOS, YPOS)
          CALL CHAINT(K, -6)
        30 CONTINUE

```

```

      CALL MOVTO2(X, -0.05)
      CALL LINTO2(X, 0.0)
30  CONTINUE
      END IF
C
C* LABEL AXES AND ADD ADDITIONAL DATA
      IF (INDIC.EQ. 0) THEN
        CALL MOVTO2(-.5, -.5)
        CALL CHAHOL(LINE1)
        RLAT1 = SNGL(DLAT1)
        CALL CHAFIX(RLAT1, -10, 4)
        CALL MOVTO2(-.5, -.75)
        CALL CHAHOL(LINE2)
        RLON1 = SNGL(DLON1)
        CALL CHAFIX(RLON1, -10, 4)
        CALL MOVTO2(-.5, -1.0)
        CALL CHAHOL(LINE3)
        WAZ = WAZ * RAD
        AZ1 = SNGL(WAZ)
        CALL CHAFIX(AZ1, -7, 2)
C
      XPOS = XEXT - 1.5
      CALL MOVTO2(XPOS, -.5)
      CALL CHAHOL(LINE1)
      RLAT2 = SNGL(DLAT2)
      CALL CHAFIX(RLAT2, -10, 4)
      CALL MOVTO2(XPOS, -.75)
      CALL CHAHOL(LINE2)
      RLON2 = SNGL(DLON2)
      CALL CHAFIX(RLON2, -10, 4)
      CALL MOVTO2(XPOS, -1.0)
      CALL CHAHOL(LINE3)
      EAZ = EAZ * RAD
      AZ2 = SNGL(EAZ)
      CALL CHAFIX(AZ2, -7, 2)
C
      END IF
C
      CALL MOVTO2(3.5, -.50)
      CALL CHAHOL(LINE4)
      YPOS = YEXT - 2.00
      CALL MOVTO2(-1.1, YPOS)
      CALL CHAANG(90.0)
      IF (ITEST0.EQ. 1) CALL CHAHOL(LINE5)
      IF (ITEST0.EQ. 2) CALL CHAHOL(LINE6)
      IF (ITEST0.EQ. 3) CALL CHAHOL(LINE7)
      CALL CHAANG(0.0)
C
      YPOS = YEXT + HT
      CALL MOVTO2(2.0, YPOS)
      IF (ITEST0.EQ. 1) CALL CHAHOL(LINE8)
      IF (ITEST0.EQ. 2) CALL CHAHOL(LINE9)
      IF (ITEST0.EQ. 3) CALL CHAHOL(LINE10)
C
C* FINALLY PLOT DATA POINTS
      CALL CHASIZ(0.075, 0.075)
      DO 50 K = 1, KOUNT1

```

```

      Y = (DATA(ITEST0,K) - YMIN) * YSCALE
      IF (U(K) .LT. 0.0) THEN
        WRITE (6,40) U(K)
40      FORMAT ('/, 5X, 'ERROR U(K)<0.0', U(K)=', F10.3, '/', 5X,
1        'PROGRAM TERMINATED', /)
        STOP
        END IF
        X = U(K) * XSCALE
        CALL MOVTO2(X, Y)
        CALL SYMBOL(3)
50  CONTINUE
C
      RETURN
      END
C**
C** SUBROUTINE GRIDDR(RLAT, RLON, IEAST, INORTH, RFREEA, RTOP, RBOUG,
1      ITC2)
C**
C** ~~~~~
C** Subroutine GRIDDR executes the first part of the gridding process
C** by summing each of the three data fields in each grid square.
C** Subroutine GRIDDR also sets flags to 1 if data occurs within grid
C** squares. This will help in the addition of extra data later.
C**
      REAL FGRID(256,256), TGRID(256,256), BGRID(256,256),
1      NGRID(256,256)
      INTEGER IFFLAG(256,256), ITFLAG(256,256), IBFLAG(256,256)
      CHARACTER ITC2*1
C
      COMMON /GRIDS/ FGRID, TGRID, BGRID, NGRID
      COMMON /FLAGS/ IFFLAG, ITFLAG, IBFLAG
      COMMON /GRDDAT/ XMIN, XMAX, YMIN, YMAX, SAMP, IPROJ
C
C* CONVERT DATA TO PROJECTION REQUIRED
      CALL TRANS(RLAT, RLON, IEAST, INORTH, X, Y, IPROJ, ITC2)
C
C* GRID DATA IF IN GRID REGION
      IF ((X.GT. XMIN .AND. X.LT. XMAX) .AND. (Y.GT. YMIN .AND. Y
1      .LT. YMAX)) THEN
C
        IX = INT((X - XMIN)/SAMP) + 1
        IY = INT((Y - YMIN)/SAMP) + 1
C
        FGRID(IX,IY) = FGRID(IX,IY) + RFREEA
        TGRID(IX,IY) = TGRID(IX,IY) + RTOP
        BGRID(IX,IY) = BGRID(IX,IY) + RBOUG
        NGRID(IX,IY) = NGRID(IX,IY) + 1.0
C
        IF (IFFLAG(IX,IY) .NE. 1) IFFLAG(IX,IY) = 1
        IF (ITFLAG(IX,IY) .NE. 1) ITFLAG(IX,IY) = 1
        IF (IBFLAG(IX,IY) .NE. 1) IBFLAG(IX,IY) = 1
C
      END IF
C
      RETURN

```

```

C** END
C**
C** SUBROUTINE GRSET(WLON, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX,
1 SAMP, IPROJ)
C**
C** Subroutine GRSET sets up coordinates for data retrieval
C** for gridding in OS/Irish grid mode.
C**
C** IMPLICIT DOUBLE PRECISION (A - H,O - Z)
C
C DOUBLE PRECISION NLAT
C
C DIMENSION CLAT(4), CLON(4)
C
C WRITE (6,10)
10 FORMAT (/, 5X, 'ENTER GRID COORDINATES BOUNDING ', /, '&', 4X,
1 'AREA: GRWEST,GREAST,GRSTH,GRNTH')
C
C READ (5,*) GRWEST, GREAST, GRSTH, GRNTH
C
C* DEFINE SEARCH AREA
XMIN = GRWEST
XMAX = GREAST
YMIN = GRSTH
YMAX = GRNTH
C
C WRITE (6,20)
20 FORMAT (/, '&', 4X, 'ENTER SAMPLING INTERVAL (METRES)')
C
C READ (5,*) SAMP
C
C* CALCULATE LAT., LON. OF CORNERS OF GRID
C
C IF (IPROJ.EQ. 1) THEN
C CALL GRTOLL(GRWEST, GRSTH, CLAT(1), CLON(1))
C CALL GRTOLL(GREAST, GRSTH, CLAT(2), CLON(2))
C CALL GRTOLL(GRWEST, GRNTH, CLAT(3), CLON(3))
C CALL GRTOLL(GREAST, GRNTH, CLAT(4), CLON(4))
C ELSE IF (IPROJ.EQ. 3) THEN
C CALL EEGRLL(GRWEST, GRSTH, CLAT(1), CLON(1))
C CALL EEGRLL(GREAST, GRSTH, CLAT(2), CLON(2))
C CALL EEGRLL(GRWEST, GRNTH, CLAT(3), CLON(3))
C CALL EEGRLL(GREAST, GRNTH, CLAT(4), CLON(4))
C END IF
C
C WRITE (7,30) GRWEST, GRSTH, CLAT(1), CLON(1)
C WRITE (7,30) GREAST, GRSTH, CLAT(2), CLON(2)
C WRITE (7,30) GRWEST, GRNTH, CLAT(3), CLON(3)
C WRITE (7,30) GREAST, GRNTH, CLAT(4), CLON(4)
C
30 FORMAT (5X, 'EASTING = ', F10.1, ' NORTHING = ', F10.1,
1 ' LATITUDE = ', F7.4, ' LONGITUDE = ', F8.4)
C

```

```

C* DETERMINE LAT., LON. RETRIEVAL AREA
AMAXLT = -1.0E+10
AMAXLN = -1.0E+10
AMINLT = 1.0E+10
AMINLN = 1.0E+10
C
DO 40 K = 1, 4
IF (CLAT(K) .GT. AMAXLT) AMAXLT = CLAT(K)
IF (CLON(K) .GT. AMAXLN) AMAXLN = CLON(K)
IF (CLAT(K) .LT. AMINLT) AMINLT = CLAT(K)
IF (CLON(K) .LT. AMINLN) AMINLN = CLON(K)
40 CONTINUE
C
C* DEFINE DATA RETRIEVAL COORDINATES
WLON = AMINLN
ELON = AMAXLN
SLAT = AMINLT
NLAT = AMAXLT
C
C* OUTPUT RESULTS
WRITE (7,50) WLON, ELON, SLAT, NLAT
50 FORMAT (/, 5X, 'DATA SEARCH AREA', /, 5X, 'WEST LONGITUDE = ',
1 F8.4, /, 5X, 'EAST LONGITUDE = ', F8.4, /, 5X,
2 'SOUTH LATITUDE = ', F7.4, /, 5X, 'NORTH LATITUDE = ',
3 F7.4, /)
C
RETURN
END
C**
C** SUBROUTINE GRTOLL ( GREAST, GRNRTH, ALAT, ALON )
*
*-T Subroutine GRTOLL ( GREAST, GRNRTH, ALAT, ALON )
*
*-A M.J.Smith 22-Mar-86
*
*-L Fortran 77
*
*-OS MTS
*
*-D+
* Returns the latitude and longitude ( ALAT, ALON ) in degrees of
* a point given its grid reference ( GREAST, GRNRTH ) in metres.
*
* If the grid reference is given to the nearest metre, the lat/long
* will be accurate to +/-0.0000089 degrees, 0.0005 minutes or
* 0.035 seconds.
*
* Uses formulae given in Snyder, J.P., (1982), " Map projections
* used by the U.S. Geological Survey ", Geological Survey bulletin
* 1532, page 68.
*
* The UK national grid is a modified UTM projection with a false
* origin at ( 0m, 0m ) and a true origin ( 400000m, 100000m ) at
* 49N, 2W.
*

```

```

* Double precision used throughout.
*-D-
*
* IMPLICIT DOUBLE PRECISION (A-H, O-Z)
* LOGICAL INITC
*
* earth constants ( Airy's 1849 spheroid )
*
* PARAMETER ( EQRAD = 6377563.4D0 )
* PARAMETER ( POLRAD = 6356256.9D0 )
* PARAMETER ( FLAT = 1. / 299.32 )
*
* other constants
*
* PARAMETER ( PI = 3.14159265358979D0 )
* PARAMETER ( DEGRAD = .1745329251994329D-01 )
*
* Initialise INITC. This ensures that constant initialisation
* is only carried out once, on the first call to this routine.
*
* DATA INITC / .TRUE. /
*
* now start the calculations
*
* IF ( INITC ) THEN
*
*   OLAT = 49.0D0
*   CMLON = -2.0D0
*   SCALE = 0.9996
*
*   CLON = CMLON * DEGRAD
*   CLAT = OLAT * DEGRAD
*
*   FLT = 1.0D0 - POLRAD / EQRAD
*   ECC = DSQRT( 2.0D0 * FLT - FLT**2 )
*   ECC2 = ECC**2
*   ECC4 = ECC**4
*   ECC6 = ECC**6
*
*   TERM1 = 1.0D0 - ( ECC2 / 4.0D0 ) - ( 3.0D0 * ECC4 / 64.0D0 ) -
%   TERM2 = { 5.0D0 * ECC6 / 256.0D0 } +
%   { 3.0D0 * ECC2 / 8.0D0 } + ( 3.0D0 * ECC4 / 32.0D0 ) +
%   { 45.0D0 * ECC6 / 1024.0D0 }
*   TERM3 = { 15.0D0 * ECC4 / 256.0D0 } + ( 45.0D0 * ECC6 /
%   1024.0D0 )
*   TERM4 = ( 35.0D0 * ECC6 / 3072.0D0 )
*
*   calculate distance along central meridian from
*   equator to latitude origin.
*
*   EQBDIS = EQRAD * ( { TERM1 * CLAT } -
%   { TERM2 * DSIN( CLAT * 2.0D0 ) } +
%   { TERM3 * DSIN( CLAT * 4.0D0 ) } -
%   { TERM4 * DSIN( CLAT * 6.0D0 ) } )
*
*   calculate e1

```

```

*
*   SRE2 = DSQRT( 1.0D0 - ECC2 )
*   E1 = ( 1.0D0 - SRE2 ) / ( 1.0D0 + SRE2 )
*
*   INITC = .FALSE.
*
* ENDIF
*
* TRUEGE = GREAST - 400000.0D0
* TRUEGN = GRNRTH + 100000.0D0
*
* calculate EQDIS
*
* EQDIS = EQBDIS + TRUEGN / SCALE
*
* calculate MU
*
* XMU = EQDIS / ( EQRAD * ( 1.0D0 - ECC2 / 4.0D0 -
%   3.0D0 * ECC4 / 64.0D0 - 5.0D0 * ECC6 / 256.0D0 ) )
*
* calculate footpoint latitude, PHI1
*
* PHIT1 = ( 3.0D0 * E1 / 2.0D0 ) - ( 27.0D0 * E1**3 / 32.0D0 )
* PHIT2 = ( 21.0D0 * E1**2 / 16.0D0 ) - ( 55.0D0 * E1**4 / 32.0D0 )
* PHIT3 = ( 151.0D0 * E1**3 / 96.0D0 )
*
* PHI1 = XMU + PHIT1 * DSIN( 2.0D0 * XMU ) +
%   PHIT2 * DSIN( 4.0D0 * XMU ) +
%   PHIT3 * DSIN( 6.0D0 * XMU )
*
* PLAT = PHI1
*
* other constants
*
* EPRIM2 = ECC2 / ( 1.0D0 - ECC2 )
* RCURVE = EQRAD / DSQRT( 1.0D0 - ECC2 * DSIN( PLAT )**2 )
* TSQLT1 = DTAN( PLAT )**2
* TSQLT2 = TSQLT1**2
* ECSSQ1 = EPRIM2 * DCOS( PLAT )**2
* ECSSQ2 = ECSSQ1**2
*
* R1 = EQRAD * ( 1.0D0 - ECC2 ) /
%   DSQRT( ( 1.0D0 - ECC2 * DSIN( PLAT ) )**3 )
* DIST1 = TRUEGE / ( RCURVE * SCALE )
* DIST2 = DIST1**2
* DIST3 = DIST1**3
* DIST4 = DIST1**4
* DIST5 = DIST1**5
* DIST6 = DIST1**6
*
* latitude...
*
* ALATT1 = 5.0D0 + ( 3.0D0 * TSQLT1 ) + ( 10.0D0 * ECSSQ1 ) -
%   ( 4.0D0 * ECSSQ2 ) - ( 9.0D0 * EPRIM2 )
* ALATT2 = 61.0D0 + ( 90.0D0 * TSQLT1 ) + ( 298.0D0 * ECSSQ1 ) +
%   ( 45.0D0 * TSQLT2 ) - ( 252.0D0 * EPRIM2 ) -
%   ( 3.0D0 * ECSSQ2 )

```

```

      ALAT = PHI1 - ( RCURVE * TAN( PHI1 ) / R1 ) *
%      ( DIST2 / 2.000 - ALATT1 * DIST4 / 24.000 +
%      ALATT2 * DIST6 / 720.000 )
      longitude...
      ALAMB1 = 1.000 + 2.000 * TSQ1 + ECSSQ1
      ALAMB2 = 5.000 - ( 2.000 * ECSSQ1 ) + ( 28.000 * TSQ1 ) -
%      ( 3.000 * ECSSQ2 ) + ( 8.000 * EPRIM2 ) +
%      ( 24.000 * TSQ2 )
      ALON = CLON + ( DIST1 - ( ALAMB1 * DIST3 / 6.000 ) +
%      ( ALAMB2 * DIST5 / 120.000 ) ) / DCOS( PLAT )
      ALAT = ALAT / DEGRAD
      ALON = ALON / DEGRAD
      END
C**
C** SUBROUTINE IMAGE(DATA, IXRANG, IYRANG, IHANCE, SAMP)
C** ~~~~~
C** Subroutine IMAGE enhances gridded array input
C** to form more useful images.
C**
      DIMENSION DATA(IXRANG,IYRANG)
      DATA IEXP, RANGE /2, 254.0/
      IF (IHANCE .LE. 3) THEN
C*
C*   GREY SCALE MODIFICATION
      AMAX = -1.0E+10
      AMIN = 1.0E+10
      DO 20 K = 1, IXRANG
        DO 10 L = 1, IYRANG
          IF (DATA(K,L) .LT. 32767.0) THEN
            IF (DATA(K,L) .GT. AMAX) AMAX = DATA(K,L)
            IF (DATA(K,L) .LT. AMIN) AMIN = DATA(K,L)
          END IF
        CONTINUE
      CONTINUE
      WRITE (6,30) AMAX, AMIN
      30 FORMAT (5X, 'MAXIMUM DATA VALUE =', F10.2, '/', 5X,
      1 'MINIMUM DATA VALUE =', F10.2, '/')
      IF (IHANCE .EQ. 2) THEN
        WRITE (6,40)
        40 FORMAT (5X, 'ENTER NEW MINIMA AND MAXIMA ', /)
        READ (5,*) AMIN, AMAX
      END IF

```

```

      IF (IHANCE .LE. 2) THEN
        DO 60 K = 1, IXRANG
          DO 50 L = 1, IYRANG
            IF (DATA(K,L) .LT. 32767.0) THEN
              DATA(K,L) = ((DATA(K,L) - AMIN)*RANGE/(AMAX - AMIN)) + 1
              IF (DATA(K,L) .GT. RANGE) DATA(K,L) = RANGE + 1
              IF (DATA(K,L) .LT. 0.0) DATA(K,L) = 0.0
            ELSE
              DATA(K,L) = 0.0
            END IF
          CONTINUE
        CONTINUE
      ELSE IF (IHANCE .EQ. 3) THEN
C*
C*   POWER SCALE
      AMAX1 = -1.0E+10
      AMIN1 = 1.0E+10
      DO 80 K = 1, IXRANG
        DO 70 L = 1, IYRANG
          IF (DATA(K,L) .LT. 32767.0) THEN
            DATA(K,L) = (((DATA(K,L) - AMIN)*RANGE/(AMAX - AMIN)) +
            1) ** IEXP
          ELSE
            DATA(K,L) = 0.0
          END IF
          IF (DATA(K,L) .GT. AMAX1) AMAX1 = DATA(K,L)
          IF (DATA(K,L) .LT. AMIN1) AMIN1 = DATA(K,L)
        CONTINUE
      CONTINUE
      WRITE (6,90) IEXP, AMIN1, AMAX1
      90 FORMAT (5X, 'EXPONENT=', I2, '/', 5X, 'MINIMUM =', F12.2, '/', 5X,
      1 'MAXIMUM =', F12.2, '/')
      WRITE (6,100)
      100 FORMAT (5X, 'ENTER APPROPRIATE MAXIMUM ', /)
      READ (5,*) AMAX2
      DO 120 K = 1, IXRANG
        DO 110 L = 1, IYRANG
          DATA(K,L) = ((DATA(K,L) - AMIN1)*RANGE/(AMAX2 - AMIN1)) +
          1
          IF (DATA(K,L) .GT. RANGE) DATA(K,L) = RANGE + 1
          IF (DATA(K,L) .LT. 0.0) DATA(K,L) = 0.0
        CONTINUE
      CONTINUE
      END IF
      ELSE IF (IHANCE .EQ. 4 .OR. IHANCE .EQ. 5 .OR. IHANCE .EQ. 6)
      THEN
        AMAX = -1.0E+10
        AMIN = 1.0 + E10
        DO 140 K = 2, IXRANG - 1
          DO 130 L = 2, IYRANG - 1
            IF (IHANCE .EQ. 4) THEN
              DATA(K - 1, L - 1) = DATA(K, L) - (DATA(K + 1, L) + DATA(K -
              1, L) + DATA(K, L) + DATA(K, L + 1) + DATA(K, L - 1)) / 5.0

```

```

      ELSE IF (IHANCE .EQ. 5) THEN
        DATA(K - 1,L - 1) = SORT((DATA(K,L) - DATA(K + 1,L))*2 +
1      (DATA(K,L) - DATA(K,L + 1))*2)
      ELSE IF (IHANCE .EQ. 6) THEN
        DATA(K - 1,L - 1) = (DATA(K,L + 1) + DATA(K,L - 1) + DATA(
1      K + 1,L) + DATA(K - 1,L)) / 4.0
      END IF
      IF (DATA(K - 1,L - 1) .GT. AMAX) AMAX = DATA(K - 1,L - 1)
      IF (DATA(K - 1,L - 1) .LT. AMIN) AMIN = DATA(K - 1,L - 1)
130    CONTINUE
140    CONTINUE
C
      WRITE (6,150) AMIN, AMAX
150    FORMAT (5X, 'MINIMUM DATA VALUE=', F12.2, '/', 5X,
1      'MAXIMUM DATA VALUE=', F12.2, '/')
C
      WRITE (6,160)
160    FORMAT (5X, 'ENTER NEW MINIMA, MAXIMA ', /)
      READ (5,*) AMIN1, AMAX1
C
      DO 180 K = 2, IXRANG - 1
        DO 170 L = 2, IYRANG - 1
          DATA(K - 1,L - 1) = ((DATA(K - 1,L - 1) - AMIN1)*RANGE/(
1      AMAX1 - AMIN1)) + 1
          IF (DATA(K - 1,L - 1) .GT. RANGE) DATA(K - 1,L - 1) = RANGE
          + 1
          IF (DATA(K - 1,L - 1) .LT. 0.0) DATA(K - 1,L - 1) = 0.0
170        CONTINUE
180      CONTINUE
C
      ELSE IF (IHANCE .EQ. 7) THEN
        CALL LUMIN(DATA, IXRANG, IYRANG, SAMP)
      END IF
C
      RETURN
      END
C**
C**
C** SUBROUTINE INPUT(NX, NY, NPTS)
C**
C** Main programme: Fft.filter
C**
C** Subroutine INPUT reads in the gravity and topography
C** arrays that form the raw data for the filter function.
C**
      REAL*4 RFREEA(50000), TOPO(50000), BOUG(50000)
C
      REAL*4 NGRID
C
      CHARACTER INFILE*7, FILE*7
C
      COMMON /FAA/ RFREEA
      COMMON /TOP/ TOPO
      COMMON /BG/ BOUG
      COMMON /AREA/ XMIN, XMAX, YMIN, YMAX, SAMP

```

```

C      DATA FSUM, TSUM, BSUM /0.0, 0.0, 0.0/
C
C* OPEN DATA FILE
C* WRITE (6,10)
10  FORMAT (/, 5X, 'Enter name of gridded input file', /)
C
      READ (5,20) INFILE
20  FORMAT (A7)
      OPEN (UNIT=3, STATUS='OLD', FILE=INFILE, ACCESS='SEQUENTIAL', FORM=
1    'UNFORMATTED')
C
C* READ AND DISPLAY HEADER DATA
      READ (UNIT=3) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
      WRITE (6,30) FILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
30  FORMAT (///, 5X, 'INPUT FILE:', A7, ///, 5X, 'MINIMUM X VALUE
1    = ', F10.1, ' METRES', /, 5X, 'MAXIMUM X VALUE = ', F10.1,
2    ' METRES', /, 5X, 'MINIMUM Y VALUE = ', F10.1,
3    ' METRES', /, 5X, 'MAXIMUM Y VALUE = ', F10.1,
4    ' METRES', /, 5X, 'SAMPLING INTERVAL = ', F10.1,
5    ' METRES', /, 5X, 'INPUT GRID DIMENSIONS', /, 5X, 'NX = ',
6    I4, 2X, 'NY = ', I4, //)
C
C* EVALUATE NEW VARIABLES
      NPTS = NX * NY
      IF (NPTS .GT. 50000) THEN
        WRITE (6,40)
40      FORMAT (/, 5X, 'Input Points exceed 50000 Programme terminates')
        STOP
      END IF
C
C* INPUT GRID DATA
      DO 60 I = 1, NX
        DO 50 J = 1, NY
          IPOS = (J - 1) * NX + I
          READ (UNIT=3) X, Y, RFREEA(IPOS), TOPO(IPOS), BOUG(IPOS),
1        NGRID, IFFLAG, ITFLAG, IBFLAG
          FSUM = FSUM + RFREEA(IPOS)
          TSUM = TSUM + TOPO(IPOS)
          BSUM = BSUM + BOUG(IPOS)
C
50      CONTINUE
60    CONTINUE
C
      CLOSE (UNIT=3, STATUS='KEEP')
C
C* DETERMINE AVERAGE DATA VALUES
      AVFAA = FSUM / REAL(NX*NY)
      AVTOP = TSUM / REAL(NX*NY)
      AVBOUG = BSUM / REAL(NX*NY)
C
      WRITE (6,70) AVFAA, AVTOP, AVBOUG
70  FORMAT (/, 5X, 'Average Free Air Gravity = ', F8.2, ' mGal', /,
1    5X, 'Average Topography = ', F8.2, ' Metres', /, 5X,
2    'Average Bouguer Gravity = ', F8.2, ' mGal', //)

```

```

C      RETURN
      END

C**
C**      SUBROUTINE INTDEG(WLON, ELON, SLAT, NLAT, LONW, LONE, LATS, LATN)
C**      ~~~~~
C**      Subroutine INTDEG calculates four integers LONW,LONE,LATS
C**      and LATN that define the range of integer degree bins
C**      to be opened for data retrieval.
C**
      REAL NLAT
C
      IF ((WLON - REAL(INT(WLON))) .GE. .9999999) THEN
        LONW = WLON + 1
      ELSE
        LONW = WLON
      END IF
      IF ((SLAT - REAL(INT(SLAT))) .GE. .9999999) THEN
        LATS = SLAT + 1
      ELSE
        LATS = SLAT
      END IF
      LATS = SLAT
      IF (AMOD(ELON,1.0) .EQ. 0.0) THEN
        LONE = INT(ELON) - 1
      ELSE
        LONE = ELON
      END IF
      IF (AMOD(NLAT,1.0) .EQ. 0.0) THEN
        LATN = INT(NLAT) - 1
      ELSE
        LATN = NLAT
      END IF
C
      RETURN
      END

C**
C**      SUBROUTINE LAMCE ( XLAT, XLON, X, Y, SF )
C**
      *
      *-T Subroutine LAMCE ( XLAT, XLON, X, Y, SF )
      *
      *-A M.J.Smith      August 1986
      *
      *-D+
      *
      *-D- Lambert conformal conic on the ellipsoid
      *
      *
      * IMPLICIT DOUBLE PRECISION ( A-H, O-Z )
      *
      *
      * PARAMETER ( PI = 3.14159265358979312D0 )
      * PARAMETER ( DEGRAD = 0.174532925199432946D-01 )
      *
      *
      * COMMON /MAPC01/ OLAT, OLON, SLAT1, SLAT2, CSFACT

```

```

      COMMON /MAPC02/ CLAT1, CLON1, CLAT2, CLON2, AZIM
      COMMON /SPHCON/ EQRAD, ECC
      *
      OLATR = OLAT * DEGRAD
      OLONR = OLON * DEGRAD
      SLAT1R = SLAT1 * DEGRAD
      SLAT2R = SLAT2 * DEGRAD
      PLAT = XLAT * DEGRAD
      PLON = XLON * DEGRAD
      *
      RM = FRM( ECC, PLAT )
      RM1 = FRM( ECC, SLAT1R )
      RM2 = FRM( ECC, SLAT2R )
      *
      T = FT( ECC, PLAT )
      T0 = FT( ECC, OLATR )
      T1 = FT( ECC, SLAT1R )
      T2 = FT( ECC, SLAT2R )
      *
      IF ( SLAT1R .EQ. SLAT2R ) THEN
        RN = SIN( SLAT1R )
      ELSE
        RN = ( LOG( RM1 ) - LOG( RM2 ) ) / ( LOG( T1 ) - LOG( T2 ) )
      ENDIF
      *
      F = RM1 / ( RN * T1**RN )
      RHO0 = EQRAD * F * T0**RN
      THETA = RN * ( PLON - OLONR )
      RHO = EQRAD * F * T**RN
      *
      X = RHO * SIN( THETA )
      Y = RHO0 - RHO * COS( THETA )
      *
      SFK = RHO * RN / ( EQRAD * RM )
      SF = SFK
      *
      END
C**
C**      SUBROUTINE LAMCEI ( X, Y, XLAT, XLON )
C**
      *
      *-T Subroutine LAMCEI ( X, Y, XLAT, XLON )
      *
      *-A M.J.Smith      August 1986
      *
      *-D+
      *
      *-D- Lambert conformal conic on the ellipsoid - inverse
      *
      *
      * IMPLICIT DOUBLE PRECISION ( A-H, O-Z )
      *
      *
      * PARAMETER ( PI = 3.14159265358979312D0 )
      * PARAMETER ( DEGRAD = 0.174532925199432946D-01 )
      *
      *
      * COMMON /MAPC01/ OLAT, OLON, SLAT1, SLAT2, CSFACT
      * COMMON /MAPC02/ CLAT1, CLON1, CLAT2, CLON2, AZIM

```

```

COMMON /SPHCON/ EQRAD, ECC
*
OLATR = OLAT * DEGRAD
OLONR = OLON * DEGRAD
SLAT1R = SLAT1 * DEGRAD
SLAT2R = SLAT2 * DEGRAD
*
RM = FRM( ECC, PLAT )
RM1 = FRM( ECC, SLAT1R )
RM2 = FRM( ECC, SLAT2R )
*
T = FT( ECC, PLAT )
T0 = FT( ECC, OLATR )
T1 = FT( ECC, SLAT1R )
T2 = FT( ECC, SLAT2R )
*
IF ( SLAT1R .EQ. SLAT2R ) THEN
  RN = SIN( SLAT1R )
ELSE
  RN = ( LOG( RM1 ) - LOG( RM2 ) ) / ( LOG( T1 ) - LOG( T2 ) )
ENDIF
*
F = RM1 / ( RN * T1**RN )
RHO0 = EQRAD * F * T0**RN
*
Note:- if RN is -ve, reverse signs of X, Y and RHO0 for
expression below.
*
IF ( RN .LT. 0.0D0 ) THEN
  X = -X
  Y = -Y
  RHO0 = -RHO0
ENDIF
*
THETA = ATAN2( X, ( RHO0 - Y ) )
*
RHO = SIGN( SQRT( X**2 + ( RHO0 - Y )**2 ), RN )
T = ( RHO / ( EQRAD * F ) )**( 1.0D0 / RN )
*
Iterate to find PLAT ( converge until difference is
less than 0.01m ( 1.0D-09rad ) )
*
PLAT = PI / 2.0D0 - 2.0 * ATAN( T )
*
100 PLOLD = PLAT
*
TERM1 = ( 1.0D0 - ECC * SIN( PLAT ) ) /
% ( 1.0D0 + ECC * SIN( PLAT ) )
PLAT = PI / 2.0D0 - 2.0D0 * ATAN( T * SQRT( TERM1**ECC ) )
PDIFF = ABS( PLAT - PLOLD )
IF ( PDIFF .GT. 1.0D-09 ) GO TO 100
*
An alternative to the iteration is to use the following:-
*
ECC2 = ECC**2
ECC4 = ECC**4

```

```

*
ECC6 = ECC**6
*
CHI = PI / 2.0D0 - 2.0D0 * ATAN( T )
*
PLAT = CHI + ( ECC2 / 24.0D0 + 5.0D0 * ECC4 / 24.0D0 +
% ( ECC6 / 12.0D0 ) * SIN( 2.0D0 * CHI ) +
% ( 7.0D0 * ECC4 / 48.0D0 + 29.0D0 * ECC6 / 240.0D0 ) *
% SIN( 4.0D0 * CHI ) +
% ( 7.0D0 * ECC6 / 120.0D0 ) * SIN( 6.0D0 * CHI ) )
*
PLON = THETA / RN + OLONR
*
XLAT = PLAT / DEGRAD
XLON = PLON / DEGRAD
*
END
C**
C**
SUBROUTINE LAMSET(WLON, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX,
1 SAMP)
C**
C**
C** Subroutine LAMSET calculates the latitude/longitude
C** region that may be gridded using a Lambert conformal
C** projection on data retrieved using database gridding
C** routines.
C**
C** Note subroutine actually recalculates corners of
C** Lambert conformal grid in terms of latitude and
C** longitude.
C**
C** IMPLICIT DOUBLE PRECISION (A - H,O - Z)
C
C DOUBLE PRECISION NLAT
C
C DIMENSION X(4), Y(4), CLAT(4), CLON(4)
C
C STORE PROJECTION CONSTANTS IN COMMON
COMMON /MAPC01/ OLAT, OLON, SLAT1, SLAT2, CSFACT
COMMON /MAPC02/ CLAT1, CLON1, CLAT2, CLON2, AZIM
COMMON /SPHCON/ EQRAD, ECC
C
C INPUT PROJECTION CONSTANTS
READ (2,*) OLAT, OLON, SLAT1, SLAT2, CSFACT
READ (2,*) EQRAD, ECC
C
WRITE (7,10) OLAT, OLON, SLAT1, SLAT2, CSFACT, EQRAD, ECC
10 FORMAT (/, 5X, 'PROJECTION CONSTANTS', //, 5X,
1 'LATITUDE OF ORIGIN = ', F8.4, /, 5X,
2 'LONGITUDE OF ORIGIN = ', F8.4, /, 5X,
3 'STANDARD PARALLEL 1 = ', F8.4, /, 5X,
4 'STANDARD PARALLEL 2 = ', F8.4, /, 5X,
5 'CENTRAL SCALE FACTOR = ', F8.4, /, 5X,
6 'EQUATORIAL RADIUS (M) = ', F10.1, /, 5X,
7 'ECCENTRICITY OF SPHEROID = ', F9.7, //)
C
C ENTER LAT. LON. REGION FOR DATA RETRIEVAL

```



```

      WRITE (6,20)
20  FORMAT (//, 5X, 'ENTER CO-ORDINATES BOUNDING DATA RETRIEVAL', /,
1    '&', 4X, 'AREA: WLON, ELON, SLAT, NLAT (DECIMAL DEGREES)')
C
      READ (5,*) WLON, ELON, SLAT, NLAT
      IF (WLON.GT. 180.0D0) WLON = WLON - 360.0D0
      IF (ELON.GT. 180.0D0) ELON = ELON - 360.0D0
C
      WRITE (6,30)
30  FORMAT (/, '&', 4X, 'ENTER SAMPLING INTERVAL (METRES)')
C
      READ (5,*) SAMP
C
      TRANSFORM CO-ORDINATES INTO LAMBERT CONFORMAL SPACE
      CALL LAMCE(SLAT, WLON, X(1), Y(1), SF1)
      CALL LAMCE(SLAT, ELON, X(2), Y(2), SF2)
      CALL LAMCE(NLAT, WLON, X(3), Y(3), SF3)
      CALL LAMCE(NLAT, ELON, X(4), Y(4), SF4)
C
      WRITE (7,40)
40  FORMAT (/, 5X, 'LAMBERT CONFORMAL CONIC COORDINATES', //)
C
      WRITE (7,50) SLAT, WLON, X(1), Y(1), SF1
      WRITE (7,50) SLAT, ELON, X(2), Y(2), SF2
      WRITE (7,50) NLAT, WLON, X(3), Y(3), SF3
      WRITE (7,50) NLAT, ELON, X(4), Y(4), SF4
50  FORMAT (5X, 'LATITUDE = ', F8.4, ' LONGITUDE = ', F8.4, ' X = ',
1    F10.1, ' Y = ', F10.1, ' SCALE FACTOR = ', F7.4)
C
C*   SET BOUNDS OF LAMBERT GRID FULLY DEFINED
      XMIN = X(3)
      XMAX = X(4)
C
C*   CHECK LOWER Y VALUES EQUAL.
      YDIFF = Y(1) - Y(2)
      IF (DABS(YDIFF).GT. 0.01D0) THEN
        WRITE (6,60) Y(1), Y(2)
60  FORMAT (/, 5X, '** ERROR IN MINIMUM VALUE OF Y FOR GRID **', /,
1    5X, 'Y(1) = ', F10.1, ' Y(2) = ', F10.1, /, 5X,
2    'Y(1) SHOULD EQUAL Y(2)', //)
        STOP
      END IF
C
C*   SET YMIN IF PASS ABOVE CODE
      YMIN = Y(1)
C
C*   DETERMINE YMAX
      XLON = OLON
      CALL LAMCE(NLAT, XLON, XORGN, YMAX, SFYMAX)
C
      WRITE (7,70) XORGN, YMAX
70  FORMAT (/, 5X, 'X ORIGIN = ', F10.1, ' YMAX = ', F10.1, //)
C
C*   INVERT CORNERS OF LAMBERT GRID
      CALL LAMCEI(XMIN, YMIN, CLAT(1), CLON(1))
      CALL LAMCEI(XMAX, YMIN, CLAT(2), CLON(2))

```

```

      CALL LAMCEI(XMIN, YMAX, CLAT(3), CLON(3))
      CALL LAMCEI(XMAX, YMAX, CLAT(4), CLON(4))
C
      WRITE (7,80)
80  FORMAT (5X, 'POSITIONS OF LAMBERT GRID CORNERS', //)
      WRITE (7,90) XMIN, YMIN, CLAT(1), CLON(1)
      WRITE (7,90) XMAX, YMIN, CLAT(2), CLON(2)
      WRITE (7,90) XMIN, YMAX, CLAT(3), CLON(3)
      WRITE (7,90) XMAX, YMAX, CLAT(4), CLON(4)
90  FORMAT (5X, 'X = ', F10.1, ' Y = ', F10.1, ' LATITUDE = ', F7.4,
1    ' LONGITUDE = ', F8.4)
C
C*   DETERMINE TOTAL LAT., LON. AREA
      AMAXLT = -1.0E+10
      AMAXLN = -1.0E+10
      AMINLT = 1.0E+10
      AMINLN = 1.0E+10
C
      DO 100 K = 1, 4
        IF (CLAT(K).GT. AMAXLT) AMAXLT = CLAT(K)
        IF (CLON(K).GT. AMAXLN) AMAXLN = CLON(K)
        IF (CLAT(K).LT. AMINLT) AMINLT = CLAT(K)
        IF (CLON(K).LT. AMINLN) AMINLN = CLON(K)
100  CONTINUE
C
C*   SET LAT., LON. LIMITS
      WLON = AMINLN
      ELON = AMAXLN
      SLAT = AMINLT
      NLAT = AMAXLT
C
      WRITE (7,110) WLON, ELON, SLAT, NLAT
110  FORMAT (/, 5X, 'DATA SEARCH AREA', /, 5X, 'WEST LONGITUDE = ',
1    F8.4, /, 5X, 'EAST LONGITUDE = ', F8.4, /, 5X,
2    'SOUTH LATITUDE = ', F8.4, /, 5X, 'NORTH LATITUDE = ',
3    F8.4, //)
C
      RETURN
      END
C**
C**
C**   SUBROUTINE LINDEL(LNUM, BINAME, INDNAM)
C**
C**   Subroutine Lindel is designed to delete a line within
C**   a data file. The line deletion is complex because of:
C**   1) update of index file;
C**   2) update of file header record;
C**   3) complex data file structure.
C**
C**   Lines are deleted by overwriting records of length zero.
C**   After deletion lines within the data record's subregion
C**   line ranges must be renumbered.
C**
      CHARACTER BINAME*7, INDNAM*7
      CHARACTER IDENT1*4, IDENT2*4, TCODE*1

```

```

C CHARACTER VAR*4, CONT*4, ITC(10)*1
C INTEGER*4 FSTREC, UNT, REG(2), GROUPN
C INTEGER*2 LEN
C DATA UNT, INCR, REG /3, 1, 1, 2/
C DATA LEN /0/
C READ (UNIT=3,REC=LNUM) RLAT, RLOX, IEAST, INORTH, RTOP, AGRV,
1 RFREEA, RBOUG, RTERRC, RDENSE, ICODE, (ITC(II),II=1,10), VAR,
2 CONT, IDENT1, IDENT2
C READ APPROPRIATE INDEX RECORD
C* ISYLAT = INT(RLAT*10.0)
C* ISYLON = INT(RLOX*10.0)
C* LAT0 = INT(RLAT) * 10
C* LON0 = INT(RLOX) * 10
C* CALL CODE(ISYLON, ISYLAT, ICODE1)
C* CALL CODE(LON0, LAT0, ICODE0)
C* GROUPN = ICODE1 - ICODE0
C* LNUM1 = (GROUPN + 1) * 1000
C READ (UNIT=4,REC=LNUM1) ICODE, FSTREC, LSTREC
C IF (ICODE1.NE. ICODE) THEN
C* WRITE (6,10) ICODE1, ICODE, BINAME, LNUM
10 FORMAT (5X, 'ERROR ON ACCESSING INDEX ICODE1.NE.ICODE', /, 5X,
1 ICODE1=', 17, 5X, 'ICODE=', 17, /, 5X, ' FILE=', A7, C
2 2X, 'LNUM=', 111, /)
C* STOP
C* END IF
C IF (LNUM.LT. FSTREC .OR. LNUM.GT. LSTREC) THEN
C* WRITE (6,20) LNUM, BINAME
20 FORMAT (/, 5X, 'ERROR LINE NUMBER ', I11, ' OUTSIDE ', /, 5X,
1 'LINE RANGE FOR GIVEN SUBREGION ', /, 5X,
2 'DATA FILE=', A7, /)
C* STOP
C* END IF
C READ AND UPDATE FILE HEADER BEFORE LINE DELETION
C* READ (UNIT=3,REC=500,IOSTAT=J1) IPOINT, ALAT, ALON, ATOP, AGRV,
1 AFREEA, ABOUG, ATERRC, STOP2, SFREA2, SBOUG2, STERC2, RMSTOP,
2 RMSFRA, RMSBOU, RMSTER
C IF (J1.NE. 0) THEN
C* WRITE (6,30) J1
30 FORMAT (5X, 'ERROR ON DIRECT HEADER READ TO UNIT 3:IOSTAT=', 14)
C* STOP
C* END IF
C UPDATE AVERAGES AND RMS VALUES
C* IF (IPOINT.EQ. 1) THEN
C* IPOINT = 0
C* ALAT = 0.0
C* ALON = 0.0

```

```

ATOP = 0.0
AAGRV = 0.0
AFREEA = 0.0
ABOUG = 0.0
ATERRC = 0.0
STOP2 = 0.0
SFREA2 = 0.0
SBOUG2 = 0.0
STERC2 = 0.0
RMSTOP = 0.0
RMSFRA = 0.0
RMSBOU = 0.0
RMSTER = 0.0
ELSE
C* IPOINT = IPOINT - 1
C* CALL AVRAGM(IPOINT, RLAT, ALAT)
C* CALL AVRAGM(IPOINT, RLOX, ALON)
C* CALL AVRAGM(IPOINT, RTOP, ATOP)
C* CALL AVRAGM(IPOINT, AGRV, AAGRV)
C* CALL AVRAGM(IPOINT, RFREEA, AFREEA)
C* CALL AVRAGM(IPOINT, RBOUG, ABOUG)
C* CALL AVRAGM(IPOINT, RTERRC, ATERRC)
C STOP2 = STOP2 - (RTOP*RTOP)
C SFREA2 = SFREA2 - (RFREEA*RFREEA)
C SBOUG2 = SBOUG2 - (RBOUG*RBOUG)
C STERC2 = STERC2 - (RTERRC*RTERRC)
C CALL RMSCAL(IPOINT, ATOP, STOP2, RMSTOP, BINAME, LNUM)
C CALL RMSCAL(IPOINT, AFREEA, SFREA2, RMSFRA, BINAME, LNUM)
C CALL RMSCAL(IPOINT, ABOUG, SBOUG2, RMSBOU, BINAME, LNUM)
C CALL RMSCAL(IPOINT, ATERRC, STERC2, RMSTER, BINAME, LNUM)
C END IF
C WRITE (UNIT=3,REC=500) IPOINT, ALAT, ALON, ATOP, AAGRV, AFREEA,
1 ABOUG, ATERRC, STOP2, SFREA2, SBOUG2, STERC2, RMSTOP,
2 RMSFRA, RMSBOU, RMSTER
C DELETE LINE FROM FILE+UPDATE INDEX FILE
C* IF (FSTREC.EQ. LSTREC) THEN
C* CALL WRITE(REG, LEN, 2, LNUM, UNT)
C* FSTREC = 0
C* LSTREC = 0
C* ELSE IF (LSTREC.GT. FSTREC) THEN
C* CALL WRITE(REG, LEN, 2, LNUM, UNT)
C* IF (LNUM.NE. LSTREC) THEN
C* NEXTL = LNUM + 1
C* CALL RENUM(UNT, NEXTL, LSTREC, LNUM, INCR, 130, 150, 170,
1 190, 210, 230, 250)
C* END IF
C* LSTREC = LSTREC - 1
C* END IF
C WRITE (UNIT=4,REC=LNUM1) ICODE, FSTREC, LSTREC
C* IF ARRIVE HERE NO ERRORS DETECTED-GO TO END

```



```

PARAMETER ( POLRAD = 6356256.9D0 )
PARAMETER ( FLAT = 1. / 299.32 )

*
* other constants
*
PARAMETER ( PI = 3.14159265358979D0 )
PARAMETER ( DEGRAD = .1745329251994329D-01 )

*
* Initialise INITC.
*
* This will ensure that constant initialisation will only
* occur the first time that the routine is used.
*
DATA INITC / .TRUE. /

*
* Set up projection constants
*
IF ( INITC ) THEN
*
* OLAT, CMLON is the coordinate origin of the UK
* national grid.
* SCALE is a scaling factor applied to minimise
* distortion over the map area.
*
OLAT = 49.0D0
CMLON = -2.0D0
SCALE = 0.9996D0

*
* now start the calculations
*
CLON = CMLON * DEGRAD
CLAT = OLAT * DEGRAD

*
FLT = 1.0D0 - POLRAD / EQRAD
ECC = DSQRT( 2 * FLT - FLT**2 )
ECC2 = ECC**2
ECC4 = ECC**4
ECC6 = ECC**6

*
EPRIM2 = ECC2 / ( 1.0D0 - ECC2 )

*
TERM1 = 1.0D0 - ( ECC2 / 4.0D0 ) - ( 3.0D0 * ECC4 / 64.0D0 ) -
% ( 5.0D0 * ECC6 / 256.0D0 )
TERM2 = ( 3.0D0 * ECC2 / 8.0D0 ) + ( 3.0D0 * ECC4 / 32.0D0 ) +
% ( 45.0D0 * ECC6 / 1024.0D0 )
TERM3 = ( 15.0D0 * ECC4 / 256.0D0 ) +
% ( 45.0D0 * ECC6 / 1024.0D0 )
TERM4 = ( 35.0D0 * ECC6 / 3072.0D0 )

*
* calculate distance along central meridian from
* equator to latitude origin.
*
EQBDIS = EQRAD * ( { TERM1 * CLAT } -
% { TERM2 * DSIN( CLAT * 2.0D0 ) } +
% { TERM3 * DSIN( CLAT * 4.0D0 ) } -
% { TERM4 * DSIN( CLAT * 6.0D0 ) } )

```

```

*
INITC = .FALSE.

*
ENDIF

*
Convert input lat/long to radians
*
PLAT = ALAT * DEGRAD
PLON = ALON * DEGRAD

*
these constants have no meaning outside of Snyder.
*
RCURVE = EQRAD / DSQRT ( 1.0D0 - ECC2 * DSIN( PLAT )**2 )
TSQLT1 = DTAN( PLAT )**2
TSQLT2 = TSQLT1**2
ECSSQ1 = EPRIM2 * DCOS( PLAT )**2
ECSSQ2 = ECSSQ1**2

*
CDIFF1 = DCOS( PLAT ) * ( PLON - CLON )
CDIFF2 = CDIFF1**2
CDIFF3 = CDIFF1**3
CDIFF4 = CDIFF1**4
CDIFF5 = CDIFF1**5
CDIFF6 = CDIFF1**6

*
calculate distance from equator to coordinate latitude
*
EQDIS = EQRAD * ( { TERM1 * PLAT } -
% { TERM2 * DSIN( PLAT * 2. ) } +
% { TERM3 * DSIN( PLAT * 4. ) } -
% { TERM4 * DSIN( PLAT * 6. ) } )

*
calculate easting GREAST
*
XTERM1 = 1. - TSQLT1 + ECSSQ1
XTERM2 = 5. - ( 18. * TSQLT1 ) + TSQLT2 + ( 72. * ECSSQ1 ) -
% ( 58. * EPRIM2 )

*
GREAST = SCALE * RCURVE * ( CDIFF1 + ( XTERM1 * CDIFF3 / 6. ) +
% ( XTERM2 * CDIFF5 / 120. ) ) + 400000.

*
calculate northing GRNRTH
*
YTERM1 = 5. - TSQLT1 + ( 9. * ECSSQ1 ) + ( 4. * ECSSQ2 )
YTERM2 = 61. - ( 58. * TSQLT1 ) + TSQLT2 + ( 600. * ECSSQ1 ) -
% ( 330. * EPRIM2 )

*
GRNRTH = SCALE * ( ( EQDIS - EQBDIS ) +
% ( RCURVE * TAN( PLAT ) * ( CDIFF2 / 2. ) +
% { YTERM1 * CDIFF4 / 24. } +
% { YTERM2 * CDIFF6 / 720. } ) ) - 100000.

*
calculate scale along parallel at PLAT, PLON
*
(Distortion from true scale of 1.0 )
*
SCALEP = SCALE * ( 1. + ( 1. + ( EPRIM2 * DCOS( PLAT )**2 ) ) *

```

```

*      %      ( XCOORD - 400000. )**2 / ( 2. * SCALE**2 * RCURVE**2 ) )
*
*      END
C**
C**      SUBROUTINE LUMIN(DATA, IXRANG, IYRANG, SAMP)
C**      ~~~~~
C**      Subroutine LUMIN creates an image of the digital
C**      terrain in data illuminated by an artificial
C**      light source.
C**
C**      DIMENSION DATA(IXRANG,IYRANG)
C
C      DATA RAD, RANGE /57.295779513, 254.0/
C
C      WRITE (6,10)
10  FORMAT (5X, 'ENTER SUN AZIMUTH CLOCKWISE FROM NORTH ', /, 5X,
1    '(DEGREES) AND SUN ELEVATION (DEGREES) ', /)
C      READ (5,*) AZ, ELEV
C
C      AZ = AZ / RAD
C      ELEV = ELEV / RAD
C
C*      CALCULATE GRADIENT PERPENDICULAR TO SOURCE
C*      DIRECTION OF SUN
C*      PS = SIN(AZ) / TAN(ELEV)
C*      QS = COS(AZ) / TAN(ELEV)
C*      R = SQRT(1.0 + PS*PS + QS*QS)
C
C      AMAX = -1.0E+10
C      AMIN = 1.0E+10
C      DO 30 K = 2, IXRANG - 1
C        DO 20 L = 2, IYRANG - 1
C
C          CALCULATE GRADIENT OF SURFACE ELEMENT DATA(K,L)
C          P = (DATA(K + 1,L) - DATA(K,L)) / SAMP
C          Q = (DATA(K,L + 1) - DATA(K,L)) / SAMP
C
C          CALCULATE REFLECTANCE OF SURFACE ELEMENT
C          WITH RESPECT TO LIGHT SOURCE (REDEFINE
C          ELEMENT K,L AS K-1,L-1)
C          DATA(K - 1,L - 1) = (1.0 + PS*P + QS*Q) / (R*(SQRT(1.0 + P*P +
1            Q*Q)))
C          DATA(K - 1,L - 1) = (-1.0) * DATA(K - 1,L - 1)
C          IF (DATA(K - 1,L - 1) .GT. AMAX) AMAX = DATA(K - 1,L - 1)
C          IF (DATA(K - 1,L - 1) .LT. AMIN) AMIN = DATA(K - 1,L - 1)
C
C      20  CONTINUE
C      30  CONTINUE
C
C      DO 50 K = 2, IXRANG - 1
C        DO 40 L = 2, IYRANG - 1
C          DATA(K - 1,L - 1) = ((DATA(K - 1,L - 1) - AMIN)*RANGE/(AMAX -
1            AMIN)) + 1
C          IF (DATA(K - 1,L - 1) .GT. RANGE) DATA(K - 1,L - 1) = RANGE +

```

```

1      1
1      IF (DATA(K - 1,L - 1) .LT. 0.0) DATA(K - 1,L - 1) = 0.0
40  CONTINUE
50  CONTINUE
C
C      RETURN
C      END
C**
C**      SUBROUTINE MRETRV(WLON, ELON, SLAT, NLAT, INDIC1)
C**      ~~~~~
C**      Subroutine MRETRV retrieves all data in area specified
C**      by WLON, ELON, SLAT AND NLAT. MRETRV is a second level
C**      subroutine being driven by DATART.
C**
C      CHARACTER BINAME*7, INDNAM*7
C      REAL NLAT
C
C      DETERMINE INTEGER DEGREE LIMITS OF BINS TO BE OPENED.
C      CALL INTDEG(WLON, ELON, SLAT, NLAT, LONW, LONE, LATS, LATN)
C
C      DO 20 LON = LONW, LONE
C        DO 10 LAT = LATS, LATN
C
C          CALL NAME(LAT, LON, BINAME, INDNAM)
C
C          IF ((LON .EQ. LONW) .AND. (INDIC1 .NE. 2)) THEN
C            ISTRT1 = INT(WLON*10.0) - INT(WLON) * 10
C            ELSE
C              ISTRT1 = 0
C            END IF
C            IF (LAT .EQ. LATS) THEN
C              ISTRT2 = INT(SLAT*10.0) - INT(SLAT) * 10
C              ELSE
C                ISTRT2 = 0
C              END IF
C              IF ((LON .EQ. LONE) .AND. (INDIC1 .NE. 1)) THEN
C                IEND1 = INT(ELON*10.0) - INT(ELON) * 10
C                IF (IEND1 .EQ. 0) IEND1 = 9
C              ELSE
C                IEND1 = 9
C              END IF
C              IF (LAT .EQ. LATN) THEN
C                IEND2 = INT(NLAT*10.0) - INT(NLAT) * 10
C                IF (IEND2 .EQ. 0) IEND2 = 9
C              ELSE
C                IEND2 = 9
C              END IF
C
C          CALL PTFILE(ISTRT1, ISTRT2, IEND1, IEND2, BINAME, INDNAM,
1            WLON, ELON, SLAT, NLAT)
C
C      10  CONTINUE
C      20  CONTINUE

```

```

      RETURN
      END
C**
C**
C** SUBROUTINE NAME(LAT, LON, BINAME, INDNAM)
C** ~~~~~
C**
C** Main programmes: Archive, C.index and Grid.proj.
C**
C** Subroutine NAME encodes the names of the 1 degree by
C** 1 degree area database data and index files containing
C** the point specified by the integer coordinates LAT and
C** LON.
C**
C** CHARACTER BINAME*7, INDNAM*7, NUMBER*5
C** CHARACTER HEADER*1, SUBSC1*1, SUBSC2*1
C
C    PARAMETER (HEADER='G')
C    PARAMETER (SUBSC1='D')
C    PARAMETER (SUBSC2='I')
C
C    INTGR = LAT + LON * 100
C
C    CONVERT INTGR TO A CHARACTER
C    USING THE MTS SUBROUTINE BTD
C    CALL BTD(INTGR, NUMBER, 5, IN, '0')
C
C    FORM BIN AND INDEX NAMES
C    BINAME = HEADER // SUBSC1 // NUMBER
C    INDNAM = HEADER // SUBSC2 // NUMBER
C
C    RETURN
C    END
C**
C**
C** SUBROUTINE NAMESQ(RLAT, RLON, BINAME, INDNAM)
C** ~~~~~
C**
C** Main programmes: Dbin.2 and Lincr.
C**
C** Subroutine Namesq generates the name of the data
C** and index files associated with the point specified
C** by the coordinates RLAT and RLON.
C**
C**
C** CHARACTER BINAME*7, NUMBER*5, INDNAM*7
C** CHARACTER HEADER*1, SUBSC1*1, SUBSC2*1
C
C    PARAMETER (HEADER='G')
C    PARAMETER (SUBSC1='D')
C    PARAMETER (SUBSC2='I')
C
C    INTGR = (INT(RLON)*100) + INT(RLAT)
C
C    CONVERT INTGR TO A CHARACTER USING

```

```

C* THE MTS SUBROUTINE BTD
C* CALL BTD(INTGR, NUMBER, 5, IN, '0')
C
C* FORM BIN AND INDEX NAMES
C* BINAME = HEADER // SUBSC1 // NUMBER
C* INDNAM = HEADER // SUBSC2 // NUMBER
C
C    RETURN
C    END
C**
C**
C** SUBROUTINE NAME2(BINAME, INDNAM)
C** ~~~~~
C**
C** Main programmes: Contr.del, Dbinwrite and Line.del.
C**
C** Subroutine NAME2 determines the index file name
C** from the data file name.
C**
C** CHARACTER BINAME*7, INDNAM*7, SUBSC1*1
C
C    PARAMETER (SUBSC1='I')
C
C    INDNAM = BINAME(1:1) // SUBSC1 // BINAME(3:7)
C
C    RETURN
C    END
C**
C**
C** SUBROUTINE OUTPUT(NX, NY, NPTS)
C** ~~~~~
C**
C** Subroutine OUTPUT writes out the data fields
C** of interest in a form compatible with
C** Binradii allowing the data to be contoured
C** or imaged.
C**
C**
C** REAL*4 RFREEA(50000), TOPO(50000), BOUG(50000)
C
C    REAL*4 NGRID
C
C    CHARACTER OTFILE*7
C
C    COMMON /FAA/ RFREEA
C    COMMON /TOP/ TOPO
C    COMMON /BG/ BOUG
C    COMMON /AREA/ XMIN, XMAX, YMIN, YMAX, SAMP
C
C    DATA NGRID, IFFLAG, ITFLAG, IBFLAG /1.0, 1, 1, 1/
C
C    WRITE (6,10)
C10 FORMAT (/, 5X, 'Enter name of Output File', /)
C    READ (5,20) OTFILE
C20 FORMAT (A7)
C

```

```

C* OPEN OUTPUT FILE
OPEN (UNIT=3, FILE=OTFILE, STATUS='NEW', ACCESS='SEQUENTIAL', FORM=
1 'UNFORMATTED')
C
C WRITE (UNIT=3) OTFILE, XMIN, XMAX, YMIN, YMAX, SAMP, NX, NY
C
C* OUTPUT DATA GRIDS
DO 40 I = 1, NX
DO 30 J = 1, NY
C
C X = (REAL(I) - 0.5) * SAMP + XMIN
Y = (REAL(J) - 0.5) * SAMP + YMIN
C
C IPOS = (J - 1) * NX + I
WRITE (UNIT=3) X, Y, RFREEA(IPOS), TOPO(IPOS), BOUG(IPOS),
1 NGRID, IFFLAG, ITFLAG, IBFLAG
C
30 CONTINUE
40 CONTINUE
C
CLOSE (UNIT=3, STATUS='KEEP')
C
RETURN
END
C**
C** SUBROUTINE PAD(AREAL, AIMAG, NX, NY, IXTOT, IYTOT)
C** ~~~~~
C** Subroutine PAD takes the real NX by NY array and
C** pads it out with zeroes to a size of 2*NX by
C** 2*NY. As the imaginary array contains only
C** zeroes it does not have to be padded and can
C** be used for workspace providing it is reset
C** to zero at the end of the routine.
C**
C** REAL*8 AREAL(1), AIMAG(1)
C
C DETERMINE BLH CORNER OF DATA ARRAY
C IN NEW ARRAY
IXSTRT = NX / 2 + 1
IYSTRT = NY / 2 + 1
C
C IXTOT = NX * 2
IYTOT = NY * 2
C
C DO 20 I = 1, NX
DO 10 J = 1, NY
C
C IPOS = (J - 1) * NX + I
IPOSNW = IXSTRT + (I - 1) + IXTOT * ((IYSTRT + J) - 2)
AIMAG(IPOSNW) = AREAL(IPOS)
C
10 CONTINUE
20 CONTINUE

```

```

C
C* REDEFINE ARRAYS
DO 40 I = 1, IXTOT
DO 30 J = 1, IYTOT
C
C IPOS = (J - 1) * IXTOT + I
AREAL(IPOS) = AIMAG(IPOS)
AIMAG(IPOS) = 0.0D0
C
30 CONTINUE
40 CONTINUE
C
RETURN
END
C**
C** SUBROUTINE POLDET(RADLN1, RADLT1, RADLN2, RADLT2, PIE, RADPLN,
1 RADPLT)
C** ~~~~~
C** Subroutine POLDET determines the pole RADPLN, RADPLT of the
C** oblique mercator projection along the geodesic between RADLN1,
C** RADLT1 and RADLN2, RADLT2.
C**
C** DOUBLE PRECISION RADLN1, RADLT1, RADLN2, RADLT2, PIE, RADPLN,
1 RADPLT, RDPLT2, ARG1, ARG2, MINUS
C
C ARG1 = DCOS(RADLT1) * DSIN(RADLT2) + DCOS(RADLN1) - DSIN(RADLT1) *
1 DCOS(RADLT2) + DCOS(RADLN2)
ARG2 = DSIN(RADLT1) * DCOS(RADLT2) + DSIN(RADLN2) - DCOS(RADLT1) *
1 DSIN(RADLT2) + DSIN(RADLN1)
C
RADPLN = DATAN2(ARG1, ARG2)
RADPLT = DATAN(-DCOS(RADPLN - RADLN1)/DTAN(RADLT1))
MINUS = -1.0D0
RDPLT2 = RADPLT * MINUS
IF (RDPLT2 .GT. RADPLT) THEN
RADPLT = RDPLT2
RADPLN = RADPLN + PIE
END IF
C
RETURN
END
C**
C** SUBROUTINE PPREP(RLAT, RLON, GRN, GRE, IPROJ)
C** ~~~~~
C** Subroutine Pprep interfaces with subroutines
C** CSTOS/CSTPIX to provide a coastline for grids from
C** Grid.proj/Binradii using any of the three possible
C** gridding projections.
C**
C** REAL*8 DLAT, DLON, DNTH, DEAST, SCFACT, OLAT, OLON, SLAT1, SLAT2,
1 CSFACT, CLAT1, CLON1, CLAT2, CLON2, AZIM, EQRAD, ECC

```

```

C      COMMON /MAPCO1/ OLAT, OLON, SLAT1, SLAT2, CSFACT
C      COMMON /MAPCO2/ CLAT1, CLON1, CLAT2, CLON2, AZIM
C      COMMON /SPHCON/ EQRAD, ECC

C      DLAT = DBLE(RLAT)
C      DLON = DBLE(RLON)
C      IF (DLON .GT. 180.000) DLON = DLON - 360.000

C      IF (IPROJ .EQ. 1) THEN
C        CALL LLTOGR(DLAT, DLON, DEAST, DNTH)
C      ELSE IF (IPROJ .EQ. 2) THEN
C        CALL LAMCE(DLAT, DLON, DEAST, DNTH, SCFACT)
C      ELSE IF (IPROJ .EQ. 3) THEN
C        CALL EELLGR(DLAT, DLON, DEAST, DNTH)
C      END IF

C      GRE = SNGL(DEAST)
C      GRN = SNGL(DNTH)

C      RETURN
C      END

C**
C** SUBROUTINE PROJECT(RLAT1, RLON1, AZ1, DIST, RLAT3, RLON3)
C**
C** Subroutine PROJECT calculates the position of RLAT3, RLON3
C** which is a distance DIST along azimuth AZ1 from RLAT1, RLON1.
C**
C** DOUBLE PRECISION CLAT1, RLON1, AZ1, DIST, RLAT3, RLON3, DELTLT
C** DOUBLE PRECISION RAD, RADIUS, BETA, GAMMA, SAZ1, CAZ1, RLAT1
C** DOUBLE PRECISION SBETA, CBETA, SGAMMA, CGAMMA, CALPHA, PIE
C** DOUBLE PRECISION ALPHA, SALPHA, CC, C, SC, RATIOA, RATIOC
C**
C      DATA RAD, RADIUS /57.295779513D0, 6371.000/
C
C      PIE = 4D0 * DATAN(1D0)
C      IF (DABS(AZ1) - 0.000 .LT. 1.0E-4 .OR. DABS(DABS(AZ1) - PIE) .LT.
1      1.0E-4) THEN
C        DELTLT = (DIST/RADIUS) * RAD
C        IF (DABS(AZ1) - 0.000 .LT. 1.0E-4) THEN
C          RLAT3 = RLAT1 + DELTLT
C        ELSE IF (DABS(DABS(AZ1) - PIE) .LT. 1.0E-4) THEN
C          RLAT3 = RLAT1 - DELTLT
C        END IF
C        RLON3 = RLON1
C      ELSE
C
C      ACCOUNT FOR +VE/-VE SIGN OF AZ1
C      ISIGN0 = 0
C      IF (AZ1 .LT. 0.000) THEN
C        AZ1 = ABS(AZ1)
C        ISIGN0 = 1
C      END IF

```

```

C      CLAT1 = 90D0 - RLAT1
C      BETA = CLAT1 / RAD
C      GAMMA = DIST / RADIUS

C      SAZ1 = DSIN(AZ1)
C      CAZ1 = DCOS(AZ1)
C      SBETA = DSIN(BETA)
C      CBETA = DCOS(BETA)
C      SGAMMA = DSIN(GAMMA)
C      CGAMMA = DCOS(GAMMA)

C      CALPHA = CBETA * CGAMMA + SBETA * SGAMMA * CAZ1
C      ALPHA = DACOS(CALPHA)
C      SALPHA = DSIN(ALPHA)

C      CC = (CGAMMA - CALPHA*CBETA) / (SALPHA*SBETA)
C      C = DACOS(CC)
C      SC = DSIN(C)

C
C* USE SIN RULE TO TEST ANSWER
C* RATIOA = SALPHA / SAZ1
C* RATIOC = SGAMMA / SC
C* IF (ABS(RATIOA - RATIOC) .GT. 1.0E-2) THEN
10  WRITE (6,10) RATIOA, RATIOC, SALPHA, SAZ1, SGAMMA, SC
11  FORMAT (5X, 'ERROR IN SPHERICAL TRIGONOMETRY ', /, 5X,
2    'CALCULATIONS ', /, 5X, 'RATIOA=',
3    'F9.5, 5X, 'RATIOC=', F9.5, /, 5X, 'SALPHA=', F9.7, 5X,
4    'SAZ1 =', F9.7, /, 5X, 'SGAMMA=', F9.7, 5X, 'SC =',
5    F9.7, //)
C* STOP
C* END IF

C
C* CALCULATE RLAT3, RLON3 IN DEGREES
C* ALPHA = ALPHA * RAD
C* C = C * RAD
C* RLAT3 = 90.000 - ALPHA
C* IF (ISIGN0 .EQ. 0) THEN
C*   RLON3 = RLON1 + C
C* ELSE IF (ISIGN0 .EQ. 1) THEN
C*   RLON3 = RLON1 - C
C* END IF
C* END IF

C      RETURN
C      END

C**
C** SUBROUTINE PTFILE(ISTRT1, ISTRT2, IEND1, IEND2, BINAME, INDNAM,
1  WLON, ELON, SLAT, NLAT)
C**
C** Subroutine PTFILE retrieves all or part of the data held in a
C** data file. The index file INDNAM is opened for direct access also.
C**
C** CHARACTER BINAME*7, INDNAM*7, IDENT1*4, IDENT2*4, TCODE*1

```



```

      CHARACTER VAR*4, CONT*4, ITC(10)*1
      LOGICAL LOGEX
      INTEGER FSTREC
      REAL NLAT
C
C* DETERMINE IF DATA FILE EXISTS
      INQUIRE (FILE=BINAME, IOSTAT=11, EXIST=LOGEX)
      IF (11.NE. 0) THEN
        WRITE (6,10) BINAME, 11
10      FORMAT (1X, 'ERROR ON INQUIRE TO FILE ', A7, ' IOSTAT=', I4)
        GO TO 90
      END IF
C
      IF (LOGEX.NEQV. .TRUE.) THEN
        WRITE (6,20) BINAME, INDNAM
20      FORMAT (1X, 'FILES ', A7, ' AND ', A7, ' DO NOT EXIST DATA ',
1        'UNAVAILABLE')
      ELSE
C* PROCESS DATA
        OPEN (UNIT=3, STATUS='OLD', FILE=BINAME, ACCESS='DIRECT', FORM=
1        'UNFORMATTED', IOSTAT=12, RECL=80)
        IF (12.NE. 0) THEN
          WRITE (6,30) BINAME, 12
30      FORMAT (1X, 'ERROR OPENING FILE ', A7, ' FOR DIR. ACCESS
1        IOSTAT=', I4)
          GO TO 90
        END IF
C
        OPEN (UNIT=4, STATUS='OLD', FILE=INDNAM, ACCESS='DIRECT', FORM=
1        'UNFORMATTED', IOSTAT=13, RECL=20)
        IF (13.NE. 0) THEN
          WRITE (6,40) INDNAM, 13
40      FORMAT (1X, 'ERROR OPENING ', A7, ' FOR DIR. ACCESS IOSTAT=',
1        I4)
          GO TO 90
        END IF
C
        DO 80 LON = ISTRT1, IEND1
          DO 70 LAT = ISTRT2, IEND2
C
            LNUM = (10*LON + LAT + 1) * 1000
            READ (UNIT=4, REC=LNUM) ICODE1, FSTREC, LSTREC
C
            IF (FSTREC.NE. 0) THEN
              DO 60 LNUM = FSTREC, LSTREC
                READ (UNIT=3, REC=LNUM, IOSTAT=15) RLAT, RLON, IEAST,
1                INORTH, RTOP, AGRV, RFREEA, RBOUG, RTERRC, RDENSE,
2                ICODE, (ITC(II), II=1,10), VAR, CONT, IDENT1, IDENT2
C
                IF (15.NE. 0) THEN
                  WRITE (6,50) BINAME, 15
50      FORMAT (1X, 'ERROR ON DIR. ACCESS READ TO FILE ', A7,
1                IOSTAT=', I4)
                  GO TO 90
                END IF
C

```

```

      IF ((RLAT.GT. SLAT .AND. RLAT.LT. NLAT) .AND. (RLON.
1      GT. WLON .AND. RLON.LT. ELON)) THEN
C
        CALL GRIDDR(RLAT, RLON, IEAST, INORTH, RFREEA, RTOP,
1      RBOUG, ITC(2))
C
        END IF
C
60      CONTINUE
      END IF
C
70      CONTINUE
80      CONTINUE
C
      END IF
C
      RETURN
C
90 STOP
      END
C**
C** SUBROUTINE READF(L3, NUM1, FILES)
C** ~~~~~
C** Subroutine READF reads from the contributor index
C** the names of all of the files holding data supplied
C** by the contributor indicated in the main programme.
C** However, the data read is quite complex requiring
C** the use of variable formats as the number of files
C** associated with a given contributor may vary with
C** time
C** CHARACTER WR(8)*10, FILES(300)*7, FMT*10
C**
C** Array files will contain all files to which a given
C** contributor has supplied data to date. The maximum size
C** of the array must be greater than the present number
C** of files.
C**
C** Array WR contains variable formats
C** DATA WR /' (3X,A7)', '(2(3X,A7))', '(3(3X,A7))', '(4(3X,A7))',
1 '(5(3X,A7))', '(6(3X,A7))', '(7(3X,A7))', '(8(3X,A7))' /
C
C DATA FMT /' /'
C READ IN DATA FILES ASSOCIATED WITH CONTRIBUTOR OF LINE L3
C IF (NUM1.LE. 8) THEN
C ALL FILES ON ONE LINE IN INDEX
C NREC1 = (L3*1000) + 1
C FMT = WR(NUM1)
C READ (3,FMT,REC=NREC1,IOSTAT=K1,ERR=50) (FILES(L),L=1,NUM1)
C ELSE
C MORE THAN EIGHT FILES/DATA ON MORE THAN ONE LINE
C NUMBER OF FULL DATA LINES=NUM1/8
C LNUM = NUM1 / 8

```

```

C      REMAINDER LREM
      LREM = MOD(NUM1,8)
C
      NREC1 = L3 * 1000 + 1
      J1 = 1
      J2 = 8
      FMT = WR(8)
C
      DO 30 I = 1, LNUM
        READ (3,FMT,REC=NREC1,ERR=70,IOSTAT=K2) (FILES(L),L=J1,J2)
        NREC1 = NREC1 + 1
        IF (I.NE. LNUM) THEN
          J1 = J1 + 8
          J2 = J2 + 8
        END IF
      30 CONTINUE
C
      IF (LREM.NE. 0) THEN
        READ IN LAST LINE OF INDEX
        J3 = J2 + 1
        J4 = J2 + LREM
        WRITE (6,40) J3, J4, NUM1
      40  FORMAT (1X, 'J3=', I4, 1X, 'J4=', I4, 1X, 'NUM1=', I4, 1X,
      1    'J4=NUM1')
        FMT = WR(LREM)
        NREC1 = (L3*1000) + LNUM + 1
        READ (3,FMT,REC=NREC1,ERR=90,IOSTAT=K3) (FILES(L),L=J3,J4)
        END IF
      END IF
C
C*   IF RUN SUCCESSFUL GO TO END
      GO TO 110
C
C*   ERROR MESSAGES
      50 WRITE (6,60) K1
      60 FORMAT (1X, 'ERROR ON READ TO UNIT 3,NUM1.LE.8,IOSTAT=', I4)
      GO TO 110
      70 WRITE (6,80) K2
      80 FORMAT (1X, 'ERROR ON COMPLETE LINE READ TO UNIT 3,NUM1.GT.8,
      1    IOSTAT=', I4)
      GO TO 110
      90 WRITE (6,100) K3
      100 FORMAT (1X, 'ERROR ON PARTIAL LINE READ TO UNIT 3,NUM1.GT.8,
      1    IOSTAT=', I4)
C
      110 RETURN
      END
C**
C**
C** SUBROUTINE RECTRET(WLON, ELON, SLAT, NLAT, HWIDTH, U, DATA, RADPLT,
      1    LAMDA0, UE, UW, KOUNT1, KOUNT2)
C**
C** ~~~~~
C** Subroutine RECTRET drives subroutine STPRET to retrieve data
C** for the rectangular area defined by WLON, ELON, SLAT and NLAT.
C** N.B. Data recovered in strips, therefore area of

```

```

C** retrieval may be larger than the actual rectangle.
C**
      DOUBLE PRECISION RADPLT, LAMDA0, UE, UW, HWIDTH
      REAL NLAT, U(2000), DATA(3,2000)
C
      SUBLAT = SLAT
      ISYLNW = INT(WLON*10.0)
      ISYLN = INT(ELON*10.0)
C
      IF (ISYLN.LT. ISYLNW) THEN
        ITEMP = ISYLNW
        ISYLNW = ISYLN
        ISYLN = ITEMP
      END IF
C
      10 CALL STPRET(WLON, SLAT, NLAT, HWIDTH, U, DATA, RADPLT, LAMDA0, UE,
      1    UW, KOUNT1, KOUNT2)
      SLAT = SUBLAT
      IF (ISYLNW.EQ. ISYLN) GO TO 20
      WLON = WLON + .1
      ISYLNW = ISYLNW + 1
      GO TO 10
C
      20 RETURN
      END
C**
C**
C** SUBROUTINE RMSCAL(IPOINT, AVG, SUMSQ, RMS, BINAME, LNUM)
C** ~~~~~
C** Main programme: Contr.del.
C**
C** Subroutine RMSCAL calculates the RMS deviation
C** of the data fields in the bin.
C**
      REAL*8 DPOINT, DSUMSQ, DAVG, ARG, DRMS
C
      CHARACTER BINAME*7
C
      DPOINT = DFLOAT(IPOINT)
      DSUMSQ = DBLE(SUMSQ)
      DAVG = DBLE(AVG)
C
      ARG = (DSUMSQ - (DPOINT*(DAVG*DAVG))) / DPOINT
      IF (ARG.LT. 0.000) THEN
        WRITE (6,10)
      10  FORMAT (1X, 'ERROR NEGATIVE ARG TO SQRT IN SUBROUTINE RMSCAL')
        WRITE (6,20) SUMSQ, AVG, IPOINT, BINAME, LNUM
      20  FORMAT (1X, 'SUMSQ=', F20.2, 1X, 'AVG=', F12.2, 1X, 'IPOINT=',
      1    I8, 1X, 'FILE=', A7, 1X, 'LNUM=', I12)
      END IF
      DRMS = SQRT(ARG)
      RMS = SNGL(DRMS)
      RETURN
      END
C**

```

```

C** SUBROUTINE RMSCAL(IPOINT, AVG, SUMSQ, RMS, RECORD)
C** ~~~~~
C** Main programmes: Dbin.2 and Line.del.
C**
C** Subroutine RMSCAL calculates the RMS deviation of the
C** data fields of interest in each bin.
C**
C** INTEGER RECORD
C
  RPOINT = REAL(IPOINT)
  ARG = (SUMSQ - (RPOINT*(AVG**2))) / RPOINT
  IF (ARG.LT. 0.0) THEN
    WRITE (6,10)
10  FORMAT (1X, 'ERROR NEGATIVE ARG TO SQRT IN SUBROUTINE RMSCAL')
    WRITE (6,20) SUMSQ, AVG, IPOINT, RECORD
20  FORMAT (1X, 'SUMSQ=', F20.2, 1X, 'AVG=', F12.2, 1X, 'IPOINT=',
1    18, 2X, 'RECORD=', 18)
    STOP
  END IF
  RMS = SQRT(ARG)
C
  RETURN
END
C**
C** SUBROUTINE SCRND(NAME)
C** ~~~~~
C** Subroutine SCRND enables the name of the data file to be
C** listed to be entered interactively.
C**
  CHARACTER NAME*7, REPLY*1, ANS*1
C
  PARAMETER (ANS='Y')
C
  ASSIGN I/O UNITS 7 AND 8 TO SCREEN
  CALL FTNCMD('ASSIGN 7=SOURCE', 18)
  CALL FTNCMD('ASSIGN 8=SINK', 16)
C
  N = 1
10  WRITE (8,20)
20  FORMAT (1X, 'ENTER INPUT FILE:TYPE ''D'' ')
  READ (7,30) NAME
30  FORMAT (A7)
  WRITE (8,40) NAME
40  FORMAT (1X, 'FILE=', A7, 1X, '(Y/N)?')
  READ (7,50) REPLY
50  FORMAT (A1)
C
  IF (REPLY.EQ. ANS) THEN
    WRITE (8,60)
60  FORMAT (1X, 'PROGRAM RUNNING')
  ELSE

```

```

    IF (N.EQ. 5) THEN
      WRITE (8,70)
70  FORMAT (1X, 'RUN UNSUCCESSFUL:TRY AGAIN')
      GO TO 90
    END IF
  C
    N = N + 1
    WRITE (8,80)
80  FORMAT (1X, 'INCORRECT NAME:TRY AGAIN')
    GO TO 10
  END IF
C
  RETURN
C
90  STOP
END
C**
C** SUBROUTINE SETUP(WLON, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX,
1  SAMP, IPROJ)
C** ~~~~~
C** Subroutine SETUP asks user which projection he wishes data
C** to be converted to before gridding and calls GRSET/LAMSET
C** to calculate Lat., Lon. search area and grid size in
C** projection coordinate space.
C**
  IMPLICIT DOUBLE PRECISION (A - H,O - Z)
C
  DOUBLE PRECISION NLAT
C
  WRITE (6,10)
10  FORMAT (/, 5X, 'ENTER PROJECTION REQUIRED ', /, 5X,
1    'ORDNANCE SURVEY (1)', /, 5X,
2    'LAMBERT CONFORMAL (2)', /, '&', 4X,
3    'IRISH GRID (3)')
C
  READ (5,*) IPROJ
C
  IF (IPROJ.EQ. 1.OR. IPROJ.EQ. 3) THEN
    CALL GRSET(WLON, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX, SAMP,
1    IPROJ)
  ELSE IF (IPROJ.EQ. 2) THEN
    CALL LAMSET(WLON, ELON, SLAT, NLAT, XMIN, XMAX, YMIN, YMAX,
1    SAMP)
  END IF
C
  RETURN
END
C**
C** SUBROUTINE STPRET(RLON, SLAT, NLAT, HWIDTH, U, DATA, RADPLT,
1  LAMDA0, UE, UW, KOUNT1, KOUNT2)
C** ~~~~~
C** Subroutine STPRET is the main data retrieval subroutine.

```

```

C**  Retrieves all data in north—south strip from box containing
C**  SLAT to box containing NLAT.
C**  Each box has an area of 0.1 degrees by 0.1 degrees.
C**
      CHARACTER BINAME*7, INDNAM*7
      INTEGER BASE
      REAL NLAT, U(2000), DATA(3,2000)
      LOGICAL LOGEX
      DOUBLE PRECISION RADPLT, LAMDA0, UE, UW, HWIDTH

C
      DUMMY = SLAT
      DUMMY1 = RCON
      IF (RCON .LT. 0.0) RCON = RCON + 360.0
      ISYLTN = INT(NLAT*10.0)
      BASE = INT(SLAT)

C
      CALL NAMESQ(SLAT, RCON, BINAME, INDNAM)

C
      INQUIRE (FILE=BINAME,EXIST=LOGEX,IOSTAT=J1)
      IF (J1 .NE. 0) THEN
        WRITE (6,10) BINAME, J1
10      FORMAT (/, 5X, 'ERROR ON INQUIRE TO FILE ', A7, ' IOSTAT=', I4)
        STOP
      END IF

C
      IF (LOGEX .EQV. .TRUE.) THEN
        OPEN (UNIT=3,STATUS='OLD',FILE=BINAME,ACCESS='DIRECT',FORM=
1      'UNFORMATTED',RECL=80,IOSTAT=J2)
        IF (J2 .NE. 0) THEN
          WRITE (6,20) BINAME, J2
20      FORMAT (/, 5X, 'ERROR OPENING FILE ', A7, ' IOSTAT=', I4)
          STOP
        END IF
        OPEN (UNIT=4,STATUS='OLD',FILE=INDNAM,ACCESS='DIRECT',FORM=
1      'UNFORMATTED',RECL=20,IOSTAT=J3)
        IF (J3 .NE. 0) THEN
          WRITE (6,30) INDNAM, J3
30      FORMAT (/, 5X, 'ERROR OPENING FILE ', A7, ' IOSTAT=', I4)
          STOP
        END IF

C
      RETRIEVE DATA FROM FIRST BOX
      CALL BOXRET(RCON, SLAT, HWIDTH, U, DATA, RADPLT, LAMDA0, UE, UW,
1      KOUNT1, KOUNT2)
      ELSE
        WRITE (6,40) BINAME
40      FORMAT (/, 5X, 'FILE ', A7, ' DOES NOT EXIST ', /, 5X,
1      'DATA UNAVAILABLE:PROGRAM TERMINATES')
        STOP
      END IF

C
      ISYLTS = INT(SLAT*10.0)
      IF (ISYLTS .EQ. ISYLTN) GO TO 100

C
      LOOP UP STRIP UNTIL ISYLTS=ISYLTN

```

```

50 SLAT = SLAT + .1
   IF (INT(SLAT) - BASE .EQ. 1) THEN
     BASE = BASE + 1
     CLOSE (UNIT=3,STATUS='KEEP')
     CLOSE (UNIT=4,STATUS='KEEP')

C
     CALL NAMESQ(SLAT, RCON, BINAME, INDNAM)

C
     INQUIRE (FILE=BINAME,EXIST=LOGEX,IOSTAT=J4)
     IF (J4 .NE. 0) THEN
       WRITE (6,60) BINAME, J4
60      FORMAT (/, 5X, 'ERROR ON INQUIRE TO FILE ', A7, ' IOSTAT=',
1      I4)
       STOP
     END IF

C
     IF (LOGEX .EQV. .TRUE.) THEN
       OPEN (UNIT=3,STATUS='OLD',FILE=BINAME,ACCESS='DIRECT',FORM=
1      'UNFORMATTED',RECL=80,IOSTAT=J5)
       IF (J5 .NE. 0) THEN
         WRITE (6,70) BINAME, J5
70      FORMAT (5X, 'ERROR OPENING FILE ', A7, ' IOSTAT=', I4)
         STOP
       END IF
       OPEN (UNIT=4,STATUS='OLD',FILE=INDNAM,ACCESS='DIRECT',FORM=
1      'UNFORMATTED',RECL=20,IOSTAT=J6)
       IF (J6 .NE. 0) THEN
         WRITE (6,80) INDNAM, J6
80      FORMAT (/, 5X, 'ERROR OPENING FILE ', A7, ' IOSTAT=', I4)
         STOP
       END IF

C
       CALL BOXRET(RCON, SLAT, HWIDTH, U, DATA, RADPLT, LAMDA0, UE,
1      UW, KOUNT1, KOUNT2)
       ELSE
         WRITE (6,90) BINAME
90      FORMAT (/, 5X, 'FILE ', A7, ' DOES NOT EXIST DATA ', /, 5X,
1      'UNAVAILABLE PROGRAM TERMINATES ', /)
         STOP
       END IF
       ELSE
         CALL BOXRET(RCON, SLAT, HWIDTH, U, DATA, RADPLT, LAMDA0, UE, UW,
1      KOUNT1, KOUNT2)
       END IF

C
       ISYLTS = INT(SLAT*10.0)
       IF (ISYLTS .EQ. ISYLTN) GO TO 100
       GO TO 50

C
100 RCON = DUMMY1
    SLAT = DUMMY
    RETURN
    END

C**
C**
      SUBROUTINE TAPER(AREAL, NX, NY, LX, LY)

```

```

C** ~~~~~
C**
C** Subroutine TAPER modifies the real array AREAL
C** using cosine tapers in both the x and y dimensions.
C**
C** IMPLICIT REAL*8(A - H,O - Z)
C
C DIMENSION AREAL(NX,NY)
C
C* DEFINE OFTEN USED VARIABLES
C* PIE = 4.0D0 * DATAN(1.0D0)
C* DNX = DFLOAT(NX)
C* DNY = DFLOAT(NY)
C* DLX = DFLOAT(LX)
C* DLY = DFLOAT(LY)
C
C* CALCULATE AND APPLY FILTER
C* FOR EACH ARRAY ELEMENT
C* DO 20 I = 1, NX
C*   DO 10 J = 1, NY
C
C*     H = 1.0D0
C
C*     IF (I .LE. LX) THEN
C*       ARG = (PIE*DFLOAT(I - 1)) / DLX
C*       H = H * (0.5D0*(1.0D0-COS(ARG)))
C*     ELSE IF (I .GT. (NX - LX)) THEN
C*       ARG = (PIE*(DNX - DFLOAT(I))) / DLX
C*       H = H * (0.5D0*(1.0D0-COS(ARG)))
C*     END IF
C
C*     IF (J .LE. LY) THEN
C*       ARG = (PIE*DFLOAT(J - 1)) / DLY
C*       H = H * (0.5D0*(1.0D0-COS(ARG)))
C*     ELSE IF (J .GT. (NY - LY)) THEN
C*       ARG = (PIE*(DNY - DFLOAT(J))) / DLY
C*       H = H * (0.5D0*(1.0D0-COS(ARG)))
C*     END IF
C
C*     AREAL(I,J) = AREAL(I,J) * H
C
C 10 CONTINUE
C 20 CONTINUE
C
C RETURN
C END
C**
C** SUBROUTINE TRANS(RLAT, RLON, IEAST, INORTH, X, Y, IPROJ, ITC2)
C** ~~~~~
C** Subroutine TRANS is a transformation programme driving
C** map projection subroutines to convert RLAT, RLON to the
C** required coordinate system.
C**

```

```

C** Flag ITC2 indicates Irish grid if set to '1'
C**
C** DOUBLE PRECISION DLAT, DLON, DX, DY
C** CHARACTER ITC2*1
C
C DLAT = DBLE(RLAT)
C DLON = DBLE(RLON)
C
C IF (DLON .GT. 180.0D0) DLON = DLON - 360.0D0
C
C IF (IPROJ .EQ. 1) THEN
C   IF (IEAST .LT. 9999995 .AND. INORTH .LT. 9999995 .AND. ITC2 .NE.
1    '1') THEN
C     X = REAL(IEAST)
C     Y = REAL(INORTH)
C   ELSE
C     CALL LLTOGR(DLAT, DLON, DX, DY)
C     X = SNGL(DX)
C     Y = SNGL(DY)
C   END IF
C ELSE IF (IPROJ .EQ. 2) THEN
C   CALL LAMCE(DLAT, DLON, DX, DY)
C   X = SNGL(DX)
C   Y = SNGL(DY)
C ELSE IF (IPROJ .EQ. 3) THEN
C   IF (ITC2 .EQ. '1' .AND. IEAST .LT. 9999995 .AND. INORTH .LT.
1    9999995) THEN
C     X = REAL(IEAST)
C     Y = REAL(INORTH)
C   ELSE
C     CALL EELLGR(DLAT, DLON, DX, DY)
C     X = SNGL(DX)
C     Y = SNGL(DY)
C   END IF
C END IF
C
C RETURN
C END
C**
C** SUBROUTINE UPCONT(KX, KY, KXN, KYN, NX, NY, DNX, DNY, ZLV, DSAMP)
C** ~~~~~
C** Subroutine Upcont applies an upward continuation
C** factor to the stored Fft components.
C**
C** REAL*8 DATAR(50000), DATAI(50000)
C** REAL*8 DNX, DNY, DKX, DKY, DSAMP, DKZ, ZLV, FILT
C
C COMMON /RCOMP/ DATAR
C COMMON /ICOMP/ DATAI
C
C DEDUCE ARRAY ELEMENT
C IPOS = (KY - 1) * NX + KX
C

```

```

C*   CALCULATE HORIZONTAL WAVENUMBER (M-1)
      DKX = DFLOAT(KXN)
      DKY = DFLOAT(KYN)
C
      DKZ = SQRT((DKX/(DNX*DSAMP))**2 + (DKY/(DNY*DSAMP))**2)
C
C*   EVALUATE AND APPLY CONTINUATION FACTOR
      FILT = EXP(DKZ*ZLVL)
C
      DATAR(IPOS) = DATAR(IPOS) * FILT
      DATAI(IPOS) = DATAI(IPOS) * FILT
C
      RETURN
      END
C**
C**
C**   SUBROUTINE UPDATE(BINAME, L3, NUM1, PCONT)
C**   ~~~~~
C**   Subroutine UPDATE compares the files for which a given
C**   contributor has supplied data, stored in the contributor
C**   index, with the name of a new file to which the contributor
C**   has also given data. If the new file is already in the index
C**   the index is not changed and the programme returns to main.
C**   However, if the file is not in the index it is added to the
C**   list of files for the given contributor.
C**
C**   CHARACTER BINAME*7, WR(8)*10, FILE(300)*7, FMT*10, PCONT*8
C**
C**   Array file will contain all files to which a given contributor
C**   has supplied data to date. Hence, the maximum size of the array
C**   must be larger than the present number of files.
C**
C**   Array WR contains variable formats
C**
      DATA WR /' (3X,A7)', '(2(3X,A7))', '(3(3X,A7))', '(4(3X,A7))',
1      '(5(3X,A7))', '(6(3X,A7))', '(7(3X,A7))', '(8(3X,A7))' /
C
      DATA FMT /'
C*   READ IN DATA FILES ASSOCIATED WITH CONTRIBUTOR OF LINE L3
C*   IF NO DATA FILES ASSOCIATED WITH CONTRIBUTOR GO TO OUTPUT.
      IF (NUM1 .EQ. 0) GO TO 30
      IF (NUM1 .LE. 8) THEN
C*   ALL FILES ON ONE LINE IN INDEX
          NREC1 = (L3*1000) + 1
          FMT = WR(NUM1)
          READ (3,FMT,REC=NREC1,IOSTAT=K1,ERR=50) (FILE(L),L=1,NUM1)
      ELSE
C*   MORE THAN EIGHT FILES/DATA ON MORE THAN ONE LINE
          NUMBER OF FULL DATA LINES=NUM1/8
          LNUM = NUM1 / 8
          REMAINDER LREM
          LREM = MOD(NUM1,8)
C
          NREC1 = L3 * 1000 + 1
          J1 = 1

```

```

      J2 = 8
      FMT = WR(8)
C
      DO 10 I = 1, LNUM
          READ (3,FMT,REC=NREC1,ERR=70,IOSTAT=K2) (FILE(L),L=J1,J2)
          NREC1 = NREC1 + 1
          IF (I .NE. LNUM) THEN
              J1 = J1 + 8
              J2 = J2 + 8
          END IF
10      CONTINUE
C
      IF (LREM .NE. 0) THEN
          READ IN LAST LINE OF INDEX
          J3 = J2 + 1
          J4 = J2 + LREM
          FMT = WR(LREM)
          NREC1 = (L3*1000) + LNUM + 1
          READ (3,FMT,REC=NREC1,ERR=90,IOSTAT=K3) (FILE(L),L=J3,J4)
      END IF
C
C*   TEST TO SEE IF FILE ALREADY IN INDEX-IF YES RETURN TO MAIN
      DO 20 J5 = 1, NUM1
          IF (BINAME .EQ. FILE(J5)) THEN
C*   'RETURN'
              GO TO 180
          END IF
20      CONTINUE
C
C*   IF GET HERE NEW FILE NOT IN INDEX.ADD FILE TO INDEX.
30      NUM1 = NUM1 + 1
          FILE(NUM1) = BINAME
C
C*   WRITE NEW FILE TO INDEX.
          IF (NUM1 .LE. 8) THEN
              NREC1 = L3 * 1000 + 1
              FMT = WR(NUM1)
              WRITE (3,FMT,REC=NREC1,ERR=110,IOSTAT=K4) (FILE(L),L=1,NUM1)
          ELSE
C
C*   MORE THAN EIGHT FILES FOR CONTRIBUTOR L3
              LNUM = NUM1 / 8
              LREM = MOD(NUM1,8)
              IF (LREM .NE. 0) THEN
                  NREC1 = (L3*1000) + LNUM + 1
                  FMT = WR(LREM)
                  J6 = (LNUM*8) + 1
                  J7 = NUM1
                  WRITE (3,FMT,REC=NREC1,ERR=130,IOSTAT=K5) (FILE(L),L=J6,J7)
              ELSE
C
C*   LAST LINE IN INDEX FOR CONTRIBUTOR HAS EIGHT FILES.
                  NREC1 = (L3*1000) + LNUM
                  FMT = WR(8)
                  J6 = (LNUM - 1) * 8 + 1

```

```

        J7 = NUM1
        WRITE (3,FMT,REC=NREC1,ERR=130,IOSTAT=K5) (FILE(L),L=J6,J7)
    END IF
END IF
C
C•   UPDATE HEADER RECORD
    NREC = L3 * 1000
    WRITE (UNIT=3,REC=NREC,FMT=40,ERR=150,IOSTAT=K6) PCNT, NUM1
40  FORMAT (1X, A8, 2X, I3)
C
C•   IF RUN SUCCESSFUL GO TO END
    GO TO 180
C
C•   ERROR MESSAGES
50  WRITE (6,60) K1
60  FORMAT (1X, 'ERROR ON READ TO UNIT 3,NUM1.LE.8,IOSTAT=', I4)
    GO TO 170
70  WRITE (6,80) K2
80  FORMAT (1X, 'ERROR ON COMPLETE LINE READ TO UNIT 3,NUM1.GT.8,
1   IOSTAT=', I4)
    GO TO 170
90  WRITE (6,100) K3
100 FORMAT (1X, 'ERROR ON PARTIAL LINE READ TO UNIT 3,NUM1.GT.8,
1   IOSTAT=', I4)
    GO TO 170
110 WRITE (6,120) K4
120 FORMAT (1X, 'ERROR ON WRITE TO UNIT 3,NUM1.LE.8,IOSTAT=', I4)
    GO TO 170
130 WRITE (6,140) K5
140 FORMAT (1X, 'ERROR ON WRITE TO UNIT 3,NUM1.GT.8,IOSTAT=', I4)
    GO TO 170
150 WRITE (6,160) K6
160 FORMAT (1X, 'ERROR ON CONTRIBUTOR HEADER(UPDATE) WRITE,IOSTAT=',
1       I4)
170 STOP
180 RETURN
    END
C••
C••
C••   SUBROUTINE UVCALC(RADLN, RADLT, RADPLT, LAMDA0, U, V)
C••   ~~~~~
C••   Subroutine UVCALC converts Lat. and lon. to uv space using
C••   the pole RADPLT, RADPLN in LAMDA0 calculated by POLDET.
C••   Scale along central line = 1.0.
C••
C••   DOUBLE PRECISION RADLN, RADLT, RADPLT, LAMDA0, U, V, RADIUS, ARG1,
1       A, CRDPLT, SRDPLT, DLNLAM
C
C   DATA RADIUS /6371.000/
C
C   CRDPLT = DCOS(RADPLT)
C   SRDPLT = DSIN(RADPLT)
C   DLNLAM = DSIN(RADLN - LAMDA0)
C

```

```

ARG1 = (DTAN(RADLT)*CRDPLT + SRDPLT*DLNLAM) / DCOS(RADLN - LAMDA0)
A = SRDPLT * DSIN(RADLT) - CRDPLT * DCOS(RADLT) * DLNLAM
C
U = RADIUS * DATAN(ARG1)
V = (RADIUS/2D0) * DLOG((1D0+A)/(1D0-A))
C
RETURN
END

```

Appendix C

Computer programmes used in the study of isostasy

Introduction

The computer programmes listed in Appendix C were used in the investigation into the nature of the isostatic compensation of the topography of the UK described in Chapter 5. The purpose of each programme is described in the documentation at the head of the programme.

General information on the compilation of the programme object code and the use of external subroutines is given in the introduction to Appendix B.


```

C**
C** Programme Coh.3layer
C**
C**
C** Programme Coh.3layer calculates the theoretical
C** coherence between gravity and topography for
C** an elastic plate loaded by surface topography
C** and two internal density contrasts. The model is
C** a three layer halfspace. The lithosphere is
C** assumed to have a uniform elastic thickness.
C**
C** Programme Details
C**
C**
C** OS MTS
C** Language Fortran 77 + *Ghost80
C**
C** Author R.Woollett
C** Date 21 st April 1987
C**
C** Run Command
C**
C**
C** Run -load+*ghost80 5 = Input 8 = Output 9 = Plotfile
C**
C*****C
C
C MAIN
C* DEFINE ARRAY SPACE + CONSTANTS
C* IMPLICIT REAL*8(A - H,O - Z)
C
C REAL*8 C2(80), LAMBDA(80), WAVE(80), F1(80), F2(80), WAVOBS(80),
1 LAMOBS(80), C2OBS(80), TE(10), D(10), C2ERR(80)
C
C REAL*4 C2R4(80), LAMBDA4(80), LAMMIN, LAMMAX, C2MIN, C2MAX, X4, Y4,
1 YLOW4, YHIGH4, TE4
C
C CHARACTER TITLE*60
C
C SET CONSTANTS
C DATA GRAV, E, V /9.81D0, 1.0D+11, 0.25D0/
C
C PIE = 4.0D0 * ATAN(1.0D0)
C
C CLEAN DATA ARRAYS
C DO 10 I = 1, 80
C C2(I) = 0.0
C C2ERR(I) = 0.0
C LAMBDA(I) = 0.0
C WAVE(I) = 0.0
C F1(I) = 0.0
C F2(I) = 0.0
C C2R4(I) = 0.0
C LAMBDA4(I) = 0.0
C WAVOBS(I) = 0.0
C LAMOBS(I) = 0.0

```

```

C2OBS(I) = 0.0
10 CONTINUE
C
C DO 20 I = 1, 10
C TE(I) = 0.0
C D(I) = 0.0
20 CONTINUE
C
C* INPUT NUMBER OF DATA POINTS AND MODEL PARAMETERS
C READ (5,*) NT, NPOINT, NOBS
C READ (5,*) P0, PC, PM, ZC, ZM
C
C* DETERMINE DENSITY CONTRASTS
C PDEL1 = PM - P0
C PDEL2 = PC - P0
C PDEL3 = PM - PC
C
C* ENTER VALUES OF TE FOR CALCULATION OF COHERENCE
C DO 30 I = 1, NT
C READ (5,*) TE(I)
C D(I) = (E*(TE(I)**3)) / (12.0D0*(1.0D0-(V**2)))
30 CONTINUE
C
C* ENTER WAVELENGTHS FOR THEORETICAL CALCULATIONS
C DO 40 I = 1, NPOINT
C READ (5,*) LAMBDA(I), F1(I), F2(I)
C LAMBDA4(I) = SNGL(LAMBDA(I))
C WAVE(I) = (2.0D0*PIE) / (LAMBDA(I)*1000.0D0)
40 CONTINUE
C
C* ENTER OBSERVED COHERENCE
C DO 50 I = 1, NOBS
C READ (5,*) WAVOBS(I), C2OBS(I), C2ERR(I)
C LAMOBS(I) = (2.0D0*PIE) / (WAVOBS(I)*1000.0D0)
50 CONTINUE
C
C* INITIALIZE DATA OUTPUT
C WRITE (8,60)
60 FORMAT (/, 5X, 'Flexural Coherence Plot', //, 5X, 'Observed Data',
1
C WRITE (8,70)
70 FORMAT (5X, 'Wavelength (Km) Wave Number (m-1) Coherency', /)
C DO 90 I = 1, NOBS
C WRITE (8,80) LAMOBS(I), WAVOBS(I), C2OBS(I)
80 FORMAT (5X, E11.5, 7X, E11.5, 8X, E11.5)
90 CONTINUE
C
C* SET UP PLOT SPACE
C READ (5,*) LAMMIN, LAMMAX, C2MIN, C2MAX
C
C CALL PAPER(1)
C CALL PSPACE(0.2, 0.8, 0.25, 0.85)
C CALL MAPXL(LAMMAX, LAMMIN, C2MIN, C2MAX)
C CALL CTRMAG(13)
C CALL SCAXLI(0.0)
C CALL POSITN(LAMMAX, C2MAX)

```

```

      CALL JOIN(LAMMIN, C2MAX)
      CALL JOIN(LAMMIN, C2MIN)
      CALL CTRMAG(10)
C
      DO 100 I = 1, NOBS
        X4 = SNGL(LAMOBS(I))
        Y4 = SNGL(C2OBS(I))
        CALL PLOTNC(X4, Y4, 237)
        YLOW4 = SNGL(C2OBS(I) - C2ERR(I))
        YHIGH4 = SNGL(C2OBS(I) + C2ERR(I))
        CALL POSITN(X4, YLOW4)
        CALL JOIN(X4, YHIGH4)
      100 CONTINUE
C
C*   CALCULATE AND PLOT EFFECTIVE COHERENCY
      DO 160 I = 1, NT
C
        WRITE (8,110) TE(I), D(I)
      110   FORMAT (/, 5X, 'Elastic Thickness = ', F9.2, /, 5X,
1         'Flexural Rigidity = ', E10.4, /)
        WRITE (8,120)
      120   FORMAT (5X, 'Wavelength (Km)   Wavenumber (m-1)   F1           F2',
1         5X, 'Coherency', //)
C
        DO 130 J = 1, NPOINT
C
          C2(J) = 0.0
          CALL COHER3(D(I), WAVE(J), F1(J), F2(J), C2(J), P0, PC, PM,
1          ZC, ZM, PDEL1, PDEL2, PDEL3, GRAV, PIE)
C
      130   CONTINUE
C
        DO 150 J = 1, NPOINT
          WRITE (8,140) LAMBDA(J), WAVE(J), F1(J), F2(J), C2(J)
      140   FORMAT (6X, E11.5, 5X, E11.5, 5X, F6.2, 5X, F6.2, 10X, E11.5)
C
          C2R4(J) = SNGL(C2(J))
      150   CONTINUE
C
          CALL CURVEQ(LAMBDA4, C2R4, 1, NPOINT)
C
      160 CONTINUE
C
C*   ANNOTATE PLOT
      CALL PSPACE(0.0, 1.0, 0.0, 1.0)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
      CALL CTRMAG(15)
      CALL PLOTCS(0.2, 0.95, 'Topography-Bouguer gravity coherence')
C
C*   ENTER TITLE
      READ (5,170) TITLE
      170 FORMAT (A60)
C
      CALL PLOTCS(0.20, 0.90, TITLE)
      CALL ITALIC(1)
      CALL PLOTCS(0.40, 0.16, 'Wavelength km')

```

```

      CALL CTRORI(90.0)
      CALL PLOTCS(0.12, 0.47, 'Coherence')
      CALL CTRORI(0.0)
C
      CALL PLOTNC(0.200, 0.12, 237)
      CALL PLOTCS(0.250, 0.12, 'Observed coherence')
      CALL POSITN(0.100, 0.08)
      CALL JOIN(0.200, 0.08)
      CALL PLOTCS(0.25, 0.070, 'Theoretical coherence')
C
C*   PLOT F1(1) AND F2(1)
      CALL PLOTCS(0.55, 0.12, 'F1 = ')
      CALL TYPENF(SNGL(F1(1)), 2)
      CALL TYPECS(' F2 = ')
      CALL TYPENF(SNGL(F2(1)), 2)
C
      IF (NT .EQ. 1) THEN
        CALL PLOTCS(0.55, 0.07, 'Te = ')
        TE4 = SNGL(TE(NT)/1000.0D0)
        CALL TYPENF(TE4, 1)
        CALL TYPECS(' km')
      END IF
C
      CALL ITALIC(0)
C
      CALL GREND
C
      STOP
      END

```



```

C
50  CONTINUE
C
C*  NUMERICALLY INTEGRATE TE.v.GH AND TE.v.HH AND TE.v.GG
    GHINT = 0.0D0
    GHERR = 0.0D0
    CALL D01GAF(TE, GH, NTE, GHINT, GHERR, IFAIL)
C
    HHINT = 0.0D0
    HHERR = 0.0D0
    CALL D01GAF(TE, HH, NTE, HHINT, HHERR, IFAIL)
C
    GGINT = 0.0D0
    GGERR = 0.0D0
    CALL D01GAF(TE, GG, NTE, GGINT, GGERR, IFAIL)
C
    C2HAT(1) = (GHINT*2) / (HHINT*GGINT)
    C2HAT4(1) = SNGL(C2HAT(1))
C
    1  WRITE (8,60) LAMBDA(1), GHINT, GHERR, HHINT, HHERR, GGINT,
60    GGERR, C2HAT(1)
    60  FORMAT (3X, 8(2X,E11.5))
C
70  CONTINUE
C
C*  PLOT RESULTS AGAINST OBSERVED DATA
    CALL PAPER(1)
    CALL PSPACE(0.2, 0.8, 0.25, 0.85)
    CALL MAPXL(LAMMAX, LAMMIN, C2MIN, C2MAX)
    CALL CTRMAG(13)
    CALL SCAXLI(0.0)
    CALL POSITN(LAMMAX, C2MAX)
    CALL JOIN(LAMMIN, C2MAX)
    CALL JOIN(LAMMIN, C2MIN)
    CALL CTRMAG(10)
C
    DO 80 K = 1, NOBS
        CALL PLOTNC(LAMOBS(K), C2OBS(K), 237)
        C2LOW = C2OBS(K) - C2ERR(K)
        CALL POSITN(LAMOBS(K), C2LOW)
        C2HIGH = C2OBS(K) + C2ERR(K)
        CALL JOIN(LAMOBS(K), C2HIGH)
    80 CONTINUE
C
    CALL CURVEO(LAMBD4, C2HAT4, 1, NPTS)
C
C*  ANNOTATE PLOT
    CALL PSPACE(0.0, 1.0, 0.0, 1.0)
    CALL MAP(0.0, 1.0, 0.0, 1.0)
C
    CALL CTRMAG(15)
    CALL PLOTCS(0.2, 0.95, 'Topography-Bouguer gravity coherence')
    CALL PLOTCS(0.2, 0.9, 'Variable Te Three layer loading model')
C
    CALL CTRMAG(12)
    CALL ITALIC(1)

```

```

    CALL PLOTCS(0.4, 0.16, 'Wavelength km')
    CALL CTRORI(90.0)
    CALL PLOTCS(0.12, 0.35, 'Coherence')
    CALL CTRORI(0.0)
C
    CALL PLOTNC(0.2, 0.12, 237)
    CALL PLOTCS(0.25, 0.12, 'Observed Coherence')
    CALL POSITN(0.1, 0.08)
    CALL JOIN(0.2, 0.08)
    CALL PLOTCS(0.25, 0.07, 'Theoretical Coherence')
C
C*  PLOT F1(1) AND F2(1)
    CALL PLOTCS(0.55, 0.12, 'F1 = ')
    CALL TYPEPF(SNGL(F1(1)), 2)
    CALL TYPECS(' F2 = ')
    CALL TYPEPF(SNGL(F2(1)), 2)
C
C*  PLOT TE RANGE
    CALL PLOTCS(0.55, 0.07, 'Te = ')
    TEMIN4 = SNGL(TEMIN/1000.0D0)
    TEMAX4 = SNGL(TEMAX/1000.0D0)
    CALL TYPEPF(TEMIN4, 1)
    CALL TYPECS(' to ')
    CALL TYPEPF(TEMAX4, 1)
    CALL TYPECS(' km')
    CALL ITALIC(0)
C
    CALL GREND
C
    STOP
    END

```

```

C**
C** Programme Isos.resp
C** ~~~~~
C**
C** Programme Isos.resp is designed to determine an isostatic response
C** function, the coherence between gravity and topography and the
C** gravity and topography power spectra from gridded representations
C** of gravity and topography generated by the database programmes
C** Grid.proj and Binradii. Before the fourier transforms of the gravity
C** and topography grids are calculated the grid edges are smoothed with
C** a cosine taper and the arrays are zero padded. A best fit plane may
C** also be removed.
C**
C** After the response and coherence etc. have been determined a
C** smoothed version of the response is convolved with the topography
C** data to generate the 'predicted gravity' (see Chapter 5). The
C** predicted gravity is then subtracted from the Bouguer gravity grid
C** to form an isostatic anomaly map.
C**
C** Note the conversion of bathymetry to topography. This allows
C** the response function to be interpreted in terms of a simple
C** land mass.
C**
C** Input command file structure
C**
C** Line 1 Title 80 Characters
C** Line 2 IOPT
C** IOPT= 0 No detrending of data arrays
C** IOPT= 1 Detrend data
C** IOPT= 2 Demean data
C** Line 3 NLVLS Number of logarithmic wavenumber bands over
C** which to smooth the response function
C** Line 4 LX, LY Length of X and Y cosine tapers
C** Line 5 Name of input file for data grids { 7 Characters }
C** Line 6 Name of output file for data grids { 7 Characters }
C**
C** All input effectively free format
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + *nag
C**
C** Author R.W.Woollett
C** Date 18 th March 1987
C**
C** Run Command
C** ~~~~~
C**
C** Run -load+*nag 5 = Input command file 8 = Output 9 = Plot data
C** ~~~~~**C
C
C* MAIN ROUTINE
C* DEFINE ARRAY SPACE AND VARIABLE TYPES

```

```

REAL*8 TREAL(70400), TIMAG(70400), GREAL(70400), GIMAG(70400),
1 QREAL(70400), QIMAG(70400), GRVPRL(70400), GRVPIM(70400),
2 TPOWER(70400), DWORK(1000), CSMTHR(50), CSMTHI(50),
3 TPSMTH(50), WAVENO(50), DKOUNT(50), QSMTHR(50), QSMTHI(50),
4 GPSMTH(50), GPOWER(70400), QDEV(50), C2(50), C2ERR(50)

REAL*8 SAMP, WAVMIN, WAVMAX, LOGMIN, LOGMAX, DAVTOP, DAVBOU

INTEGER*4 ND(2)

CHARACTER TITLE*80

COMMON /TOPO/ TREAL, TIMAG
COMMON /GRVTY/ GREAL, GIMAG
COMMON /GRVPD/ GRVPRL, GRVPIM
COMMON /RESP/ QREAL, QIMAG
COMMON /PWRSPC/ TPOWER, GPOWER
COMMON /INTRVL/ SAMP
COMMON /SMOOTH/ CSMTHR, CSMTHI, TPSMTH, GPSMTH, WAVENO, DKOUNT,
1 QSMTHR, QSMTHI, C2, QDEV, C2ERR
COMMON /LIMITS/ WAVMIN, WAVMAX, LOGMIN, LOGMAX
COMMON /LEVELS/ NLVLS
COMMON /AREA/ XMIN, XMAX, YMIN, YMAX

C
C* DEFINE *NAG VARIABLES
DATA LWORK, NDIM, IFAIL /1000, 2, 0/

C
C* SET UNDEFINED VARIABLES TO ZERO
DO 10 I = 1, 70400
TREAL(I) = 0.0
TIMAG(I) = 0.0
GREAL(I) = 0.0
GIMAG(I) = 0.0
GRVPRL(I) = 0.0
GRVPIM(I) = 0.0
QREAL(I) = 0.0
QIMAG(I) = 0.0
TPOWER(I) = 0.0
GPOWER(I) = 0.0
10 CONTINUE

C
DO 20 I = 1, 1000
DWORK(I) = 0.0
20 CONTINUE

C
DO 30 I = 1, 50
CSMTHR(I) = 0.0
CSMTHI(I) = 0.0
TPSMTH(I) = 0.0
GPSMTH(I) = 0.0
WAVENO(I) = 0.0
DKOUNT(I) = 0.0
QSMTHR(I) = 0.0
QSMTHI(I) = 0.0
C2(I) = 0.0
QDEV(I) = 0.0
30 CONTINUE

```

```

      C2ERR(1) = 0.0
30 CONTINUE
C
C*   ENTER ADDITIONAL DATA FOR RUN
      READ (5,40) TITLE
40 FORMAT (A80)
      WRITE (6,50) TITLE
      WRITE (8,50) TITLE
50 FORMAT (/, A80, /)
C
C*   ENTER PROGRAMME CONTROL INPUT
C*   1) IS DATA TO BE DETRENDED 0=NO 1=YES
C*   2) NUMBER OF SMOOTHING LEVELS
C*   3) ENTER SIZE OF TAPERS
      READ (5,*) IOPT
      READ (5,*) NLVLS
      READ (5,*) LX, LY
C
C*   INPUT BASIC GRAVITY AND TOPOGRAPHY ARRAYS
      CALL INPUT(NX, NY, NPTS, AVTOP, AVBOUG)
      DAVTOP = DBLE(AVTOP)
      DAVBOU = DBLE(AVBOUG)
C
C*   DETREND OR DEMEAN DATA IF REQUIRED
      IF (IOPT.EQ. 1) THEN
        CALL DETRND(TREAL, NX, NY, SAMP)
        CALL DETRND(GREAL, NX, NY, SAMP)
      ELSE IF (IOPT.EQ. 2) THEN
        DO 70 I = 1, NX
          DO 60 J = 1, NY
            IPOS = (J - 1) * NX + I
            TREAL(IPOS) = TREAL(IPOS) - DAVTOP
            GREAL(IPOS) = GREAL(IPOS) - DAVBOU
          60 CONTINUE
        70 CONTINUE
      END IF
C
C*   MODIFY ARRAYS WITH COSINE TAPER
      CALL TAPER(TREAL, NX, NY, LX, LY)
      CALL TAPER(GREAL, NX, NY, LX, LY)
C
C*   PAD ARRAYS WITH ZEROES
      CALL PAD(TREAL, TIMAG, NX, NY, IXTOT, IYTOT)
      CALL PAD(GREAL, GIMAG, NX, NY, IXTOT, IYTOT)
C
C*   FFT TOPOGRAPHY
      ND(1) = IXTOT
      ND(2) = IYTOT
      N = ND(1) * ND(2)
      CALL C06FJF(NDIM, ND, N, TREAL, TIMAG, DWORK, LWORK, IFAIL)
C
C*   CALCULATE SMOOTHED RESPONSE FUNCTION
      CALL ADMIT(NX, NY, IXTOT, IYTOT, NDIM, ND, N, DWORK, LWORK, IFAIL)
C
C*   APPROXIMATE SMOOTHED Q IN RAW Q ARRAY
      CALL QPRD(IXTOT, IYTOT)

```

```

C
C*   PREDICT GRAVITY OVER ARRAY
      CALL GRVPRD(NX, NY, IXTOT, IYTOT, NDIM, ND, N, DWORK, LWORK,
1      IFAIL)
C
C*   INVERT TOPOGRAPHY FFT
      CALL C06GCF(TIMAG, N, IFAIL)
      CALL C06FJF(NDIM, ND, N, TREAL, TIMAG, DWORK, LWORK, IFAIL)
      CALL C06GCF(TIMAG, N, IFAIL)
C
C*   OUTPUT DATA
      CALL OUTPUT(NX, NY, IXTOT, IYTOT)
C
      STOP
      END

```

```

C**
C** Programme Q.te.3layer
C** ~~~~~
C**
C** Programme Q.te.3layer calculates the theoretical
C** amplitude response for the three layer isostatic
C** model. The value of the elastic thickness of the
C** lithosphere is assumed to vary uniformly between
C** TEMIN and TEMAX.
C**
C**
C** The technique is taken from Forsyth (1985), but
C** it is applied to a more sophisticated form of
C** loading model.
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + *Nag
C**
C** Author R.W.Woollett
C** Date 16th May 1988
C**
C** Run Command
C** ~~~~~
C**
C** Run -load+*nag 5 = Input 8 = Results 9 = Plotfile
C**
C** ~~~~~**C
C
C MAIN
C IMPLICIT REAL*8(A - H,O - Z)
C
C REAL*8 D(100), F1(10), F2(10), GH(100), MH(100), LAMBDA(100),
1 QHAT(100), Q(100), TE(100), WAVE(100)
C
C REAL*4 LAMBD4(100), LAMOBS(100), QERR(100), QHAT4(100), QOBS(100),
1 WAVOBS(100)
C
C REAL*4 LAMMIN, LAMMAX, QMIN, QMAX, QLOW, QHIGH, TEMIN4, TEMAX4
C
C DATA D, F1, F2, LAMBDA, TE, WAVE /100*0.0D0, 10*0.0D0, 10*0.0D0,
1 100*0.0D0, 100*0.0D0, 100*0.0D0/
C DATA LAMBD4, LAMOBS, QERR, QOBS, WAVOBS /100*0.0, 100*0.0,
1 100*0.0, 100*0.0, 100*0.0/
C DATA G, GRAV, E, V /6.67D-11, 9.81D0, 1.0D+11, 0.25D0/
C DATA IFAIL /0/
C
C PIE = 4.0D0 * ATAN(1.0D0)
C
C ENTER MODEL PARAMETERS
C READ (5,*) P0, PC, PM, ZC, ZM
C PDEL1 = PM - P0
C PDEL2 = PC - P0
C PDEL3 = PM - PC

```

```

C
C* ENTER DATA FOR CALCULATIONS
C* READ (5,*) NPTS, NOBS, NF
C
C* ENTER WAVELENGTHS AT WHICH TO EVALUATE THEORETICAL RESPONSE
C* DO 10 I = 1, NPTS
C*   READ (5,*) LAMBDA(I)
C*   LAMBD4(I) = SNGL(LAMBDA(I))
C*   WAVE(I) = 2.0D0 * PIE / (LAMBDA(I)*1000.0D0)
10 CONTINUE
C
C* ENTER RANGE OF ELASTIC THICKNESSES AND INTEGRATION INTERVAL
C* READ (5,*) TEMIN, TEMAX, TEDEL
C* NTE = NINT(SNGL((TEMAX - TEMIN)/TEDEL)) + 1
C
C* DO 20 J = 1, NTE
C*   TE(J) = TEMIN + DFLOAT(J - 1) * TEDEL
C*   D(J) = (E*(TE(J)**3)) / (12.0D0*(1.0D0-(V**2)))
20 CONTINUE
C
C* ENTER PLOT DATA
C* READ (5,*) LAMMIN, LAMMAX, QMIN, QMAX
C
C* ENTER OBSERVED RESPONSE
C* DO 30 K = 1, NOBS
C*   READ (5,*) WAVOBS(K), QOBS(K), QERR(K)
C*   LAMOBS(K) = (2.0*SNGL(PIE)) / (WAVOBS(K)*1000.0)
30 CONTINUE
C
C* ENTER LOADING RATIOS
C* DO 40 L = 1, NF
C*   READ (5,*) F1(L), F2(L)
40 CONTINUE
C
C* INITIALIZE PLOT
C* CALL PAPER(1)
C* CALL PSPACE(0.2, 0.8, 0.25, 0.825)
C* CALL MAPXL(LAMMAX, LAMMIN, QMIN, QMAX)
C* CALL CTRMAG(13)
C* CALL SCAXLI(0.0)
C* CALL POSITN(LAMMAX, QMAX)
C* CALL JOIN(LAMMIN, QMAX)
C* CALL JOIN(LAMMIN, QMIN)
C* CALL CTRMAG(10)
C
C* DO 50 K = 1, NOBS
C*   CALL PLOTNC(LAMOBS(K), QOBS(K), 237)
C*   QLOW = QOBS(K) - QERR(K)
C*   CALL POSITN(LAMOBS(K), QLOW)
C*   QHIGH = QOBS(K) + QERR(K)
C*   CALL JOIN(LAMOBS(K), QHIGH)
50 CONTINUE
C
C* LOOP THROUGH F1, F2 CALCULATING AMPLITUDE RESPONSE QHAT
C* DO 110 L = 1, NF
C

```

```

C      WRITE (8,60) F1(L), F2(L)
60      FORMAT (/, 10X, 'F1 = ', F5.2, 2X, 'F2 = ', F5.2, /)
C
C*     CALCULATE QHAT AT EACH WAVENUMBER
C      WRITE (8,70)
70      FORMAT (10X, 'Results for variable flexural rigidity', //, 7X,
1      'Lambda GH Int. GH Error HH Int.', 2X,
2      'HH Error Q', /)
C
C      DO 100 I = 1, NPTS
C
C          QHAT(I) = 0.0D0
C          QHAT4(I) = 0.0
C
C          DO 80 J = 1, NTE
C
C              Q(J) = 0.0D0
C              HH(J) = 0.0D0
C              GH(J) = 0.0D0
C
C              WT = 0.0D0
C              HT = 0.0D0
C              HT2 = 0.0D0
C
C          C*     DETERMINE SURFACE TOPOGRAPHY GENERATED BY
C          C*     SURFACE LOADING
C          CALL MOHOT(P0, PM, D(J), WAVE(I), GRAV, WT)
C          CALL SURFT(WT, PM, P0, D(J), WAVE(I), GRAV, HT)
C          HT2 = HT * HT
C
C          CALL QCAL(D(J), WAVE(I), F1(L), F2(L), Q(J), HH(J), P0, PC,
1          PM, ZC, ZM, PDEL1, PDEL2, PDEL3, GRAV, G, PIE)
C
C          HH(J) = HH(J) * HT2
C          GH(J) = Q(J) * HH(J)
C
C      80      CONTINUE
C
C*     NUMERICALLY INTEGRATE TE.v.GH AND TE.v.HH
C          GHINT = 0.0D0
C          GHERR = 0.0D0
C          CALL D01GAF(TE, GH, NTE, GHINT, GHERR, IFAIL)
C
C          HHINT = 0.0D0
C          HHERR = 0.0D0
C          CALL D01GAF(TE, HH, NTE, HHINT, HHERR, IFAIL)
C
C          QHAT(I) = GHINT / HHINT
C          QHAT4(I) = SNGL(QHAT(I))
C
C          WRITE (8,90) LAMBDA(I), GHINT, GHERR, HHINT, HHERR, QHAT(I)
90      FORMAT (3X, 6(2X,E11.5))
C
C      100      CONTINUE
C
C          CALL CURVED(LAMBDA4, QHAT4, 1, NPTS)

```

```

C      110      CONTINUE
C
C*     ANNOTATE PLOT
C          CALL PSPACE(0.0, 1.0, 0.0, 1.0)
C          CALL MAP(0.0, 1.0, 0.0, 1.0)
C
C          CALL CTRMAG(15)
C          CALL PLOTCS(0.2, 0.975, 'Observed and Theoretical Response')
C          CALL PLOTCS(0.2, 0.925, 'Variable Te Three layer loading')
C
C          CALL CTRMAG(12)
C          CALL ITALIC(1)
C          CALL PLOTCS(0.4, 0.16, 'Wavelength km')
C          CALL CTRORI(90.0)
C          CALL PLOTCS(0.10, 0.35, 'Amplitude response mGal/m')
C          CALL CTRORI(0.0)
C
C          CALL PLOTNC(0.25, 0.12, 237)
C          CALL PLOTCS(0.35, 0.12, 'Observed response')
C          CALL POSITN(0.2, 0.08)
C          CALL JOIN(0.3, 0.08)
C          CALL PLOTCS(0.35, 0.07, 'Theoretical response')
C
C          CALL PLOTCS(0.60, 0.12, 'Te =')
C          TEMIN4 = SNGL(TEMIN/1000.0D0)
C          TEMAX4 = SNGL(TEMAX/1000.0D0)
C          CALL TYPENF(TEMIN4, 1)
C          CALL TYPECS(' to ')
C          CALL TYPENF(TEMAX4, 1)
C          CALL TYPECS(' km')
C
C          CALL CTRMAG(10)
C          CALL PLOTCS(0.2, 0.02, 'F1 = ')
C          DO 120 I = 1, NF
C              CALL TYPENF(SNGL(F1(I)), 2)
C              IF (I .LT. NF) THEN
C                  CALL TYPECS(' ')
C              END IF
C          120      CONTINUE
C
C          CALL TYPECS(' F2 = ')
C          DO 130 I = 1, NF
C              CALL TYPENF(SNGL(F2(I)), 2)
C              IF (I .LT. NF) THEN
C                  CALL TYPECS(' ')
C              END IF
C          130      CONTINUE
C
C          CALL GREND
C
C          STOP
C          END

```



```

C**
C** Programme Q.3layer
C**
C**
C** Programme Q.3layer is designed to calculate
C** and plot the amplitude response function for
C** the three layer isostatic model assuming a
C** uniform elastic thickness for the lithosphere.
C**
C** Programme Details
C**
C**
C** OS MTS
C** Language Fortran 77 + *Ghost80
C**
C** Author R.W.Woollett
C** Date 27 th April 1988
C**
C** Run Command
C**
C**
C** Run -LOAD+*GHOST80 5 = Input 8 = Output 9 = Plotfile
C**

```

```

C-----C
C
C MAIN
C IMPLICIT REAL*8(A - H,O - Z)
C
C REAL*8 LAMBDA(75), WAVE(75), Q(75), F1(75), F2(75), LAMOBS(75),
1 WAVOBS(75), QOBS(75)
C
C REAL*4 Q4(75), LAMBDA4(75), LAMMIN, LAMMAX, QMIN, QMAX, X4, Y4,
1 ERROBS(75), YLOW4, YHIGH4, TE4
C
C CHARACTER TITLE*60
C
C SET GEOPHYSICAL CONSTANTS
C DATA GRAY, E, V /9.81D0, 1.0D+11, 0.25D0/
C DATA G /6.67D-11/
C
C PIE = 4.0D0 * ATAN(1.0D0)
C
C CLEAN DATA ARRAYS
C DO 10 I = 1, 75
C LAMBDA(I) = 0.0
C WAVE(I) = 0.0
C Q(I) = 0.0
C F1(I) = 0.0
C F2(I) = 0.0
C LAMOBS(I) = 0.0
C WAVOBS(I) = 0.0
C QOBS(I) = 0.0
C Q4(I) = 0.0
C LAMBDA4(I) = 0.0
C ERROBS(I) = 0.0
10 CONTINUE

```

```

C
C* INITIALIZE PLOT
C* READ (5,*) LAMMIN, LAMMAX, QMIN, QMAX
C
C CALL PAPER(1)
C CALL PSPACE(0.2, 0.8, 0.25, 0.825)
C CALL MAPXL(LAMMAX, LAMMIN, QMIN, QMAX)
C CALL CTRMAG(13)
C CALL SCAXLI(0.0)
C CALL POSITN(LAMMAX, QMAX)
C CALL JOIN(LAMMIN, QMAX)
C CALL JOIN(LAMMIN, QMIN)
C CALL CTRMAG(10)
C
C* ENTER MODEL PARAMETERS
C* READ (5,*) P0, PC, PM, ZC, ZM
C* PDEL1 = PM - P0
C* PDEL2 = PC - P0
C* PDEL3 = PM - PC
C
C* INITIALIZE OUTPUT
C* WRITE (8,20)
20 FORMAT (/, 5X, 'Response Function Fitting', //, 5X,
1 'Observed Data', /)
C* WRITE (8,30)
30 FORMAT (5X, 'Wavelength (Km) Wavenumber (m-1) Response', /)
C
C* ENTER OBSERVED DATA
C* READ (5,*) NOBS
C* DO 50 I = 1, NOBS
C* READ (5,*) WAVOBS(I), QOBS(I), ERROBS(I)
C* LAMOBS(I) = (2.0D0*PIE) / (WAVOBS(I)*1000.0D0)
C
C WRITE (8,40) LAMOBS(I), WAVOBS(I), QOBS(I)
40 FORMAT (5X, F11.2, 3X, E11.5, 2X, E11.5)
C
C* PLOT OBSERVED DATA
C* X4 = SNGL(LAMOBS(I))
C* Y4 = SNGL(QOBS(I))
C* CALL PLOTNC(X4, Y4, 237)
C* YLOW4 = Y4 - ERROBS(I)
C* CALL POSITN(X4, YLOW4)
C* YHIGH4 = Y4 + ERROBS(I)
C* CALL JOIN(X4, YHIGH4)
C
C 50 CONTINUE
C
C* ENTER ELASTIC THICKNESS
C* READ (5,*) TE
C* D = (E*(TE**3)) / (12.0D0*(1.0D0-(V**2)))
C
C WRITE (8,60) TE, D
60 FORMAT (5X, 'Theoretical Results', //, 5X, 'Elastic Thickness = ',
1 F9.2, /, 5X, 'Flexural Rigidity = ', E11.5, /)
C
C* ENTER CALCULATION MODE

```

```

C* IMODE = 1 CONSTANT LOADING RATIOS F1, F2
C* IMODE = 2 F1, F2 VARY WITH WAVELENGTH
  READ (5,*) IMODE
  IF (IMODE .EQ. 1) THEN
    READ (5,*) IFTYPE
    DO 70 I = 1, IFTYPE
      READ (5,*) F1(I), F2(I)
  70 CONTINUE
  END IF
C
C* ENTER DATA POINTS AT WHICH TO
C* EVALUATE RESPONSE
  READ (5,*) NPOINT
  IF (IMODE .EQ. 1) THEN
    DO 80 I = 1, NPOINT
      READ (5,*) LAMBDA(I)
  80 CONTINUE
  ELSE IF (IMODE .EQ. 2) THEN
    DO 90 I = 1, NPOINT
      READ (5,*) LAMBDA(I), F1(I), F2(I)
  90 CONTINUE
  END IF
C
  DO 100 I = 1, NPOINT
    WAVE(I) = (2.0D0*PIE) / (LAMBDA(I)*1000.0D0)
    LAMBDA4(I) = SNGL(LAMBDA(I))
  100 CONTINUE
C
  IF (IMODE .EQ. 1) THEN
C
C* CALCULATE RESPONSE FOR SEVERAL
C* CONSTANT F RATIOS
    DO 150 I = 1, IFTYPE
      WRITE (8,110) F1(I), F2(I)
  110 1 FORMAT (5X, 'Intermediate Subsurface Load/Surface load=',
      2 F6.2, /, 5X,
      'Deep Subsurface load/Surface load =', F6.2, //)
C
      WRITE (8,120)
  120 1 FORMAT (5X, 'Wavelength (Km) Wavenumber (m-1) F1 F2', 5X,
      'Response', //)
C
      DO 140 J = 1, NPOINT
        Q(J) = 0.0
        CALL QCAL3(D, WAVE(J), F1(I), F2(I), Q(J), P0, PC, PM, ZC,
          ZM, PDEL1, PDEL2, PDEL3, GRAV, G, PIE)
C
        WRITE (8,130) LAMBDA(J), WAVE(J), F1(I), F2(I), Q(J)
  130 1 FORMAT (5X, F11.2, 1X, E11.5, 1X, F6.2, 1X, F6.2, 1X, E11.5)
C
        Q4(J) = SNGL(Q(J))
C
  140 CONTINUE
C
      CALL CURVEO(LAMBDA4, Q4, 1, NPOINT)

```

```

C
  150 CONTINUE
C
  ELSE IF (IMODE .EQ. 2) THEN
    WRITE (8,160)
  160 1 FORMAT (5X, 'Wavelength (Km) Wavenumber (m-1) F1 F2', 5X,
      'Response', //)
C
    DO 180 I = 1, NPOINT
      Q(I) = 0.0
C
      CALL QCAL3(D, WAVE(I), F1(I), F2(I), Q(I), P0, PC, PM, ZC, ZM,
        PDEL1, PDEL2, PDEL3, GRAV, G, PIE)
C
      WRITE (8,170) LAMBDA(I), WAVE(I), F1(I), F2(I), Q(I)
  170 1 FORMAT (5X, F11.2, 1X, E11.5, 1X, F6.2, 1X, F6.2, 1X, E11.5)
C
      Q4(I) = SNGL(Q(I))
C
  180 CONTINUE
C
      CALL CURVEO(LAMBDA4, Q4, 1, NPOINT)
C
    END IF
C
C* ANNOTATE PLOT
  CALL PSPACE(0.0, 1.0, 0.0, 1.0)
  CALL MAP(0.0, 1.0, 0.0, 1.0)
C
  READ (5,190) TITLE
  190 FORMAT (A60)
C
  CALL CTRMAG(15)
  CALL PLOTCS(0.2, 0.975, 'Observed and theoretical response')
  CALL PLOTCS(0.2, 0.925, 'Three layer loading model')
C
  CALL CTRMAG(12)
  CALL PLOTCS(0.2, 0.875, TITLE)
C
  CALL ITALIC(1)
  CALL PLOTCS(0.4, 0.16, 'Wavelength km')
  CALL CTRORI(90.0)
  CALL PLOTCS(0.10, 0.35, 'Amplitude response mGal/m')
  CALL CTRORI(0.0)
C
  CALL PLOTNC(0.250, 0.12, 237)
  CALL PLOTCS(0.35, 0.12, 'Observed Response')
  CALL POSITN(0.200, 0.08)
  CALL JOIN(0.300, 0.08)
  CALL PLOTCS(0.35, 0.070, 'Theoretical Response')
  CALL PLOTCS(0.60, 0.12, 'Te = ')
  TE4 = SNGL(TE/1000.0D0)
  CALL TYPENF(TE4, 1)
  CALL TYPECS(' km')
C
  IF (IMODE .EQ. 1) THEN

```

```

      CALL CTRMAG(10)
      CALL PLOTCS(0.2, 0.02, 'F1= ')
      DO 200 I = 1, IFTYPE
        CALL TYPENF(SNGL(F1(I)), 2)
        IF (I .LT. IFTYPE) THEN
          CALL TYPECS(' ')
        END IF
200    CONTINUE
C
      CALL TYPECS('      F2= ')
      DO 210 I = 1, IFTYPE
        CALL TYPENF(SNGL(F2(I)), 2)
        IF (I .LT. IFTYPE) THEN
          CALL TYPECS(' ')
        END IF
210    CONTINUE
C
      END IF
C
      CALL GREND
C
      RETURN
      END

```

```

C**
C**
C** Programme Radial.spec
C** ~~~~~
C**
C** Programme Radial.spec analyses gravity and
C** topography grids generating a plot of the
C** logarithm of the smoothed power spectrum
C** against wavenumber or log wavenumber.
C**
C** The programme also allows the smoothed power
C** spectra to be normalized according to the
C** technique proposed by Bechtel et al. (1987).
C**
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + *nag
C**
C** Author R.W.Woollett
C** Date 28 th July 1987
C**
C** Run Command
C** ~~~~~
C**
C** Run -load+*nag+*ghost80 8 = Output 9 = Plotfile

```

```

C-----C
C*
C* MAIN
C* DEFINE VARIABLES AND ARRAY SPACE
C* REAL*8 DATAR(40000), DATAI(40000), WAVE(150), AMP(150),
C* 1 DKOUNT(150), DWORK(1000), AMPNRM(150)
C
C* REAL*8 SAMP, WAVMIN, WAVMAX, DAVDAT
C
C* INTEGER ND(2)
C
C* COMMON /GRID/ DATAR, DATAI
C* COMMON /SMOOTH/ AMP, WAVE, DKOUNT, AMPNRM
C* COMMON /INTRVL/ SAMP
C* COMMON /AREA/ XMIN, XMAX, YMIN, YMAX
C* COMMON /LVL/ NLVL
C* COMMON /LIMITS/ WAVMIN, WAVMAX
C
C* DEFINE *NAG CONSTANTS
C* DATA LWORK, NDIM, IFAIL /1000, 2, 0/
C
C* CLEAN ARRAY SPACE
C* DO 10 I = 1, 40000
C
C*   DATAR(I) = 0.0
C*   DATAI(I) = 0.0
C

```

```

10 CONTINUE
C
C   DO 20 I = 1, 150
C
C     AMP(I) = 0.0
C     WAVE(I) = 0.0
C     DKOUNT(I) = 0.0
C     AMPNRM(I) = 0.0
C
C 20 CONTINUE
C
C   DO 30 I = 1, LWORK
C
C     DWORK(I) = 0.0
C
C 30 CONTINUE
C
C* ENTER DATA
C* 40 WRITE (6,50)
C* 50 FORMAT (/, 5X, 'Enter number of averaging levels ', /)
C*   READ (5,*) NLVL
C
C   IF (NLVL .GT. 150) THEN
C     WRITE (6,60)
C* 60   FORMAT (/, 5X, 'Number of levels exceeds 150:Re-enter data', /)
C     GO TO 40
C   END IF
C
C   WRITE (6,70)
C* 70   FORMAT (/, 5X, 'Enter costaper lengths lx, ly ', /)
C*   READ (5,*) LX, LY
C
C   CALL INPUT(NX, NY, NPTS, AVDAT)
C
C* DETREND DATA IF REQUIRED
C* 80 WRITE (6,90)
C* 90   FORMAT (/, 5X, 'Is the input array to be detrended', /, 5X,
C* 1   'Yes (0) No (1)', /)
C*   READ (5,*) ITREND
C*   IF (ITREND .NE. 0 .AND. ITREND .NE. 1) GO TO 80
C
C   IF (ITREND .EQ. 0) THEN
C     CALL DETRND(DATAR, NX, NY, SAMP)
C   END IF
C
C* REMOVE MEAN IF REQUIRED
C* 100 WRITE (6,110)
C* 110   FORMAT (/, 5X, 'Do you wish to remove mean value from array', /,
C* 1   'Yes (0) No (1)', /)
C
C   READ (5,*) IMEAN
C   IF (IMEAN .NE. 0 .AND. IMEAN .NE. 1) GO TO 100
C
C   IF (IMEAN .EQ. 0) THEN
C     DAVDAT = DBLE(AVDAT)
C     DO 130 I = 1, NX

```

```

      DO 120 J = 1, NY
C
      IPOS = (J - 1) * NX + 1
      DATAR(IPOS) = DATAR(IPOS) - DAVDAT
C
120  CONTINUE
130  CONTINUE
C
      END IF
C
C*  MODIFY DATA FOR FFT
      CALL TAPER(DATAR, NX, NY, LX, LY)
C
C*  PAD DATA WITH ZEROES IF REQUIRED
140 WRITE (6,150)
150 FORMAT ('/, 5X, 'Do you wish to pad array with zeroes', '/', 5X,
1       'Yes (0) No (1)', '/')
C
      READ (5,*) IPAD
      IF (IPAD .NE. 0 .AND. IPAD .NE. 1) GO TO 140
C
      IF (IPAD .EQ. 0) THEN
        CALL PAD(DATAR, DATA1, NX, NY, IXTOT, IYTOT)
      END IF
C
C*  IF IPAD=1 DEFINE IXTOT, IYTOT
      IF (IPAD .EQ. 1) THEN
        IXTOT = NX
        IYTOT = NY
      END IF
C
C*  FOURIER TRANSFORM DATA
      ND(1) = IXTOT
      ND(2) = IYTOT
      N = IXTOT * IYTOT
C
      CALL C06FJF(NDIM, ND, N, DATAR, DATA1, DWORK, LWORK, IFAIL)
C
C*  ANALYSE SPECTRUM
      CALL AMPSPM(IXTOT, IYTOT)
C
C*  PLOT RADIAL SPECTRA
      CALL PLOT
C
      STOP
      END

```

```

C**
C** Appendix C: Subroutine library
C** ~~~~~
C** This subroutine library contains all of the subroutines
C** referred to in the programmes listed in Appendix C.
C** Where different subroutines with the same name occur in
C** two or more programmes there is a comment at the head of
C** each subroutine specifying the main programme or programmes
C** which call the subroutine.
C**
C** ~~~~~***C
C**
C** SUBROUTINE ADMIT(NX, NY, IXTOT, IYTOT, NDIM, ND, N, DWORK, LWORK,
1 IFAIL)
C** ~~~~~
C** Subroutine ADMIT calculates the smoothed admittance
C** function for the gravity and topography data. The coherence
C** and power spectra are also estimated.
C**
C** REAL*8 TREAL(70400), TIMAG(70400), GREAL(70400), GIMAG(70400),
1 QREAL(70400), QIMAG(70400), TPOWER(70400), DWORK(LWORK),
2 CSMTHR(50), CSMTHI(50), TPSMTH(50), WAVENO(50), DKOUNT(50),
3 QSMTHR(50), QSMTHI(50), GPOWER(70400), GPSMTH(50), C2(50),
4 QDEV(50), C2ERR(50)
C
C REAL*8 WAVMIN, WAVMAX, LOGMIN, LOGMAX, DNX, DNY, DNMAX, SAMP, PIE,
1 QVAR, QAMP, QPHASE, C2GG, GG, FG
C
C INTEGER*4 ND(2)
C
C COMMON /TOPO/ TREAL, TIMAG
C COMMON /GRVTY/ GREAL, GIMAG
C COMMON /RESP/ QREAL, QIMAG
C COMMON /PWRSPC/ TPOWER, GPOWER
C COMMON /SMOOTH/ CSMTHR, CSMTHI, TPSMTH, GPSMTH, WAVENO, DKOUNT,
1 QSMTHR, QSMTHI, C2, QDEV, C2ERR
C COMMON /LIMITS/ WAVMIN, WAVMAX, LOGMIN, LOGMAX
C COMMON /INTRVL/ SAMP
C COMMON /LEVELS/ NLVLS
C
C PIE = 4.0D0 * DATAN(1.0D0)
C
C QVAR = 0.0D0
C
C CLEAN ARRAYS TO BE RE-USED
C DO 10 I = 1, 70400
C QREAL(I) = 0.0
C QIMAG(I) = 0.0
10 CONTINUE
C
C DO 20 I = 1, 50
C CSMTHR(I) = 0.0D0
C CSMTHI(I) = 0.0D0
C TPSMTH(I) = 0.0D0
C GPSMTH(I) = 0.0D0
C WAVENO(I) = 0.0D0
C DKOUNT(I) = 0.0D0
C QSMTHR(I) = 0.0D0
C QSMTHI(I) = 0.0D0
C C2(I) = 0.0D0
C QDEV(I) = 0.0D0
C C2ERR(I) = 0.0D0
20 CONTINUE
C
C DO 30 I = 1, LWORK
C DWORK(I) = 0.0
30 CONTINUE
C
C FOURIER TRANSFORM GRAVITY DATA
C CALL C06FJF(NDIM, ND, N, GREAL, GIMAG, DWORK, LWORK, IFAIL)
C
C As fourier transform of topography
C already exists calculate raw admittance
C Note:
C smoothed admittance is stored in QSMTHR, QSMTHI
C At this point array
C QREAL: holds real part of cross spectrum
C QIMAG: holds imaginary part of cross spectrum
C TPOWER: holds power spectrum of topography
C
C DO 50 I = 1, IXTOT
C DO 40 J = 1, IYTOT
C
C IPOS = (J - 1) * IXTOT + I
C QREAL(IPOS) = GREAL(IPOS) * TREAL(IPOS) + GIMAG(IPOS) * TIMAG(
1 IPOS)
C QIMAG(IPOS) = GIMAG(IPOS) * TREAL(IPOS) - GREAL(IPOS) * TIMAG(
1 IPOS)
C TPOWER(IPOS) = TREAL(IPOS) ** 2 + TIMAG(IPOS) ** 2
C GPOWER(IPOS) = GREAL(IPOS) ** 2 + GIMAG(IPOS) ** 2
C
C 40 CONTINUE
C 50 CONTINUE
C
C INITIATE SMOOTHING OF CROSS AND
C TPOWER/GPOWER SPECTRA
C DNX = DBLE(REAL(IXTOT))
C DNY = DBLE(REAL(IYTOT))
C IF (IXTOT .GE. IYTOT) THEN
C DNMAX = DNX
C ELSE
C DNMAX = DNY
C END IF
C
C CALCULATE MIN, MAX WAVENUMBERS
C EXCLUDING K=0
C WAVMIN = 2.0D0 * PIE * (1.0D0/(DNMAX*SAMP))

```

```

WAVMAX = 2.0D0 * PIE * SQRT(2.0D0*((1.0D0/(SAMP*2.0D0))**2))
LOGMIN = LOG10(WAVMIN)
LOGMAX = LOG10(WAVMAX)
C
C* SUM DATA IN LOG SPACED
C* INTERVALS OF WAVENUMBER
DO 80 KX = 1, IXTOT / 2 + 1
  KXN = KX - 1
  DO 60 KY = 1, IYTOT / 2 + 1
    KYN = KY - 1
    CALL SMTHR(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
60  CONTINUE
  DO 70 KY = IYTOT / 2 + 2, IYTOT
    KYN = IYTOT - (KY - 1)
    CALL SMTHR(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
70  CONTINUE
80  CONTINUE
C
DO 110 KX = IXTOT / 2 + 2, IXTOT
  KXN = IXTOT - (KX - 1)
  DO 90 KY = 1, IYTOT / 2 + 1
    KYN = KY - 1
    CALL SMTHR(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
90  CONTINUE
  DO 100 KY = IYTOT / 2 + 2, IYTOT
    KYN = IYTOT - (KY - 1)
    CALL SMTHR(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
100 CONTINUE
110 CONTINUE
C
C* AVERAGE SUMS GENERATED IN SMTHR
DO 120 I = 1, NLVLS
  IF (DKOUNT(I) .GT. 0.5) THEN
    CSMTHR(I) = CSMTHR(I) / DKOUNT(I)
    CSMTHI(I) = CSMTHI(I) / DKOUNT(I)
    TPSMTH(I) = TPSMTH(I) / DKOUNT(I)
    WAVENO(I) = WAVENO(I) / DKOUNT(I)
    GPSMTH(I) = GPSMTH(I) / DKOUNT(I)
  ELSE
    CSMTHR(I) = 0.0
    CSMTHI(I) = 0.0
    TPSMTH(I) = 0.0
    GPSMTH(I) = 0.0
    WAVENO(I) = 0.0
  END IF
120 CONTINUE
C
C* CALCULATE SMOOTHED RESPONSE FUNCTION + COHERENCY
DO 130 I = 1, NLVLS
  IF (DKOUNT(I) .GT. 1.0) THEN
    QSMTHR(I) = CSMTHR(I) / TPSMTH(I)
    QSMTHI(I) = CSMTHI(I) / TPSMTH(I)
    C2(I) = (CSMTHR(I)**2 + CSMTHI(I)**2) / (TPSMTH(I)*GPSMTH(I))
    C2ERR(I) = (1.0D0-C2(I)) * SQRT(2.0D0*C2(I)/DKOUNT(I))
    C2(I) = ((DKOUNT(I)*C2(I)) - 1.0D0) / (DKOUNT(I) - 1.0D0)
  ELSE

```

```

    QSMTHR(I) = 0.0
    QSMTHI(I) = 0.0
    C2(I) = 0.0
    C2ERR(I) = 0.0
  END IF
130 CONTINUE
C
C* CALCULATE ERROR IN RESPONSE FUNCTION
DO 150 I = 1, NLVLS
  IF (DKOUNT(I) .GT. 0.5) THEN
    QVAR = ((GPSMTH(I)/TPSMTH(I)) - (QSMTHR(I)**2 + QSMTHI(I)**2))
    / DKOUNT(I)
    IF (QVAR .LT. 0.0D0) THEN
      WRITE (6,140) I, GPSMTH(I), TPSMTH(I), QSMTHR(I), QSMTHI(I),
        QVAR
140  FORMAT (/, 5X, 'Error - Variable QVAR assigned -ve value', /
1      5X, '*** DATA REVIEW ***', //, 5X,
2      '*** LEVEL = ', I4, 7X, '***', //, 5X,
3      '*** GPSMTH = ', E11.5, '***', //, 5X,
4      '*** TPSMTH = ', E11.5, '***', //, 5X,
5      '*** QSMTHR = ', E11.5, '***', //, 5X,
6      '*** QSMTHI = ', E11.5, '***', //, 5X,
7      '*** QVAR = ', E11.5, '***', //, 5X,
8      '*** Setting QVAR = -QVAR to allow', //, 5X,
9      'continuation of execution ***', //)
    C
    QVAR = -1.0D0 * QVAR
    END IF
  ELSE
    QDEV(I) = SQRT(QVAR)
  ELSE
    QVAR = 0.0D0
    QDEV(I) = 0.0D0
  END IF
150 CONTINUE
C
C* DETERMINE FRACTION OF LINEARLY RELATED POWER
C* REPRESENTED IN RESPONSE FUNCTION
C2GG = 0.0D0
GG = 0.0D0
FG = 0.0D0
NSMPL = 0
C
DO 160 I = 1, NLVLS
  IF (DKOUNT(I) .GT. 0.5) THEN
    NSMPL = NSMPL + 1
    C2GG = C2GG + C2(I) * GPSMTH(I)
    GG = GG + GPSMTH(I)
  END IF
C
160 CONTINUE
C
FG = C2GG / GG
C
WRITE (6,170) FG, NSMPL

```

```

170 FORMAT (/ , 5X, 'Linear Power present = ', E11.5, / , 5X,
1      'Wavenumber annuli sampled = ', I4, /)
C
C*   OUTPUT SMOOTHED RESPONSE FUNCTION
C*   IN AMPLITUDE/PHASE FORM + COHERENCY
      WRITE (8,180)
180  FORMAT (/ , 5X, 'Response Function Results', /)
      WRITE (8,190)
190  FORMAT (4X, 'Q Amplitude', 7X, 'Q Phase', 3X, 'Wave Number', 2X,
1      'Input Points', 2X, 'Standard Dev', 2X, 'Coherency', 5X,
2      'Coh. Error', /)
      DO 210 I = 1, NLVLS
          CALL POLAR(QSMTHR(I), QSMTHI(I), QAMP, QPHASE)
          QAMP = -QAMP
          WRITE (8,200) QAMP, QPHASE, WAVENO(I), DKOUNT(I), QDEV(I),
1      C2(I), C2ERR(I)
200  FORMAT (7(3X,E11.5))
210  CONTINUE
C
C*   OUTPUT DATA TO UNIT 9 ALSO
C*   FOR DATA PLOTTING
      WRITE (9,220) NLVLS
220  FORMAT (2X, I4)
      DO 240 I = 1, NLVLS
          CALL POLAR(QSMTHR(I), QSMTHI(I), QAMP, QPHASE)
          QAMP = -QAMP
          WRITE (9,230) QAMP, QPHASE, WAVENO(I), DKOUNT(I), QDEV(I),
1      C2(I), TSPSMTH(I), GPSMTH(I), C2ERR(I)
230  FORMAT (9(2X,E11.5))
240  CONTINUE
C
C*   INVERT FOURIER TRANSFORM
C*   OF GRAVITY
      CALL C06GCF(GIMAG, N, IFAIL)
      CALL C06FJF(NDIM, ND, N, GREAL, GIMAG, DWORK, LWORK, IFAIL)
      CALL C06GCF(GIMAG, N, IFAIL)
C
      RETURN
      END
C**
C**   SUBROUTINE AMPSPM(IXTOT, IYTOT)
C**   ~~~~~
C**   Subroutine AMPSPM is designed to calculate
C**   the radial power spectra of the data
C**   arrays Datar and Datal. A plot of log( Power)
C**   against K or log( K) may then be analysed.
C**
      REAL*8 AMP(150), WAVE(150), DKOUNT(150), AMPNRM(150)
C
      REAL*8 DNX, DNY, SAMP, PIE, WAVMIN, WAVMAX, LOGAMP, LOGWAV, MU
C
      COMMON /SMOOTH/ AMP, WAVE, DKOUNT, AMPNRM
      COMMON /LVL/ NLVL
      COMMON /INTRVL/ SAMP

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```

      COMMON /LIMITS/ WAVMIN, WAVMAX
C
      DATA MU /0.000/
C
      PIE = 4.0D0 * ATAN(1.0D0)
      DNX = DFLOAT(IXTOT)
      DNY = DFLOAT(IYTOT)
C
      WAVMIN = 0.0D0
      WAVMAX = 2.0D0 * PIE * SQRT(2.0D0*((1.0D0/(SAMP*2.0D0))**2))
C
      SUM TERMS IN WAVE NUMBER BANDS
      DO 30 KX = 1, IXTOT / 2 + 1
          KXN = KX - 1
          DO 10 KY = 1, IYTOT / 2 + 1
              KYN = KY - 1
              CALL SPSCUM(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
10      CONTINUE
          DO 20 KY = IYTOT / 2 + 2, IYTOT
              KYN = IYTOT - (KY - 1)
              CALL SPSCUM(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
20      CONTINUE
30      CONTINUE
C
      DO 60 KX = IXTOT / 2 + 2, IXTOT
          KXN = IXTOT - (KX - 1)
          DO 40 KY = 1, IYTOT / 2 + 1
              KYN = KY - 1
              CALL SPSCUM(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
40      CONTINUE
          DO 50 KY = IYTOT / 2 + 2, IYTOT
              KYN = IYTOT - (KY - 1)
              CALL SPSCUM(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
50      CONTINUE
60      CONTINUE
C
C*   AVERAGE POWER SPECTRA
      DO 70 I = 1, NLVL
          IF (DKOUNT(I) .GT. 0.9) THEN
              AMP(I) = AMP(I) / DKOUNT(I)
              WAVE(I) = WAVE(I) / DKOUNT(I)
          ELSE
              AMP(I) = 0.0
              WAVE(I) = 0.0
          END IF
70      CONTINUE
C
C*   OUTPUT RESULTS
      WRITE (8,80)
80  FORMAT (/ , 5X, 'Averaged Power Spectra of Compensation', /)
C
      WRITE (8,90)
90  FORMAT (5X, 'Wave Number m-1 Log10 Wavenumber Power Spectra ',
1      5X, 'Log10 (Power) Points Sampled', /)
C
      DO 110 I = 1, NLVL

```



```

      IF (DKOUNT(I) .GT. 0.9) THEN
        LOGAMP = LOG10(AMP(I))
        LOGWAV = LOG10(WAVE(I))
      ELSE
        LOGAMP = 0.0
        LOGWAV = 0.0
      END IF

C
      WRITE (8,100) WAVE(I), LOGWAV, AMP(I), LOGAMP, DKOUNT(I)
100  FORMAT (7X, E11.5, 5X, E11.5, 5X, E11.5, 9X, E11.5, 7X, E11.5)
110  CONTINUE
C
C*  NORMALIZE POWER SPECTRA
      WRITE (6,120)
120  FORMAT (/, 5X, 'Enter Power Spectra normalization factor ', /)
      READ (5,*) MU
C
      DO 130 I = 1, NLVL
C
      IF (DKOUNT(I) .GT. 0.9) THEN
        AMPNRM(I) = LOG10(AMP(I)) - (MU*LOG10(WAVE(I)))
      ELSE
        AMPNRM(I) = 0.0
      END IF
C
130  CONTINUE
C
C*  OUTPUT RESULTS
      WRITE (8,140)
140  FORMAT (/, 5X, 'Normalized Power Spectra', /)
C
      WRITE (8,150) MU
150  FORMAT (5X, 'Wavenumber m=1      Normalized Power Spectra:Mu= ',
1      F5.2, //)
C
      DO 170 I = 1, NLVL
        WRITE (8,160) WAVE(I), AMPNRM(I)
160  FORMAT (5X, E11.5, 10X, E11.5)
170  CONTINUE
C
      RETURN
END
C**
C**  SUBROUTINE COH(D, WAVE, F1, F2, P0, PC, PM, ZC, ZM, PDEL1, PDEL2,
1  PDEL3, GRAV, PIE, TERMNR, TERMD, TERMBD)
C**
C**  ~~~~~
C**  Subroutine Coh calculates the component parts
C**  of the coherence for a flexural rigidity D at the
C**  wavenumber WAVE. A three layer model is used with
C**  the two load ratios being given by F1 and F2.
C**
C**  The component parts are the estimates of
C**  the theoretical cross and power spectra.
C**

```

```

      IMPLICIT REAL*8(A - H, O - Z)
C
      REAL*8 MU, MUN, MUD, MU2
C
C*  DEFINE COMPONENT TERMS
      P02 = P0 * P0
      ALPHA = 2.0D0 * PIE * PDEL3 * EXP(-1.0D0*WAVE*ZM)
      ALPHA2 = ALPHA * ALPHA
      BETA = 2.0D0 * PIE * PDEL2 * EXP(-1.0D0*WAVE*ZC)
      BETA2 = BETA * BETA
C
      XI = 1.0D0+(D*(WAVE**4)) / (PDEL1*GRAV)
      PSI = 1.0D0+(D*(WAVE**4)) / ((PM - PDEL2)*GRAV)
      PHI = 1.0D0+(D*(WAVE**4)) / (PC*GRAV)
C
      SIGMAN = F1 * (P0 + (P02/(PDEL1*XI)))
      SIGMAD = (-1.0D0*PDEL2) * (1.0D0+((PM - PDEL2)*PSI/PDEL2))
      SIGMA = SIGMAN / SIGMAD
      SIGMA2 = SIGMA * SIGMA
C
      MUN = F2 * (P0 + (P02/(PDEL1*XI)))
      MUD = (-1.0D0*PDEL3) * (1.0D0+((PC*PHI)/PDEL3))
      MU = MUN / MUD
      MU2 = MU * MU
C
C*  CALCULATE COHERENCE PARTS
C*  CALCULATE NUMERATOR AND DENOMINATOR FIRST
      TERM1N = (-1.0D0*P0*ALPHA) / (PDEL1*XI)
      TERM2N = (-1.0D0*P0*BETA) / (PDEL1*XI)
      TERM3N = SIGMA2 * ALPHA
      TERM4N = (-1.0D0*SIGMA2*(PM - PDEL2)*PSI*BETA) / PDEL2
      TERM5N = (-1.0D0*PC*MU2*PHI*ALPHA) / PDEL3
      TERM6N = MU2 * BETA
C
      TERMNR = (TERM1N + TERM2N + TERM3N + TERM4N + TERM5N + TERM6N)
C
      TERMD = 1.0D0+SIGMA2 + MU2
C
      TERM1D = ((-1.0D0*P0)/(PDEL1*XI)) ** 2
      TERM2D = SIGMA2
      TERM3D = ((-1.0D0*PC*MU*PHI)/PDEL3) ** 2
      TERM4D = ((-1.0D0*P0)/(PDEL1*XI)) ** 2
      TERM5D = ((-1.0D0*SIGMA*(PM - PDEL2)*PSI)/PDEL2) ** 2
      TERM6D = MU2
C
      TERM7D = ((-1.0D0*P0)/(PDEL1*XI)) ** 2
      TERM8D = (-1.0D0*SIGMA2*(PM - PDEL2)*PSI) / PDEL2
      TERM9D = (-1.0D0*PC*PHI*MU2) / PDEL3
C
      TERMBD = (TERM1D + TERM2D + TERM3D) * ALPHA2 + 2.0D0 * ALPHA *
1BETA * (TERM7D + TERM8D + TERM9D) + (TERM4D + TERM5D + TERM6D) *
2BETA2
C
      RETURN
END
C**

```

```

C** SUBROUTINE COHER3(D, WAVE, F1, F2, C2, P0, PC, PM, ZC, ZM, PDEL1,
1 PDEL2, PDEL3, GRAV, PIE)
C**
C** Subroutine Coher3 calculates the coherence at
C** wavenumber WAVE given the flexural rigidity D
C** and the ratios of subsurface to surface loading
C** F1 and F2.
C**
C** IMPLICIT REAL*8(A - H,O - Z)
C
C REAL*8 MU, MUN, MUD, MU2
C
C* DEFINE COMPONENT TERMS
P02 = P0 * P0
ALPHA = 2.0D0 * PIE * PDEL3 * EXP(-1.0D0*WAVE*ZM)
ALPHA2 = ALPHA * ALPHA
BETA = 2.0D0 * PIE * PDEL2 * EXP(-1.0D0*WAVE*ZC)
BETA2 = BETA * BETA
C
X1 = 1.0D0+(D*(WAVE**4)) / (PDEL1*GRAV)
PSI = 1.0D0+(D*(WAVE**4)) / ((PM - PDEL2)*GRAV)
PHI = 1.0D0+(D*(WAVE**4)) / (PC*GRAV)
C
SIGMAN = F1 * (P0 + (P02/(PDEL1*X1)))
SIGMAD = (-1.0D0*PDEL2) * (1.0D0+((PM - PDEL2)*PSI/PDEL2))
SIGMA = SIGMAN / SIGMAD
SIGMA2 = SIGMA * SIGMA
C
MUN = F2 * (P0 + (P02/(PDEL1*X1)))
MUD = (-1.0D0*PDEL3) * (1.0D0+((PC*PHI)/PDEL3))
MU = MUN / MUD
MU2 = MU * MU
C
C* CALCULATE COHERENCE
C* CALCULATE NUMERATOR AND DENOMINATOR FIRST
TERM1N = (-1.0D0*P0*ALPHA) / (PDEL1*X1)
TERM2N = (-1.0D0*P0*BETA) / (PDEL1*X1)
TERM3N = SIGMA2 * ALPHA
TERM4N = (-1.0D0*SIGMA2*(PM - PDEL2)*PSI*BETA) / PDEL2
TERM5N = (-1.0D0*PC*MU2*PHI*ALPHA) / PDEL3
TERM6N = MU2 * BETA
C
TERMN = (TERM1N + TERM2N + TERM3N + TERM4N + TERM5N + TERM6N) ** 2
C
TERMD = 1.0D0+SIGMA2 + MU2
C
TERM1D = ((-1.0D0*P0)/(PDEL1*X1)) ** 2
TERM2D = SIGMA2
TERM3D = ((-1.0D0*PC*MU*PHI)/PDEL3) ** 2
TERM4D = ((-1.0D0*P0)/(PDEL1*X1)) ** 2
TERM5D = ((-1.0D0*SIGMA*(PM - PDEL2)*PSI)/PDEL2) ** 2
TERM6D = MU2

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C
TERM7D = ((-1.0D0*P0)/(PDEL1*X1)) ** 2
TERM8D = (-1.0D0*SIGMA2*(PM - PDEL2)*PSI) / PDEL2
TERM9D = (-1.0D0*PC*PHI*MU2) / PDEL3
C
TERMBD = (TERM1D + TERM2D + TERM3D) * ALPHA2 + 2.0D0 * ALPHA *
1BETA * (TERM7D + TERM8D + TERM9D) + (TERM4D + TERM5D + TERM6D) *
2BETA2
C
TERMD = TERMD + TERMBD
C
C2 = TERMN / TERMD
C
RETURN
END
C**
C** SUBROUTINE DETRND(AREAL, NX, NY, SAMP)
C**
C** Subroutine DETRND removes the mean and trends
C** from a two dimensional array by fitting and
C** then subtracting a best fit (least squares) plane
C** to the data.
C**
C** IMPLICIT REAL*8(A - H,O - Z)
C
C DIMENSION AREAL(NX,NY), A(3,3), B(3), C(3), AA(3,3), WKS1(3),
1 WKS2(3)
C
C* DEFINE MATRIX *NAG CONSTANTS
DATA N, IA, IAA, IFAIL /3, 3, 3, 0/
C
C* SET UNDEFINED ARRAY TO ZERO
DO 20 I = 1, N
C
B(I) = 0.0D0
C(I) = 0.0D0
WKS1(I) = 0.0D0
WKS2(I) = 0.0D0
C
DO 10 J = 1, N
C
A(I,J) = 0.0D0
AA(I,J) = 0.0D0
C
10 CONTINUE
20 CONTINUE
C
C* INITIALIZE SUMMATION COEFFICIENTS
X1SUM = 0.0D0
X2SUM = 0.0D0
YSUM = 0.0D0
X12SUM = 0.0D0
X1X2SM = 0.0D0
X1YSUM = 0.0D0

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```

X22SUM = 0.000
X2YSUM = 0.000
Y2SUM = 0.000
C
C* DETERMINE SUMMATION COEFFICIENTS
DO 40 I = 1, NX
  DO 30 J = 1, NY
    C
    X1 = DFLOAT(I - 1) * SAMP
    X2 = DFLOAT(J - 1) * SAMP
    Y = AREAL(I,J)
    C
    X1SUM = X1SUM + X1
    X2SUM = X2SUM + X2
    YSUM = YSUM + Y
    X12SUM = X12SUM + X1 * X1
    X1X2SM = X1X2SM + X1 * X2
    X1YSUM = X1YSUM + X1 * Y
    X22SUM = X22SUM + X2 * X2
    X2YSUM = X2YSUM + X2 * Y
    Y2SUM = Y2SUM + Y * Y
    C
  30 CONTINUE
40 CONTINUE
C
C* DEFINE NORMAL EQUATION MATRIX AND COLUMN VECTOR
A(1,1) = DFLOAT(NX*NY)
A(1,2) = X1SUM
A(1,3) = X2SUM
A(2,1) = X1SUM
A(2,2) = X12SUM
A(2,3) = X1X2SM
A(3,1) = X2SUM
A(3,2) = X1X2SM
A(3,3) = X22SUM
C
B(1) = YSUM
B(2) = X1YSUM
B(3) = X2YSUM
C
C* SOLVE NORMAL EQUATIONS
CALL F04ATF(A, IA, B, N, C, AA, IAA, WKS1, WKS2, IFAIL)
C
C* DETERMINE STANDARD VARIANCES
SST = Y2SUM - ((YSUM**2)/DFLOAT(NX*NY))
C
YESUM = 0.000
YE2SUM = 0.000
C
C* CALCULATE VARIATION OF ESTIMATED Y
AND DETREND DATA
DO 60 I = 1, NX
  DO 50 J = 1, NY
    C
    X1 = DFLOAT(I - 1) * SAMP
    X2 = DFLOAT(J - 1) * SAMP

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C
YE = C(1) + C(2) * X1 + C(3) * X2
YESUM = YESUM + YE
YE2SUM = YE2SUM + YE * YE
C
AREAL(I,J) = AREAL(I,J) - YE
C
50 CONTINUE
60 CONTINUE
C
SSR = YE2SUM - ((YESUM**2)/DFLOAT(NX*NY))
C
SSD = SST - SSR
PFIT = (SSR/SST) * 100.000
C
C* OUTPUT SOLUTION VECTOR
WRITE (6,70) (C(I),I=1,N)
70 FORMAT (/, 5X, 'Best Fit Plane Solution', /, 5X, 'C(1) = ', E12.6,
1 'Y = C(1) + C(2)*X1 + C(3)*X2 ', //, 5X, 'C(2) = ', E12.6, /, 5X, 'C(3) = ', E12.6, //)
2 /, 5X, 'C(2) = ', E12.6, /, 5X, 'C(3) = ', E12.6, //)
C
WRITE (6,80) SST, SSR, SSD, PFIT
80 FORMAT (/, 5X, 'Variation of Sum of Squares', //, 5X,
1 'True Y = ', E12.6, /, 5X, 'Est. Y = ', E12.6, /, 5X,
2 'Standard Deviation from Trend = ', E12.6, /, 5X,
3 'Percentage Fit of Plane = ', F10.2, //)
C
RETURN
END
C**
C** SUBROUTINE GRVPRD(NX, NY, IXTOT, IYTOT, NDIM, ND, N, DWORK, LWORK,
1 IFAIL)
C**
C** ~~~~~
C** Subroutine GRVPRD (gravity predict) predicts
C** the gravity linearly related to the surface topography
C** by convolving the smoothed admittance determined in
C** subroutine ADMIT with the topography.
C**
C**
REAL*8 TREAL(70400), TIMAG(70400), GREAL(70400), GIMAG(70400),
1 QREAL(70400), QIMAG(70400), GRVPRD(70400), GRVPIM(70400),
2 DWORK(LWORK)
REAL*8 RESSQD
C
INTEGER*4 ND(2)
C
COMMON /TC,PO/ TREAL, TIMAG
COMMON /GRVTY/ GREAL, GIMAG
COMMON /GRVPD/ GRVPRD, GRVPIM
COMMON /RESP/ QREAL, QIMAG
COMMON /AREA/ XMIN, XMAX, YMIN, YMAX
C
C* DETERMINE GRAVITY AT EACH WAVENUMBER
DO 20 I = 1, IXTOT

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      DO 10 J = 1, IYTOT
C
      IPOS = (J - 1) * IXTOT + 1
      GRVPRL(IPOS) = GREAL(IPOS) * TREAL(IPOS) - QIMAG(IPOS) *
1      TIMAG(IPOS)
      GRVPIM(IPOS) = GREAL(IPOS) * TIMAG(IPOS) + QIMAG(IPOS) *
1      TREAL(IPOS)
C
10  CONTINUE
20  CONTINUE
C
C*  INVERT TRANSFORM TO OBTAIN REAL GRAVITY PREDICTION
      CALL C06GCF(GRVPIM, N, IFAIL)
      CALL C06FJF(NDIM, ND, N, GRVPRL, GRVPIM, DWORK, LWORK, IFAIL)
      CALL C06GCF(GRVPIM, N, IFAIL)
C
C*  CALCULATE SUM OF SQUARED RESIDUALS BETWEEN TRUE
C*  AND PREDICTED GRAVITY VALUES + ISOSTATIC ANOMALY
      RESSQD = 0.0D0
      IXSTRT = NX / 2 + 1
      IYSTRT = NY / 2 + 1
C
      DO 40 I = 1, NX
      DO 30 J = 1, NY
        IPOS = IXSTRT + (I - 1) + IXTOT * ((IYSTRT + J) - 2)
        GREAL(IPOS) = GREAL(IPOS) - GRVPRL(IPOS)
        RESSQD = RESSQD + GREAL(IPOS) ** 2
30  CONTINUE
40  CONTINUE
C
      WRITE (6,50) RESSQD
50  FORMAT (/, 5X, 'Sum of Squared Residuals between', /, 5X,
1      'True and Predicted Gravity over', /, 5X,
2      'Original Input Array = ', E10.4, ' MGAL', //)
C
      RETURN
      END
C*
C*  SUBROUTINE INPUT(NX, NY, NPTS, AVTOP, AVBOUG)
C*  ~~~~~
C*  Main programme: Isos.resp
C*
C*  Subroutine INPUT reads in the gravity and topography
C*  arrays that form the raw data for the response
C*  function calculations.
C*
      REAL*8 TREAL(70400), TIMAG(70400), GREAL(70400), GIMAG(70400)
      REAL*8 SAMP, PWATER, PCRUSTR
C
      REAL*4 NGRID
C
      CHARACTER INFILE*7, FILE*7
C
      COMMON /TOPO/ TREAL, TIMAG

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      COMMON /GRVTY/ GREAL, GIMAG
      COMMON /INTRVL/ SAMP
      COMMON /AREA/ XMIN, XMAX, YMIN, YMAX
C
      DATA TSUM, BSUM /0.0, 0.0/
      DATA PWATER, PCRUSTR /1030.0D0, 2700.0D0/
C
C*  OPEN DATA FILE
      READ (5,10) INFILE
10  FORMAT (A7)
      OPEN (UNIT=3, STATUS='OLD', FILE=INFILE, ACCESS='SEQUENTIAL', FORM=
1      'UNFORMATTED')
C
C*  READ AND DISPLAY HEADER DATA
      READ (UNIT=3) FILE, XMIN, XMAX, YMIN, YMAX, RSAMP, NX, NY
      WRITE (6,20) FILE, XMIN, XMAX, YMIN, YMAX, RSAMP, NX, NY
20  FORMAT (/, 5X, 'INPUT FILE:', A7, /, 5X, 'MINIMUM X VALUE'
1      ' ', F10.1, ' METRES', /, 5X, 'MAXIMUM X VALUE' =
2      ' ', F10.1, ' METRES', /, 5X, 'MINIMUM Y VALUE' = ' ', F10.1,
3      ' METRES', /, 5X, 'MAXIMUM Y VALUE' = ' ', F10.1,
4      ' METRES', /, 5X, 'SAMPLING INTERVAL' = ' ', F10.1,
5      ' METRES', /, 5X, 'INPUT GRID DIMENSIONS', /, 5X, 'NX = ',
6      I4, 2X, 'NY = ', I4, //)
C
C*  EVALUATE NEW VARIABLES
      SAMP = DBLE(RSAMP)
      NPTS = NX * NY
C
C*  INPUT GRID DATA
      DO 50 I = 1, NX
      DO 40 J = 1, NY
C
        IPOS = (J - 1) * NX + 1
        READ (UNIT=3) X, Y, FGRID, TGRID, BGRID, NGRID, IFLAG,
1      ITFLAG, IBFLAG
        IF (TGRID .GE. 0.0) THEN
          TREAL(IPOS) = DBLE(TGRID)
        ELSE IF (TGRID .LT. 0.0) THEN
          TREAL(IPOS) = DBLE(TGRID) * ((PCRUSTR - PWATER)/PCRUSTR)
        ELSE
          WRITE (6,30)
          FORMAT (/, 5X, 'Error on Topography Input', /)
30  STOP
        END IF
        GREAL(IPOS) = DBLE(BGRID)
        TSUM = TSUM + TGRID
        BSUM = BSUM + BGRID
C
40  CONTINUE
50  CONTINUE
C
      CLOSE (UNIT=3, STATUS='KEEP')
C
C*  DETERMINE AVERAGE DATA VALUES
      AVTOP = TSUM / REAL(NX*NY)
      AVBOUG = BSUM / REAL(NX*NY)

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C      WRITE (6,60) AVTOP, AVBOUG
60  FORMAT (/, 5X, 'AVERAGE TOPOGRAPHY = ', F8.2, ' METRES', /, 5X,
1    'AVERAGE BOUGUER GRAVITY = ', F7.2, ' MGAL', //)
C
C      RETURN
C      END
C**
C**      SUBROUTINE INPUT(NX, NY, NPTS, AVDAT)
C**      ~~~~~
C**      Main programme: Radial.spec
C**
C**      Subroutine INPUT reads in the raw data grid
C**      to be analysed.
C**
C      REAL*8 DATAR(40000), DATAI(40000)
C
C      REAL*8 SAMP
C
C      REAL*4 NGRID
C
C      CHARACTER INFILE*7, FILE*7
C
C      COMMON /GRID/ DATAR, DATAI
C      COMMON /INTRVL/ SAMP
C      COMMON /AREA/ XMIN, XMAX, YMIN, YMAX
C
C      DATA DSUM /0.0/
C
C      OPEN DATA FILE
C      WRITE (6,10)
10  FORMAT (/, 5X, 'Enter name of gridded input file', /)
C
C      READ (5,20) INFILE
20  FORMAT (A7)
C      OPEN (UNIT=3, STATUS='OLD', FILE=INFILE, ACCESS='SEQUENTIAL', FORM=
1    'UNFORMATTED')
C
C      READ AND DISPLAY HEADER DATA
C      READ (UNIT=3) FILE, XMIN, XMAX, YMIN, YMAX, RSAMP, NX, NY
C      WRITE (6,30) FILE, XMIN, XMAX, YMIN, YMAX, RSAMP, NX, NY
30  FORMAT (/, 5X, 'INPUT FILE: ', A7, //, 5X, 'MINIMUM X VALUE
1    = ', F10.1, ' METRES', /, 5X, 'MAXIMUM X VALUE
2    = ', F10.1, ' METRES', /, 5X, 'MINIMUM Y VALUE
3    = ', F10.1, ' METRES', /, 5X, 'MAXIMUM Y VALUE
4    = ', F10.1, ' METRES', /, 5X, 'SAMPLING INTERVAL
5    = ', F10.1, ' METRES', /, 5X, 'INPUT GRID DIMENSIONS', /, 5X, 'NX = ',
6    14, 2X, 'NY = ', 14, //)
C
C      EVALUATE NEW VARIABLES
C      SAMP = DBLE(RSAMP)
C      NPTS = NX * NY
C
C      INPUT GRID DATA

```

```

40  WRITE (6,50)
50  FORMAT (/, 5X, 'Enter desired data field 1, 2 or 3', /)
C      READ (5,*) ITYPE
C
C      DO 80 I = 1, NX
C      DO 70 J = 1, NY
C
C      IPOS = (J - 1) * NX + I
C      READ (UNIT=3) X, Y, FGRID, TGRID, BGRID, NGRID, IFLAG,
1    ITFLAG, IBFLAG
C      IF (ITYPE .EQ. 1) THEN
C      DATAR(IPOS) = DBLE(FGRID)
C      DSUM = DSUM + FGRID
C      ELSE IF (ITYPE .EQ. 2) THEN
C      DATAR(IPOS) = DBLE(TGRID)
C      DSUM = DSUM + TGRID
C      ELSE IF (ITYPE .EQ. 3) THEN
C      DATAR(IPOS) = DBLE(BGRID)
C      DSUM = DSUM + BGRID
C      ELSE
C      WRITE (6,60)
60  FORMAT (/, 5X, 'Error Itype incorrectly specified', /)
C      GO TO 40
C      END IF
C
C      70  CONTINUE
C      80  CONTINUE
C
C      CLOSE (UNIT=3, STATUS='KEEP')
C
C      DETERMINE AVERAGE DATA VALUE
C      AVDAT = DSUM / REAL(NX*NY)
C
C      WRITE (6,90) AVDAT
90  FORMAT (/, 5X, 'Average Data Value = ', F8.2, /)
C
C      RETURN
C      END
C**
C**      SUBROUTINE MOHOT(P0, PM, D, WAVE, GRAV, WT)
C**      ~~~~~
C**      Subroutine Mohot comprises the first part of
C**      the determination of HT. The deflection of the
C**      Moho due to an initial surface load of amplitude
C**      1.0 is determined.
C**
C      IMPLICIT REAL*8(A - H, O - Z)
C
C      FLEX1 = 1.0D0 + (D * (WAVE**4)) / (PM * GRAV)
C      WT = (-1.0D0 * P0) / (PM * FLEX1)
C
C      RETURN
C      END

```

```

C**
C**
SUBROUTINE OUTPUT(NX, NY, IXTOT, IYTOT)
~~~~~
C**
C**      Subroutine OUTPUT writes out the isostatic
C**      anomaly, topography and the gravitational
C**      effect of the isostatic compensation in a form
C**      compatible with the input to Image.proj.
C**
C**      REAL*8 TREAL(70400), TIMAG(70400), GREAL(70400), GIMAG(70400),
1      GRVPRL(70400), GRVPIM(70400)
C
C      REAL*8 SAMP
C      REAL*4 NGRID
C
C      CHARACTER OTFILE*7
C
C      COMMON /TOPO/ TREAL, TIMAG
C      COMMON /GRVTY/ GREAL, GIMAG
C      COMMON /GRVPD/ GRVPRL, GRVPIM
C      COMMON /INTRVL/ SAMP
C      COMMON /AREA/ XMIN, XMAX, YMIN, YMAX
C
C      DATA NGRID, IFFLAG, ITFLAG, IBFLAG /1.0, 1, 1, 1/
C
C      RSAMP = SNGL(SAMP)
C
C*      ENTER OUTPUT FILE NAME AND OPEN FILE
C      READ (5,10) OTFILE
10  FORMAT (A7)
C
C      OPEN (UNIT=3,STATUS='NEW',FILE=OTFILE,ACCESS='SEQUENTIAL',FORM=
1      'UNFORMATTED')
C
C      WRITE (UNIT=3) OTFILE, XMIN, XMAX, YMIN, YMAX, RSAMP, NX, NY
C
C*      OUTPUT DATA
C      IXSTRT = NX / 2 + 1
C      IYSTRT = NY / 2 + 1
C
C      DO 30 I = 1, NX
C        DO 20 J = 1, NY
C
C          X = (REAL(I) - 0.5) * RSAMP + XMIN
C          Y = (REAL(J) - 0.5) * RSAMP + YMIN
C
C          IPOS = IXSTRT + (I - 1) + IXTOT * ((IYSTRT + J) - 2)
C
C*      CONVERT DATA TO REAL*4
C      CGRID = SNGL(GRVPRL(IPOS))
C      TGRID = SNGL(TREAL(IPOS))
C      AGRID = SNGL(GREAL(IPOS))
C      WRITE (UNIT=3) X, Y, CGRID, TGRID, AGRID, NGRID, IFFLAG,
1      ITFLAG, IBFLAG

```

```

C
20  CONTINUE
30  CONTINUE
C
C      CLOSE (UNIT=3,STATUS='KEEP')
C
C      RETURN
C      END
C**
C**
SUBROUTINE PAD(AREAL, AIMAG, NX, NY, IXTOT, IYTOT)
~~~~~
C**
C**      Subroutine PAD takes the real NX by NY array AREAL
C**      and pads it out with zeroes to a size of 2*NX by
C**      2*NY. As the imaginary array contains only
C**      zeroes it does not have to be padded and may
C**      be used for workspace providing it is reset
C**      to zero at the end of the subroutine.
C**
C**      REAL*8 AREAL(1), AIMAG(1)
C
C*      DETERMINE BLH CORNER OF DATA ARRAY
C      IN NEW ARRAY
C      IXSTRT = NX / 2 + 1
C      IYSTRT = NY / 2 + 1
C
C      IXTOT = NX * 2
C      IYTOT = NY * 2
C
C      DO 20 I = 1, NX
C        DO 10 J = 1, NY
C
C          IPOS = (J - 1) * NX + I
C          IPOSNW = IXSTRT + (I - 1) + IXTOT * ((IYSTRT + J) - 2)
C          AIMAG(IPOSNW) = AREAL(IPOS)
C
C      10  CONTINUE
C      20  CONTINUE
C
C*      REDEFINE ARRAYS
C      DO 40 I = 1, IXTOT
C        DO 30 J = 1, IYTOT
C
C          IPOS = (J - 1) * IXTOT + I
C          AREAL(IPOS) = AIMAG(IPOS)
C          AIMAG(IPOS) = 0.000
C
C      30  CONTINUE
C      40  CONTINUE
C
C      RETURN
C      END
C**
C**

```

```

SUBROUTINE PLOT
~~~~~
C**
C**
C** Subroutine Plot provides a simple plot of
C** the radial power spectra.
C**
C**
C CHARACTER TITLE*40
C
C REAL*8 AMP(150), WAVE(150), DKOUNT(150), AMPNRM(150)
C
C REAL*8 XMIN8, XMAX8, YMIN8, YMAX8, XB, YB
C
C COMMON /SMOOTH/ AMP, WAVE, DKOUNT, AMPNRM
C COMMON /LVL/ NLVL
C
C DATA XMIN8, XMAX8, YMIN8, YMAX8 /1.0D+10, -1.0D+10, 1.0D+10,
1 -1.0D+10/
C
C* INITIALIZE GHOST80
CALL PAPER(1)
CALL PSPACE(0.2, 0.8, 0.2, 0.8)
C
C 10 WRITE (6,20)
20 FORMAT (/, 5X, 'Enter desired form of X axis', /, 5X,
1 'Linear (0) Logarithmic (1)', /)
C READ (5,*) IAXIS
IF (IAXIS.NE. 0 .AND. IAXIS.NE. 1) GO TO 10
C
C* DETERMINE RANGE OF DATA
DO 30 I = 1, NLVL
C
C IF (DKOUNT(I) .GT. 0.9) THEN
C IF (IAXIS.EQ. 0) THEN
C IF (WAVE(I) .LT. XMIN8) XMIN8 = WAVE(I)
C IF (WAVE(I) .GT. XMAX8) XMAX8 = WAVE(I)
C ELSE
C XB = LOG10(WAVE(I))
C IF (XB .LT. XMIN8) XMIN8 = XB
C IF (XB .GT. XMAX8) XMAX8 = XB
C END IF
C
C YB = LOG10(AMP(I))
C IF (YB .LT. YMIN8) YMIN8 = YB
C IF (YB .GT. YMAX8) YMAX8 = YB
C END IF
C
C 30 CONTINUE
C
C XMIN4 = SNGL(XMIN8)
C XMAX4 = SNGL(XMAX8)
C YMIN4 = SNGL(YMIN8)
C YMAX4 = SNGL(YMAX8)
C
C CALL MAP(XMIN4, XMAX4, YMIN4, YMAX4)
CALL SCALES

```

```

CALL POSITN(XMIN4, YMAX4)
CALL JOIN(XMAX4, YMAX4)
CALL JOIN(XMAX4, YMIN4)
C
C* PLOT DATA
DO 40 I = 1, NLVL
C
C IF (DKOUNT(I) .GT. 0.9) THEN
C
C IF (IAXIS.EQ. 0) THEN
C X = SNGL(WAVE(I))
C ELSE
C XB = LOG10(WAVE(I))
C X = SNGL(XB)
C END IF
C
C YB = LOG10(AMP(I))
C Y = SNGL(YB)
C
C CALL PLOTNC(X, Y, 232)
C
C END IF
C
C 40 CONTINUE
C
C* ANNOTATE PLOT
CALL PSPACE(0.0, 1.0, 0.0, 1.0)
CALL MAP(0.0, 1.0, 0.0, 1.0)
C
C WRITE (6,50)
50 FORMAT (/, 5X, 'Enter First Plot Title', /)
C READ (5,60) TITLE
60 FORMAT (A40)
C
C CALL CTRMAG(13)
CALL PLOTCS(0.3, 0.85, TITLE)
C
C CALL CTRMAG(11)
CALL ITALIC(1)
C
C IF (IAXIS.EQ. 0) THEN
C CALL PLOTCS(0.35, 0.08, 'Wavenumber m-1')
C ELSE
C CALL PLOTCS(0.325, 0.08, 'Log10 wavenumber')
C END IF
C
C CALL CTRORI(90.0)
CALL PLOTCS(0.105, 0.3, 'Log10 ( power spectrum )')
CALL CTRORI(0.0)
C
C CALL ITALIC(0)
C
C* PLOT NORMALIZED POWER SPECTRA
CALL FRAME
CALL PSPACE(0.2, 0.8, 0.2, 0.8)
C

```

```

      YMIN8 = 1.0D+10
      YMAX8 = -1.0D+10
C
      DO 70 I = 1, NLVL
C
        IF (DKOUNT(I) .GT. 0.9) THEN
          IF (AMPNRM(I) .LT. YMIN8) YMIN8 = AMPNRM(I)
          IF (AMPNRM(I) .GT. YMAX8) YMAX8 = AMPNRM(I)
        END IF
C
      70 CONTINUE
C
      YMIN4 = SNGL(YMIN8)
      YMAX4 = SNGL(YMAX8)
C
      CALL MAP(XMIN4, XMAX4, YMIN4, YMAX4)
      CALL SCALES
      CALL POSITN(XMIN4, YMAX4)
      CALL JOIN(XMAX4, YMAX4)
      CALL JOIN(XMAX4, YMIN4)
C
      C. PLOT DATA POINTS
      DO 80 I = 1, NLVL
C
        IF (DKOUNT(I) .GT. 0.9) THEN
          IF (IAXIS .EQ. 0) THEN
            X = SNGL(WAVE(I))
          ELSE
            XB = LOG10(WAVE(I))
            X = SNGL(XB)
          END IF
C
          Y = SNGL(AMPNRM(I))
          CALL PLOTNC(X, Y, 232)
        END IF
C
      80 CONTINUE
C
      ANNOTATE PLOT
      CALL PSPACE(0.0, 1.0, 0.0, 1.0)
      CALL MAP(0.0, 1.0, 0.0, 1.0)
C
      CALL CTRMAG(13)
      CALL PLOTCS(0.3, 0.85, 'Normalized power spectrum')
      CALL CTRMAG(11)
      CALL ITALIC(1)
      IF (IAXIS .EQ. 0) THEN
        CALL PLOTCS(0.35, 0.08, 'Wavenumber m-1')
      ELSE
        CALL PLOTCS(0.325, 0.08, 'Log10 wavenumber')
      END IF
C
      CALL CTRORI(90.0)
      CALL PLOTCS(0.08, 0.3, 'Normalized Log10 (power spectrum)')
      CALL CTRORI(0.0)
      CALL ITALIC(0)

```

```

C
      CALL GREND
      RETURN
      END
C**
C**
      SUBROUTINE POLAR(X, Y, AMP, PHASE)
      ~~~~~
C**
C** Subroutine Polar converts complex
C** numbers into amplitude and phase.
C**
      REAL*8 X, Y, AMP, PHASE
C
      AMP = 0.0D0
      PHASE = 0.0D0
C
      PIE = 4.0D0 * DATAN(1.0D0)
      AMP = SQRT(X**2 + Y**2)
      IF (ABS(X) .GT. 1.0D-10) THEN
        PHASE = DATAN((-1.0D0)*Y/X) * 180.0D0 / PIE
      ELSE
        IF (ABS(Y) .GT. 1.0E-08) THEN
          PHASE = 89.0
        ELSE
          PHASE = 99999.9
        END IF
      END IF
C
      RETURN
      END
C**
C**
      SUBROUTINE QCAL(D, WAVE, F1, F2, Q, TERMD, P0, PC, PM, ZC, ZM,
      1 PDEL1, PDEL2, PDEL3, GRAV, G, PIE)
      ~~~~~
C**
C** Subroutine Qcal calculates the value of the response
C** function Q at wavenumber WAVE for any given subsurface/
C** surface load ratios F1, F2.
C**
C** Qcal also returns the denominator in the expression
C** for Q which is used in the calculation of the
C** topography power spectrum.
C**
      IMPLICIT REAL*8(A - H, O - Z)
C
      REAL*8 MU, MUN, MUD, MU2
C
      C. DEFINE COMPONENT TERMS
      P02 = P0 * P0
      ALPHA = 2.0D0 * PIE * G * PDEL3 * EXP(-1.0D0*WAVE*ZM) * 1.0D+05
      BETA = 2.0D0 * PIE * G * PDEL2 * EXP(-1.0D0*WAVE*ZC) * 1.0D+05
C
      XI = 1.0D0+(D*(WAVE**4)) / (PDEL1*GRAV)

```



```

      PSI = 1.0D0+(D*(WAVE**4)) / ((PM - PDEL2)*GRAV)
      PHI = 1.0D0+(D*(WAVE**4)) / (PC*GRAV)
C
      SIGMAN = F1 * (P0 + (P02/(PDEL1*X1)))
      SIGMAD = (-1.0D0*PDEL2) * (1.0D0+((PM - PDEL2)*PSI/PDEL2))
      SIGMA = SIGMAN / SIGMAD
      SIGMA2 = SIGMA * SIGMA
C
      MUN = F2 * (P0 + (P02/(PDEL1*X1)))
      MUD = (-1.0D0*PDEL3) * (1.0D0+((PC*PHI)/PDEL3))
      MU = MUN / MUD
      MU2 = MU * MU
C
C* CALCULATE Q
C* CALCULATE NUMERATOR AND DENOMINATOR FIRST
      TERM1N = (-1.0D0*P0*ALPHA) / (PDEL1*X1)
      TERM2N = (-1.0D0*P0*BETA) / (PDEL1*X1)
      TERM3N = SIGMA2 * ALPHA
      TERM4N = (-1.0D0*SIGMA2*(PM - PDEL2)*PSI*BETA) / PDEL2
      TERM5N = (-1.0D0*PC*MU2*PHI*ALPHA) / PDEL3
      TERM6N = MU2 * BETA
C
      TERMN = TERM1N + TERM2N + TERM3N + TERM4N + TERM5N + TERM6N
C
      TERMD = 1.0D0+SIGMA2 + MU2
C
      Q = TERMN / TERMD
C
      RETURN
      END
C**
C** SUBROUTINE QCAL3(D, WAVE, F1, F2, Q, P0, PC, PM, ZC, ZM, PDEL1,
1 PDEL2, PDEL3, GRAV, G, PIE)
C**
C** ~~~~~
C** Subroutine Qcal3 calculates the value of the response
C** function Q at wavenumber WAVE for any given subsurface/
C** surface load ratios F1, F2.
C**
C** IMPLICIT REAL*8(A - H,O - Z)
C
C REAL*8 MU, MUN, MUD, MU2
C
C* DEFINE COMPONENT TERMS
      P02 = P0 * P0
      ALPHA = 2.0D0 * PIE * G * PDEL3 * EXP(-1.0D0*WAVE*ZM) * 1.0D+05
      BETA = 2.0D0 * PIE * G * PDEL2 * EXP(-1.0D0*WAVE*ZC) * 1.0D+05
C
      X1 = 1.0D0+(D*(WAVE**4)) / (PDEL1*GRAV)
      PSI = 1.0D0+(D*(WAVE**4)) / ((PM - PDEL2)*GRAV)
      PHI = 1.0D0+(D*(WAVE**4)) / (PC*GRAV)
C
      SIGMAN = F1 * (P0 + (P02/(PDEL1*X1)))
      SIGMAD = (-1.0D0*PDEL2) * (1.0D0+((PM - PDEL2)*PSI/PDEL2))

```

```

      SIGMA = SIGMAN / SIGMAD
      SIGMA2 = SIGMA * SIGMA
C
      MUN = F2 * (P0 + (P02/(PDEL1*X1)))
      MUD = (-1.0D0*PDEL3) * (1.0D0+((PC*PHI)/PDEL3))
      MU = MUN / MUD
      MU2 = MU * MU
C
C* CALCULATE Q
C* CALCULATE NUMERATOR AND DENOMINATOR FIRST
      TERM1N = (-1.0D0*P0*ALPHA) / (PDEL1*X1)
      TERM2N = (-1.0D0*P0*BETA) / (PDEL1*X1)
      TERM3N = SIGMA2 * ALPHA
      TERM4N = (-1.0D0*SIGMA2*(PM - PDEL2)*PSI*BETA) / PDEL2
      TERM5N = (-1.0D0*PC*MU2*PHI*ALPHA) / PDEL3
      TERM6N = MU2 * BETA
C
      TERMN = TERM1N + TERM2N + TERM3N + TERM4N + TERM5N + TERM6N
C
      TERMD = 1.0D0+SIGMA2 + MU2
C
      Q = TERMN / TERMD
C
      RETURN
      END
C**
C** SUBROUTINE QPRD(IXTOT, IYTOT)
C**
C** ~~~~~
C** Subroutine QPRD inserts the smoothed response function
C** calculated in subroutine ADMIT into the arrays QREAL
C** and QIMAG. This is achieved by determining the wavenumber
C** associated with each array element in QREAL and QIMAG. The
C** array elements are then set to the value of the smoothed
C** response for the sampling level associated with the
C** array element wavenumber.
C**
      REAL*8 QREAL(70400), QIMAG(70400), TPOWER(70400), GPOWER(70400)
      REAL*8 DNX, DNY, PIE
C
      COMMON /RESP/ QREAL, QIMAG
      COMMON /PWRSPC/ TPOWER, GPOWER
C
      PIE = 4.0D0 * DATAN(1.0D0)
      DNX = DBLE(REAL(IXTOT))
      DNY = DBLE(REAL(IYTOT))
C
C* SET ARRAY ELEMENT QREAL(1),
C* QIMAG(1) TO NORMALIZED VALUE
      QREAL(1) = QREAL(1) / TPOWER(1)
      QIMAG(1) = QIMAG(1) / TPOWER(1)
C
C* RESET Q
      WRITE (6,10)

```

```

10 FORMAT (/, 5X, 'Resetting Q to smoothed values', /)
C
DO 40 KX = 1, IXTOT / 2 + 1
  KXN = KX - 1
  DO 20 KY = 1, IYTOT / 2 + 1
    KYN = KY - 1
    CALL QRESET(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
  20 CONTINUE
  DO 30 KY = IYTOT / 2 + 2, IYTOT
    KYN = IYTOT - (KY - 1)
    CALL QRESET(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
  30 CONTINUE
  40 CONTINUE
C
DO 70 KX = IXTOT / 2 + 2, IXTOT
  KXN = IXTOT - (KX - 1)
  DO 50 KY = 1, IYTOT / 2 + 1
    KYN = KY - 1
    CALL QRESET(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
  50 CONTINUE
  DO 60 KY = IYTOT / 2 + 2, IYTOT
    KYN = IYTOT - (KY - 1)
    CALL QRESET(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
  60 CONTINUE
  70 CONTINUE
C
RETURN
END
C**
C**
SUBROUTINE QRESET(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
C**
C**
C** Subroutine QRESET inserts the smoothed response function
C** determined in ADMIT into the arrays QREAL and QIMAG following
C** the driver instructions given by subroutine QPRD.
C**
REAL*8 QREAL(70400), QIMAG(70400), CSMTHR(50), CSMTHI(50),
1  TPSMTH(50), WAVENO(50), DKOUNT(50), QSMTHR(50), QSMTHI(50),
2  GPSMTH(50), C2(50), ODEV(50), C2ERR(50)
C
REAL*8 DNX, DNY, DKX, DKY, DKZ, PIE, WAVMIN, WAVMAX, LOGMIN,
1  LOGMAX, SAMP, LOGWAV, DELTAW, SYM
C
COMMON /RESP/ QREAL, QIMAG
COMMON /INTRVL/ SAMP
COMMON /SMOOTH/ CSMTHR, CSMTHI, TPSMTH, GPSMTH, WAVENO, DKOUNT,
1  QSMTHR, QSMTHI, C2, ODEV, C2ERR
COMMON /LIMITS/ WAVMIN, WAVMAX, LOGMIN, LOGMAX
COMMON /LEVELS/ NLVLS
C
C* CALCULATE POSITION OF ELEMENT
C* IN ARRAYS
C* IPOS = (KY - 1) * IXTOT + KX
C

```

```

DELTAW = (LOGMAX - LOGMIN) / DBLE(REAL(NLVLS))
C
IF (KXN .GT. 0 .OR. KYN .GT. 0) THEN
  DKX = DBLE(REAL(KXN))
  DKY = DBLE(REAL(KYN))
C
  DKZ = SQRT((DKX/(SAMP*DNX))**2 + (DKY/(SAMP*DNY))**2)
  DKZ = 2.000 * PIE * DKZ
C
  LOGWAV = LOG10(DKZ)
C
  IF (LOGWAV .GE. LOGMIN .AND. LOGWAV .LT. LOGMAX) THEN
    RLVL = SNGL(LOGWAV - LOGMIN) / SNGL(DELTAW)
    LEVEL = INT(RLVL) + 1
    QREAL(IPOS) = QSMTHR(LEVEL)
C
C* MODIFY ARRAY DEPENDING ON
C* SYMMETRY FORM
C* SYM = 1.000
    IF (KY .LE. (IYTOT/2 + 1)) THEN
      IF (KYN .EQ. 0) THEN
        IF (KX .GT. (IXTOT/2 + 1)) SYM = -1.000
      ELSE IF (KYN .EQ. (IYTOT/2)) THEN
        IF (KX .GT. (IXTOT/2 + 1)) SYM = -1.000
      END IF
    ELSE
      SYM = -1.000
    END IF
    QIMAG(IPOS) = QSMTHI(LEVEL) * SYM
C
  ELSE
C
    ASSIGN K=N/2 WAVENUMBER TO
    LEVEL NLVLS
    C* LEVEL = NLVLS
    QREAL(IPOS) = QSMTHR(LEVEL)
    QIMAG(IPOS) = QSMTHI(LEVEL)
    END IF
C
  END IF
C
RETURN
END
C**
C**
SUBROUTINE SMTHR(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
C**
C**
C** Subroutine SMTHR smooths the cross and power
C** spectra by summing the data in log spaced
C** intervals in the wave domain. The actual
C** averages are calculated at the end of the
C** subroutine ADMIT.
C**
C**

```

```

      REAL*8 QREAL(70400), QIMAG(70400), TPOWER(70400), CSMTHR(50),
1      CSMTHI(50), TPSMTH(50), WAVENO(50), DKOUNT(50), QSMTHR(50),
2      QSMTHI(50), GPOWER(70400), GPSMTH(50), C2(50), QDEV(50),
3      C2ERR(50)
C
      REAL*8 DNX, DNY, DKX, DKY, DKZ, PIE, WAVMIN, WAVMAX, SAMP, LOGMIN,
1      LOGMAX, LOGWAV, DELTAW, SYM, XCON, YCON, XYCON
C
      COMMON /RESP/ QREAL, QIMAG
      COMMON /PWRSPC/ TPOWER, GPOWER
      COMMON /INTRVL/ SAMP
      COMMON /SMOOTH/ CSMTHR, CSMTHI, TPSMTH, GPSMTH, WAVENO, DKOUNT,
1      QSMTHR, QSMTHI, C2, QDEV, C2ERR
      COMMON /LIMITS/ WAVMIN, WAVMAX, LOGMIN, LOGMAX
      COMMON /LEVELS/ NLVLS
C
C*      CALCULATE POSITION OF DATA ELEMENT
C*      IN MAIN ARRAY
      IPOS = (KY - 1) * IXTOT + KX
C
C*      CALCULATE LOG LENGTH OF EACH LEVEL
      DELTAW = (LOGMAX - LOGMIN) / (DBLE(REAL(NLVLS)))
C
      IF (KXN .GT. 0 .OR. KYN .GT. 0) THEN
C
C*          CALCULATE TRUE WAVENUMBER
          DKX = DBLE(REAL(KXN))
          DKY = DBLE(REAL(KYN))
C
          DKZ = SQRT((DKX/(DNX*SAMP))**2 + (DKY/(DNY*SAMP))**2)
          DKZ = 2.0D0 * PIE * DKZ
C
          LOGWAV = LOG10(DKZ)
C
          IF (LOGWAV .GE. LOGMIN .AND. LOGWAV .LT. LOGMAX) THEN
              RLVL = SNGL(LOGWAV - LOGMIN) / SNGL(DELTAW)
              LEVEL = INT(RLVL) + 1
C
              XCON = 1.0D0
              YCON = 1.0D0
              IF (KXN .EQ. (IXTOT/2)) XCON = 2.0D0
              IF (KYN .EQ. (IYTOT/2)) YCON = 2.0D0
              XYCON = XCON * YCON
C
              CSMTHR(LEVEL) = CSMTHR(LEVEL) + QREAL(IPOS) * XYCON
C
C*          MODIFY IMAGINARY TERM CORRESPONDING
C*          TO ODD SYMMETRY TERM
              SYM = 1.0D0
              IF (KY .LE. (IYTOT/2 + 1)) THEN
                  IF (KYN .EQ. 0) THEN
                      IF (KX .GT. (IXTOT/2 + 1)) SYM = -1.0D0
                      ELSE IF (KYN .EQ. (IYTOT/2)) THEN
                          IF (KX .GT. (IXTOT/2 + 1)) SYM = -1.0D0
                      END IF
                  ELSE
                      SYM = -1.0D0
                  END IF
              ELSE
                  SYM = -1.0D0
              END IF
          END IF
      END IF

```

```

      SYM = -1.0D0
      END IF
C
      CSMTHI(LEVEL) = CSMTHI(LEVEL) + QIMAG(IPOS) * (SYM*XYCON)
C
      TPSMTH(LEVEL) = TPSMTH(LEVEL) + TPOWER(IPOS) * XYCON
      GPSMTH(LEVEL) = GPSMTH(LEVEL) + GPOWER(IPOS) * XYCON
      WAVENO(LEVEL) = WAVENO(LEVEL) + DKZ * XYCON
      DKOUNT(LEVEL) = DKOUNT(LEVEL) + 1.0D0 * XYCON
C
      END IF
      END IF
C
      RETURN
      END
C**
C**      SUBROUTINE SPCSUM(KX, KY, KXN, KYN, IXTOT, IYTOT, DNX, DNY, PIE)
C**      ~~~~~
C**      Subroutine SPCSUM sums all the estimates of the
C**      power spectra in a user defined number of
C**      wavenumber bands. The average of these sums is
C**      calculated on returning to the subroutine AMPSPM.
C**
      REAL*8 DATAR(40000), DATAI(40000), AMP(150), WAVE(150),
1      DKOUNT(150), AMPNRM(150)
C
      REAL*8 SAMP, WAVMIN, WAVMAX, DNX, DNY, DKX, DKY, DKZ, WDELTA,
1      XCON, YCON, XYCON
C
      COMMON /GRID/ DATAR, DATAI
      COMMON /SMOOTH/ AMP, WAVE, DKOUNT, AMPNRM
      COMMON /LVL/ NLVL
      COMMON /INTRVL/ SAMP
      COMMON /LIMITS/ WAVMIN, WAVMAX
C
C*      CALCULATE ELEMENT POSITION IN ARRAY
      IPOS = (KY - 1) * IXTOT + KX
C
      WDELTA = (WAVMAX - WAVMIN) / DFLOAT(NLVL)
C
      DKX = DFLOAT(KXN)
      DKY = DFLOAT(KYN)
C
      DKZ = SQRT((DKX/(DNX*SAMP))**2 + (DKY/(DNY*SAMP))**2)
      DKZ = 2.0D0 * PIE * DKZ
C
      IF (DKZ .GT. WAVMIN .AND. DKZ .LT. WAVMAX) THEN
          RLVL = SNGL(DKZ - WAVMIN) / SNGL(WDELTA)
          LEVEL = INT(RLVL) + 1
C
          XCON = 1.0D0
          YCON = 1.0D0
          IF (KXN .EQ. (IXTOT/2)) XCON = 2.0D0

```

```

      IF (KYN .EQ. (IYTOT/2)) YCON = 2.0D0
      XYCON = XCON * YCON
C
      AMP(LEVEL) = AMP(LEVEL) + (DATAR(IPOS)**2 + DATAI(IPOS)**2) *
1 XYCON
      WAVE(LEVEL) = WAVE(LEVEL) + DKZ * XYCON
      DKOUNT(LEVEL) = DKOUNT(LEVEL) + 1.0D0 * XYCON
C
      END IF
C
      RETURN
      END
C..
C..
      SUBROUTINE SURFT(WT, PM, P0, D, WAVE, GRAV, HT)
C..
C..
      Subroutine Surft calculates the surface topography
C.. HT due to an initial surface load of amplitude 1.0
C.. from WT determined in subroutine Mohot.
C..
C..
      IMPLICIT REAL*8(A - H,O - Z)
C
      PDEL = PM - P0
      FLEX2 = 1.0D0 + (D*(WAVE**4)) / (PDEL*GRAV)
      HT = (-1.0D0*WT*PDEL*FLEX2) / P0
C
      RETURN
      END
C..
C..
      SUBROUTINE TAPER(AREAL, NX, NY, LX, LY)
C..
C..
      Subroutine TAPER tapers the real array AREAL
C.. using cosine tapers in both the x and
C.. y dimensions.
C..
C..
      IMPLICIT REAL*8(A - H,O - Z)
C
      DIMENSION AREAL(NX,NY)
C
      C*
      DEFINE OFTEN USED VARIABLES
      PIE = 4.0D0 * DATAN(1.0D0)
      DNX = DFLOAT(NX)
      DNY = DFLOAT(NY)
      DLX = DFLOAT(LX)
      DLY = DFLOAT(LY)
C
      C*
      CALCULATE AND APPLY FILTER
      FOR EACH ARRAY ELEMENT
      DO 20 I = 1, NX
        DO 10 J = 1, NY
C

```

```

      H = 1.0D0
C
      IF (I .LE. LX) THEN
        ARG = (PIE*DFLOAT(I - 1)) / DLX
        H = H * (0.5D0*(1.0D0-COS(ARG)))
      ELSE IF (I .GT. (NX - LX)) THEN
        ARG = (PIE*(DNX - DFLOAT(I))) / DLX
        H = H * (0.5D0*(1.0D0-COS(ARG)))
      END IF
C
      IF (J .LE. LY) THEN
        ARG = (PIE*DFLOAT(J - 1)) / DLY
        H = H * (0.5D0*(1.0D0-COS(ARG)))
      ELSE IF (J .GT. (NY - LY)) THEN
        ARG = (PIE*(DNY - DFLOAT(J))) / DLY
        H = H * (0.5D0*(1.0D0-COS(ARG)))
      END IF
C
      AREAL(I,J) = AREAL(I,J) * H
C
      10 CONTINUE
      20 CONTINUE
C
      RETURN
      END

```

Appendix D

Computer programmes used in the study of the Tertiary central igneous complexes of Mull and Skye, NW Scotland

Introduction

Appendix D contains two programmes used in the modelling of the structure of the crust in the vicinity of the Tertiary central igneous complexes of Mull and Skye described in Chapter 6. Both programmes are comprehensively documented to facilitate their further use.

General information on the execution of these programmes under the MTS operating system is given in the introduction to Appendix B.

```

C**
C** Programme Radial.grav
C** ~~~~~
C**
C** Programme Radial.grav calculates the gravity anomalies
C** produced by density contrasts with axial symmetry. The
C** technique used was developed by Karner and Bodine (1981)
C** and is basically a modification of Parker's method with
C** the Hankel transform replacing the fourier transform to
C** account for the axial symmetry.
C**
C** The density contrasts are modelled as topography above
C** or below a base level interface.
C**
C** The input to the programme consists of a radial profile
C** of the density contrasts and a set of instructions to
C** control the plotting of a radial profile of the axisymmetric
C** gravity anomaly.
C**
C** Input on unit 5: Density contrast information
C** ~~~~~
C**
C** Line 1: TITLE Title for output file
C** Line 2: NLayer Number of density contrasts/interfaces
C** to be modelled.
C** Repeat for NLayer bodies
C**
C** NPTS, SAMP, Z0, PDEL, NORDER, ERR2, IBody, NBody,
C** ISBDIV, IBDPLT
C**
C** NPTS Number of station points at which to specify
C** density contrast and calculate anomaly.
C** SAMP Interval spacing of stations (units km).
C** Z0 Depth of interface at large radius. The
C** topography of the density contrasts should
C** deviate from Z0 at small radii and level off
C** at a depth of Z0 at large radii. Note z
C** positive upwards (units km)
C** PDEL Density contrast of body/interface
C** (units kg/m**3)
C** NORDER Maximum number of iterations for Parker's
C** method (Recommend 30)
C** ERR2 Covergence factor for iterations
C** (Recommend 0.001)
C** IBody If radial extent of density contrast less than
C** radial extent of profile (recommended) set to 1
C** (Otherwise set to 0)
C** NBody If IBody set to 1, NBody should specify the
C** station number of the first station where the
C** topography of the density contrast levels off to
C** the outer radii level
C** ISBDIV Set to 1: controls accuracy of Abel transform but
C** values greater than 1 should not be required for
C** general use.
C** IBDPLT = 0 Plot density contrast as discrete body
C** e.g. Igneous complex

```

```

C** = 1 Plot density contrast as interface
C** e.g. Moho.
C** NBody*HEIGHT Height of each station up to and including
C** level for each station up to and including
C** station NBody. This corresponds to a radial
C** distance of 0 km to (NBody-1)*SAMP km.
C**
C** Note: NPTS should be constant for all layers in
C** any single model. The value of 2*(NPTS-1) should
C** have factors such as 2, 4, 5 or 10 etc. for the
C** fft.
C**
C** Example input: This input models the gravity effect of the
C** upper part of the main Mull complex in the Moine assemblage
C** basement.
C**
C** 01
C** 257 1.0 -8.0 250.0 30 0.001 1 13 1 0
C** 7.0
C** 7.0
C** 7.0
C** 7.0
C** 7.0
C** 7.0
C** 7.0
C** 6.5
C** 6.0
C** 4.0
C** 2.0
C** 0.0
C**
C** The complex has a density contrast of 250 kg/m**3 with the
C** Moine assemblage and extends out to a radius of 12 km. The
C** base of this section of the complex is at a depth of 8 km,
C** the top at a depth of 1 km.
C**
C** Input on unit 7: Plot data
C** ~~~~~
C**
C** Line 1 IPLT = 1 Plot theoretical anomaly
C** If IPLT = 1
C** Line 2 IOBS > 0 Plot observed data also
C** If IOBS > 0
C** Line 3 NOBS Number of observed points
C** XOBS, OBS = NOBS
C** XOBS = radial distance to observed data point (km)
C** OBS = observed value of gravity anomaly (mGal)
C**
C** PTITLE Title for plot
C**
C** All input free format
C**
C** Programme Details
C** ~~~~~

```

```

C** OS MTS
C** Language Fortran 77 +nag +ghost80
C**
C** Author R.W.Woollett
C** Date 19 th October 1987
C**
C** Run Command
C** ~~~~~
C** Run -load+nag+ghost80 5 = Model input 7 = Obs. Data Input
C**                               8 = Output 9 = Plotfile
C**
C*****C
C*  DEFINE VARIABLES AND ARRAY SPACE:
C*  IMPLICIT REAL*8(A - H,O - Z)
C
C*  CHARACTER TITLE*80, PTITLE*50
C
C*  REAL*4 ZPLT(5,2048), ANMPLT(2048), X(2048), XOBS(100), OBS(100),
C*  1 Z0PLT(5)
C*  REAL*4 RSAMP
C
C*  INTEGER NBODY(5), IBDPLT(5)
C*  INTEGER RES
C
C*  DIMENSION ABELR(2048), ABELI(2048), ANOM(2048), AUX1(2048),
C*  1 AUX2(2048), DWORK(2048), FW(2048), TOTANM(2048),
C*  2 W(2048), WAVE(2048), Z(2048)
C
C*  DATA ABELR, ABELI, ANOM, AUX1 /2048*0.0, 2048*0.0, 2048*0.0, 2048*
C*  1 0.0/
C*  DATA AUX2, DWORK, FW, TOTANM /2048*0.0, 2048*0.0, 2048*0.0,
C*  1 2048*0.0/
C*  DATA W, WAVE /2048*0.0, 2048*0.0/
C*  DATA X, ANMPLT, XOBS, OBS, Z0PLT /2048*0.0, 2048*0.0, 100*0.0,
C*  1 100*0.0, 5*0.0/
C*  DATA NBODY, IBDPLT, IPLT, IOBS, NOBS /5*0, 5*0, 0, 0, 0/
C
C*  CALL TIME(0)
C
C*  DO 10 I = 1, 5
C*  DO 10 J = 1, 2048
C*  ZPLT(I,J) = 0.0
C*  10 CONTINUE
C
C*  ENTER DATA
C*  READ (5,20) TITLE
C*  20 FORMAT (A80)
C
C*  READ (5,*) NLAYER
C*  IF (NLAYER .GT. 5) THEN
C*  WRITE (6,30)
C*  30 FORMAT (/, 5X, 'Error:Max. number of density contrasts is 5 ', /
C*  1 )

```

```

STOP
END IF
C
DO 80 I = 1, NLAYER
C
WRITE (6,40) I
40 FORMAT (/, 5X, 'Processing Layer ', I2, /)
C
SET Z TO ZERO
DO 50 J = 1, 2048
Z(J) = 0.0
50 CONTINUE
C
READ (5,*) NPTS, SAMP, Z0, PDEL, NORDER, ERR2, IBODY, NBODY(I),
1 ISBDIV, IBDPLT(1)
Z0PLT(1) = SNGL(Z0)
C
DO 60 J = 1, NBODY(I)
READ (5,*) Z(J)
ZPLT(I,J) = SNGL(Z(J))
60 CONTINUE
C
CALCULATE GRAVITY ANOMALY AT SURFACE
GENERATED BY DENSITY CONTRAST
CALL PARKHL(WAVE, Z, ANOM, ABELR, ABELI, AUX1, AUX2, DWORK, FW,
1 W, NPTS, SAMP, Z0, PDEL, NORDER, ERR2, IBODY, NBODY(I),
2 ISBDIV)
C
ADD SINGLE LAYER ANOMALY TO TOTAL
DO 70 J = 1, NPTS
TOTANM(J) = TOTANM(J) + ANOM(J)
C
70 CONTINUE
C
80 CONTINUE
C
WRITE OUT FINAL RESULTS
WRITE (8,90) TITLE
90 FORMAT (/, A80, /)
WRITE (8,100)
100 FORMAT (/, 5X, 'Programme Results', //, 5X, ' X Value Anomal
1y ', /)
C
DO 120 J = 1, NPTS
XPOS = DFLOAT(J - 1) * SAMP
WRITE (8,110) XPOS, TOTANM(J)
110 FORMAT (3X, 2(2X,G11.5))
120 CONTINUE
C
PLOT ANOMALY IF REQUESTED
READ (7,*) IPLT
IF (IPLT .EQ. 1) THEN
READ (7,*) IOBS
IF (IOBS .GT. 0) THEN
READ (7,*) NOBS

```

```

        IF (NOBS .GT. 100) THEN
          WRITE (6,130)
130      FORMAT (/, 5X, 'Error: Number of observed data points', /,
1          5X, 'exceeds limit of 100', /)
          IOBS = 0
        ELSE
          DO 140 I = 1, NOBS
            READ (7,*) XOBS(I), OBS(I)
140      CONTINUE
          END IF
        END IF
C
      READ (7,150) PTITLE
150    FORMAT (A50)
C
      RSAMP = SNGL(SAMP)
      DO 160 I = 1, NPTS
        ANMPLT(I) = SNGL(TOTANM(I))
160    CONTINUE
C
C*    PLOT ANOMALY
      CALL PLOT(ZPLT, NBDY, IBDPLT, Z0PLT, NLayer, X, ANMPLT, NPTS,
1          RSAMP, IOBS, NOBS, XOBS, OBS, PTITLE)
C
      END IF
C
      CALL TIME(1, 0, RES)
      WRITE (6,170) RES
170    FORMAT (/, 5X, 'C.P.U Time required for calculation = ', I8,
1          ' Milliseconds', /)
C
      STOP
      END

```



```

C**
C** Programme Radial.load
C** ~~~~~
C**
C** Programme Radial.load is designed to
C** calculate the radial deflection of the
C** lithosphere generated by the load of the
C** Skye and Mull igneous complexes.
C** The loading algorithm approximates the mass
C** excess of the complexes as surface loads.
C**
C** As with programme Radial.grav the loads are
C** specified by radial profiles of their axial
C** distribution. The programme first calculates
C** the deflection and then calculates an
C** approximation of the resulting gravity anomalies.
C**
C** Input on unit 5: Load definition.
C** ~~~~~
C**
C** Line 1 TITLE Title for output file
C** Line 2 TE, PMANTL, PINFIL TE = Elastic thickness of the
C**                               lithosphere in metres.
C**                               PMANTL = Density of upper mantle
C**                               (units kg/m**3)
C**                               PINFIL = Density of material
C**                               infilling deflection.
C**
C** Line 3 NPTS, SAMP, ISBDIV, NORDER ERR2
C** NPTS = Number of station points at which load +
C**         deflection + gravity anomalies are to be defined.
C**         NPTS should have a constant value for all loads.
C**         2*(NPTS-1) should have factors such as 2, 4, 5 or
C**         10 etc. for the FFT.
C** SAMP = Interval spacing between stations in metres.
C** ISBDIV = Set to 1, controls accuracy of Abel transform.
C** NORDER = Maximum number of iterations for Parker's
C**           method (Recommend 30).
C** ERR2 = Convergence limit for iterations
C**         (Recommend 0.001).
C**
C** Line 4 NLOADS Number of radial loads
C**
C** Repeat for NLOADS times
C**
C** Z0, PDEL, IBODY, NBODY
C**
C** Z0 = Depth of loading interface at large radii. Loads
C**       should deviate from Z0 at small radii and level
C**       off at Z0 for large radii (units metres).
C** PDEL = Density contrast of load (kg/m**3).
C** IBODY = If density contrast levels off at radii less
C**          than the total extent of the model set IBODY
C**          to 1 to improve efficiency of Abel transform
C**          algorithm.
C** NBODY = If IBODY = 1, NBODY should specify the first
C**          station at which the density contrast topography

```

```

C**
C** levels off at Z0.
C**
C** Continue input after loads
C**
C** NLAYER = Number of density contrasts within lithosphere
C**
C** Repeat for NLAYER times
C**
C** ISURF, ZLAYER, PCRSTL
C** ISURF = 0 Density contrast at surface
C**         = 1 Density contrast not at surface
C** ZLAYER = Depth to density contrast in metres
C** PCRSTL = Density contrast in kg/m**3
C**
C** Input on unit 7: Plot data
C** ~~~~~
C**
C** Line 1 IPLT = 1 Plot data
C** IF IPLT = 1
C** Line 2 IOBS > 0 Plot observed data
C** IF IOBS > 0
C** Line 3 NOBS Number of data points
C** Repeat NOBS times
C**         X OBS = X coordinate of observation
C**         OBS = Observed value of gravity anomaly
C**               (units metres, mGal).
C**
C** Programme Details
C** ~~~~~
C**
C** OS MTS
C** Language Fortran 77 + *nag + *ghost80
C**
C** Author R.W.Woollett
C** Date 15 th February 1988
C**
C** Run Command
C** ~~~~~
C**
C** Run -load+*nag+*ghost80 5 = Model input 7 = Plot data 8 = Output
C**                           9 = Plotfile
C** ~~~~~
C** *****C
C
C* MAIN
C* IMPLICIT REAL*8(A - H,O - Z)
C
C* CHARACTER TITLE*80, PTITLE*50
C
C* INTEGER RES
C
C* DIMENSION ABELR(2048), ABELI(2048), ANOM(2048), AUX1(2048),
C* 1 AUX2(2048), DFLCT(2048), DWORK(2048), FW(2048),
C* 2 HLOAD(2048), PLOAD(5,2048), TLOAD(2048), TOTANM(2048),
C* 3 W(2048), WAVE(2048), Z(2048)

```

```

      DIMENSION IBODY(5), NBODY(5), PCONTR(5), ZDEPTH(5), Z0(5)
C
      REAL*4 ANMPLT(2048), DFPLT(2048), PLPLT(5,2048), X(2048)
      REAL*4 OBS(100), XOBS(100), ZDPLT(5), Z0PLT(5)
      REAL*4 RSAMP, TE4KM
C
      DATA ABELR, ABELI, ANOM, AUX1, AUX2, DFLCT, DWORK, FW, HLOAD,
1      TLOAD, TOTANM, W, WAVE, Z /2048*0.0D0, 2048*0.0D0,
2      2048*0.0D0, 2048*0.0D0, 2048*0.0D0, 2048*0.0D0, 2048*0.0D0,
3      2048*0.0D0, 2048*0.0D0, 2048*0.0D0, 2048*0.0D0, 2048*0.0D0,
4      2048*0.0D0, 2048*0.0D0/
C
      DATA IBODY, NBODY, PCONTR, ZDEPTH, Z0 /5*0, 5*0, 5*0.0D0, 5*0.0D0,
1      5*0.0D0/
C
      DATA ANMPLT, DFPLT, X /2048*0.0, 2048*0.0, 2048*0.0/
      DATA OBS, XOBS, ZDPLT, Z0PLT /100*0.0, 100*0.0, 5*0.0, 5*0.0/
C
      DATA E, V, GRAV /1.0D+11, 0.25D0, 9.81D0/
C
      DATA NBDYMX, IPLT, IOBS, NOBS /0, 0, 0, 0/
C
      INITIATE CALCULATION TIME COUNT
      CALL TIME(0)
C
      PIE = 4.0D0 * ATAN(1.0D0)
C
      DO 20 I = 1, 5
        DO 10 J = 1, 2048
          PLOAD(I,J) = 0.0D0
          PLPLT(I,J) = 0.0
10      CONTINUE
20      CONTINUE
C
      ENTER FLEXURAL PARAMETERS + LOAD DATA
      READ (5,30) TITLE
30      FORMAT (A80)
C
      READ (5,*) TE, PMANTL, PINFIL
      TE4KM = SNGL(TE) / 1000.0
      PDEL = PMANTL - PINFIL
      D = (E*(TE**3)) / (12.0D0*(1.0D0-(V**2)))
C
      READ (5,*) NPTS, SAMP, ISBDIV, NORDER, ERR2
      READ (5,*) NLOADS
C
      IF (NLOADS.GT. 5) THEN
        WRITE (6,40)
40      FORMAT (/, 5X, 'Error:Maximum number of loads exceeded', /, 5X,
1      'Only five loads are allowed', /)
        STOP
      END IF
C
      DO 60 ILOAD = 1, NLOADS
C
        READ (5,*) Z0(ILOAD), PCONTR(ILOAD), IBODY(ILOAD), NBODY(ILOAD)

```

```

      IF (NBODY(ILOAD).GT. NBDYMX) NBDYMX = NBODY(ILOAD)
C
      DO 50 J = 1, NBODY(ILOAD)
        READ (5,*) PLOAD(ILOAD,J)
        PLPLT(ILOAD,J) = SNGL(PLOAD(ILOAD,J))
        TLOAD(J) = TLOAD(J) + (PLOAD(ILOAD,J)*PCONTR(ILOAD)*GRAV)
50      CONTINUE
C
      60 CONTINUE
C
      WRITE (6,70)
70      FORMAT (/, 5X, 'Calculating lithospheric deformation', /)
C
      DETERMINE HANKEL TRANSFORM OF LOAD
      NPTS2 = 2 * (NPTS - 1)
      IF (NPTS2.GT. 2048) THEN
        WRITE (6,80)
80      FORMAT (/, 5X, 'Error reflected array size exceeds 2048', /)
        STOP
      END IF
C
      CALL HANKEL(TLOAD, ABELR, ABELI, HLOAD, NPTS, NPTS2, SAMP, ISBDIV,
1      DWORK, IBODY, NBDYMX)
C
      DETERMINE HORIZONTAL WAVENUMBERS
      CALL WAVE1D(WAVE, NPTS2, SAMP)
C
      DETERMINE DEFLECTION
      DO 90 I = 1, NPTS
        FLEX = 1.0D0+(D*(WAVE(I)**4))/(PDEL*GRAV))
        HLOAD(I) = HLOAD(I) / (PDEL*GRAV*FLEX)
90      CONTINUE
C
      INVERT DEFLECTION
      PSAMP = (2.0D0*PIE) / (DFLOAT(NPTS2)*SAMP)
C
      CALL HANKEL(HLOAD, ABELR, ABELI, DFLCT, NPTS, NPTS2, PSAMP,
1      ISBDIV, DWORK, 0, 0)
C
      OUTPUT RESULTS
      WRITE (8,100) TITLE
100     FORMAT (/, A80, /)
C
      WRITE (8,110) TE, D, PMANTL, PINFIL
110     FORMAT (/, 5X, 'Flexural Parameters', //, 5X,
1      'Elastic Thickness = ', F7.1, ' Metres', /, 5X,
2      'Flexural Rigidity = ', E11.5, ' Nm', /, 5X,
3      'Mantle Density = ', F6.1, ' Kg/m**3', /, 5X,
4      'Infill Density = ', F6.1, ' Kg/m**3', /)
C
      WRITE (8,120) NLOADS
120     FORMAT (/, 5X, 'Number of specified loads = ', I2, /)
C
      WRITE (8,130)
130     FORMAT (/, 5X, ' Programme results', //, 5X,
1      ' X Value Deflection (Metres)', //)

```

```

C      DO 150 J = 1, NPTS
C
C          XPOS = DFLCT(J - 1) * SAMP
C          WRITE (8,140) XPOS, DFLCT(J)
140      FORMAT (3X, 2(2X,G11.5))
C
C      150 CONTINUE
C
C*      CALCULATE GRAVITY EFFECT OF DEFORMATION
C*      AND LOAD (USE AVERAGE POSITION FOR LOAD)
C          DFTSUM = 0.0D0
C          DO 160 I = 1, NBDYMX
C              DFTSUM = DFTSUM + DFLCT(I)
160      CONTINUE
C
C          DFTAVG = DFTSUM / DFLCT(NBDYMX)
C
C          DO 170 ILOAD = 1, NLOADS
C              Z0(ILOAD) = Z0(ILOAD) - DFTAVG
C              Z0PLT(ILOAD) = SNGL(Z0(ILOAD))
170      CONTINUE
C
C*      DETERMINE GRAVITY EFFECT OF LOADS AFTER FLEXURE
C          DO 210 ILOAD = 1, NLOADS
C
C              WRITE (6,180) ILOAD
180          FORMAT (/, 5X, 'Calculating gravity anomaly for load ', I2, /)
C
C              DO 190 I = 1, NPTS
C                  Z(I) = PLOAD(ILOAD, I)
190          CONTINUE
C
C              CALL PARKHL(WAVE, Z, ANOM, ABELR, ABELI, AUX1, AUX2, DWORK, FW,
1              W, NPTS, SAMP, Z0(ILOAD), PCNTR(ILOAD), NORDER, ERR2,
2              IBODY(ILOAD), NBDY(ILOAD), ISBDIV)
C
C              DO 200 I = 1, NPTS
C                  TOTANM(I) = TOTANM(I) + ANOM(I)
200          CONTINUE
210      CONTINUE
C
C*      ENTER CRUSTAL LAYER MODEL
C          READ (5,*) NLAYER
C          IF (NLAYER .GT. 5) THEN
C              WRITE (6,220)
220          FORMAT (/, 5X, 'Error:Only 5 crustal layers allowed'. /)
C              STOP
C          END IF
C
C          DO 260 ILAYER = 1, NLAYER
C
C              WRITE (6,230) ILAYER
230          FORMAT (/, 5X, 'Calculating gravity anomaly for layer ', I2, /)
C
C              READ (5,*) ISURF, ZDEPTH(ILAYER), PCRSTL

```

```

ZDPLT(ILAYER) = SNGL(ZDEPTH(ILAYER))
DO 240 I = 1, NPTS
    IF (DFLCT(I) .GE. 0.0D0) THEN
        Z(I) = (-1.0D0) * DFLCT(I)
    ELSE IF (DFLCT(I) .LT. 0.0D0) THEN
        IF (ISURF .EQ. 0) THEN
            Z(I) = 0.0D0
        ELSE
            Z(I) = (-1.0D0) * DFLCT(I)
        END IF
    END IF
240 CONTINUE
C
C*      CALCULATE GRAVITY EFFECT OF CRUSTAL DEFORMATION
C          CALL PARKHL(WAVE, Z, ANOM, ABELR, ABELI, AUX1, AUX2, DWORK, FW,
1          W, NPTS, SAMP, ZDEPTH(ILAYER), PCRSTL, NORDER, ERR2, 0, 0,
2          ISBDIV)
C
C          DO 250 I = 1, NPTS
C              TOTANM(I) = TOTANM(I) + ANOM(I)
250      CONTINUE
260      CONTINUE
C
C*      OUTPUT RESULTS
C          WRITE (8,270)
270      FORMAT (/, 5X, ' X Value      Gravity Anomaly mGal', //)
C
C          DO 290 I = 1, NPTS
C              XPOS = DFLCT(I - 1) * SAMP
C              WRITE (8,280) XPOS, TOTANM(I)
280          FORMAT (3X, 2(2X,G11.5))
290      CONTINUE
C
C*      PLOT RESULTS
C          READ (7,*) IPLT
C          IF (IPLT .EQ. 1) THEN
C              READ (7,*) IOBS
C              IF (IOBS .GT. 0) THEN
C                  READ (7,*) NOBS
C                  IF (NOBS .GT. 100) THEN
C                      WRITE (6,300)
300          FORMAT (/, 5X, 'Error number of observed data points', /,
1          5X, 'exceeds limit of 100'. /)
C                      IOBS = 0
C                  ELSE
C                      DO 310 I = 1, NOBS
C                          READ (7,*) XOBS(I), OBS(I)
310                      CONTINUE
C                      END IF
C                  END IF
C
C          READ (7,320) PTITLE
320      FORMAT (A50)
C
C          RSAMP = SNGL(SAMP)
C          DO 330 I = 1, NPTS

```

```

      DFPLT(I) = SNGL(DFLCT(I))
      ANMPLT(I) = SNGL(TOTANM(I))
330  CONTINUE
C
C*   PLOT ANOMALY
      CALL PLOT2(PLPLT, NBODY, Z0PLT, NLOADS, DFPLT, ZDPLT, NLAYER, X,
1      ANMPLT, NPTS, RSAMP, IOBS, NOBS, XOBS, OBS, PTITLE, TE4KM)
C
      END IF
C
      CALL TIME(1, 0, RES)
      WRITE (6,340) RES
340  FORMAT (/, 5X, 'C.P.U Time required for calculation = ', I8,
1      'Milliseconds', /)
C
      STOP
      END

```



```

      DWORK(I) = 0.0
      DATOUT(I) = 0.0
20 CONTINUE
C
C• CALCULATE ABEL TRANSFORM
  CALL ABEL(DATIN, ABELR, N, SAMP, ISBDIV, IBODY, NBODY)
C
C• REFLECT ARRAY TO OBTAIN REAL
C• COEFFICIENTS ONLY
  CALL REFLCT(ABELR, N, N2)
C
C• CALCULATE 1D-FFT
  CALL C06FCF(ABELR, ABELI, N2, DWORK, IFAIL)
C
C• SCALE RESULT
  DN2 = DFLOAT(N2)
  SCALE = (SQRT(DN2)*SAMP) / (2.000*PIE)
C
  DO 30 I = 1, N2
    ABELR(I) = ABELR(I) * SCALE
    ABELI(I) = ABELI(I) * SCALE
    DATOUT(I) = ABELR(I)
30 CONTINUE
C
  RETURN
  END
C••
C•• SUBROUTINE PARKHL(WAVE, Z, ANOM, ABELR, ABELI, AUX1, AUX2, DWORK,
1      FW, W, NPTS, SAMP, Z0, PDEL, NORDER, ERR2, IBODY,
2      NBODY, ISBDIV)
C•• ~~~~~
C•• Subroutine Parkhl calculates the gravity anomaly at
C•• the surface generated by the interface described by Z,
C•• assuming the interface displays radial symmetry.
C••
C•• Note scale factor (Line label 70). If main programme is
C•• Radial.grav set scale factor to 1.0D+08 for kms,
C•• otherwise for programme Radial.load use scale factor
C•• 1.0D+05 for metres.
C••
  IMPLICIT REAL*8(A - H, O - Z)
C
  DIMENSION ABELR(2048), ABELI(2048), ANOM(2048), AUX1(2048),
1      AUX2(2048), DWORK(2048), FW(2048), W(2048), WAVE(2048),
2      Z(2048)
C
  DATA G /6.67D-11/
C
  PIE = 4.0D0 * ATAN(1.0D0)
C
C• CLEAN ARRAY SPACE
  DO 10 I = 1, NPTS
    ANOM(I) = 0.0

```

```

      AUX1(I) = 1.0D0
      AUX2(I) = 0.0
      FW(I) = 1.0D0
      W(I) = 0.0
10 CONTINUE
C
C• DETERMINE FFT WAVENUMBERS
  NPTS2 = 2 * (NPTS - 1)
  IF (NPTS2 .GT. 2048) THEN
    WRITE (6,20)
20    FORMAT (/, 5X, 'Error:Reflected Array size exceeds 2048', /)
    STOP
  END IF
C
  CALL WAVE1D(WAVE, NPTS2, SAMP)
C
C• CALCULATE SUMMATION
  SUM = 1.0D0
  OLDSUM = 0.0
  DO 60 K = 1, NORDER
    WRITE (6,30) K
30    FORMAT (5X, 'Initiating Iteration ', I2)
    C
    SUM = SUM * DFLOAT(K)
    C
    DO 40 I = 1, NPTS
      AUX1(I) = AUX1(I) * Z(I)
40    CONTINUE
    C
    CALL HANKEL(AUX1, ABELR, ABELI, AUX2, NPTS, NPTS2, SAMP, ISBDIV,
1      DWORK, IBODY, NBODY)
    C
    TERMSM = 0.0
    C
    DO 50 I = 1, NPTS
      TERM = (AUX2(I)*FW(I)/SUM) * EXP(Z0*WAVE(I))
      W(I) = W(I) + TERM
      TERMSM = TERMSM + TERM
      FW(I) = FW(I) * WAVE(I)
50    CONTINUE
    C
    IF (K .GT. 1) THEN
      IF (ABS(TERMSM) .LT. ABS((ERR2*OLDSUM))) GO TO 70
    END IF
    C
    OLDSUM = OLDSUM + TERMSM
    C
    60 CONTINUE
    C
    C• SCALE DATA AND APPLY UPWARD CONTINUATION FACTOR
70    SCALE = 2.0D0 * PIE * G * PDEL * 1.0D+08
    C
    DO 80 I = 1, NPTS
      W(I) = W(I) * SCALE
80    CONTINUE

```

```

C
C*   INVERT TRANSFORM
PSAMP = (2.0D0*PIE) / (DFLOAT(NPTS2)*SAMP)
C
CALL HANKEL(W, ABELR, ABELI, ANOM, NPTS, NPTS2, PSAMP, ISBDIV,
1  DWORK, 0, 0)
C
RETURN
END
C**
C**   SUBROUTINE PLOT(ZPLT, NBDY, IBDPLT, Z0PLT, NLYR, X, ANMPLT,
1  NPTS, RSAMP, IOBS, NOBS, XOBS, OBS, PTITLE)
C**   ~~~~~
C**   Subroutine Plot generates a plot of the calculated/
C**   observed anomaly and the causative density contrasts.
C**
CHARACTER PTITLE*50
C
INTEGER NBDY(5), IBDPLT(5)
C
DIMENSION ZPLT(5,2048), Z0PLT(5), X(2048), ANMPLT(2048),
1  XOBS(100), OBS(100)
C
C*   PLOT ANOMALY
XMIN = 0.0
NPTSPT = NPTS
C
IF (IOBS.NE. 2) XMAX = REAL(NPTS - 1) * RSAMP
C
C*   CHECK RANGE OF OBSERVED VALUES
IF (IOBS.GT. 0) THEN
DO 10 I = 1, NOBS
IF (XOBS(I) .LT. XMIN) XMIN = XOBS(I)
IF (XOBS(I) .GT. XMAX) XMAX = XOBS(I)
10  CONTINUE
END IF
C
DO 20 I = 1, NPTS
X(I) = REAL(I - 1) * RSAMP
IF (IOBS.EQ. 2 .AND. X(I) .GT. XMAX) THEN
NPTSPT = I - 1
GO TO 30
END IF
20  CONTINUE
C
30  AMIN = 1.0E+10
AMAX = -1.0E+10
C
DO 40 I = 1, NPTSPT
IF (ANMPLT(I) .LT. AMIN) AMIN = ANMPLT(I)
IF (ANMPLT(I) .GT. AMAX) AMAX = ANMPLT(I)
40  CONTINUE
C

```

```

IF (IOBS.GT. 0) THEN
DO 50 I = 1, NOBS
IF (OBS(I) .LT. AMIN) AMIN = OBS(I)
IF (OBS(I) .GT. AMAX) AMAX = OBS(I)
50  CONTINUE
END IF
C
AMIN = AMIN - (AMAX - AMIN) * 0.05
AMAX = AMAX + (AMAX - AMIN) * 0.05
C
C*   INITIALIZE GHOST80
CALL PAPER(1)
CALL PSPACE(0.2, 0.8, 0.55, 0.8)
CALL MAP(XMIN, XMAX, AMIN, AMAX)
CALL BORDER
CALL SCALES
C
IF (IOBS.GT. 0) THEN
CALL PTPLT(XOBS, OBS, 1, NOBS, 248)
END IF
C
CALL CURVEO(X, ANMPLT, 1, NPTSPT)
C
C*   PLOT BODY/DENSITY CONTRASTS
ZMIN = 1.0E+10
ZMAX = -1.0E+10
C
DO 70 I = 1, NLYR
DO 60 J = 1, NPTSPT
ZPLT(I,J) = ZPLT(I,J) + Z0PLT(I)
IF (ZPLT(I,J) .LT. ZMIN) ZMIN = ZPLT(I,J)
IF (ZPLT(I,J) .GT. ZMAX) ZMAX = ZPLT(I,J)
60  CONTINUE
70  CONTINUE
C
IF (ZMAX.LT. 0.0) THEN
ZMAX = 0.0
ELSE IF (ZMAX.GT. 0.0) THEN
WRITE (6,80) ZMAX
80  FORMAT (/, 5X, 'Error: Zmax (', G11.5, ') greater than zero', /)
STOP
END IF
C
ZMIN = ZMIN - (ZMAX - ZMIN) * 0.05
C
C*   PLOT DENSITY CONTRAST BOUNDARIES
CALL PSPACE(0.2, 0.8, 0.2, 0.45)
CALL MAP(XMIN, XMAX, ZMIN, ZMAX)
CALL BORDER
CALL SCALES
C
DO 100 I = 1, NLYR
CALL POSITN(X(1), ZPLT(I,1))
IF (IBDPLT(I).EQ. 0) THEN

```

```

      JEND = NBODY(1)
      ELSE
        JEND = NPTSPT
      END IF
      DO 90 J = 2, JEND
        CALL JOIN(X(J), ZPLT(I,J))
90    CONTINUE
      IF (IBDPLT(1) .EQ. 0) CALL JOIN(X(1), ZPLT(I,NBODY(1)))
100  CONTINUE
C
C*  ANNOTATE PLOT
CALL PSPACE(0.0, 1.0, 0.0, 1.0)
CALL MAP(0.0, 1.0, 0.0, 1.0)
C
CALL CTRMAG(17)
CALL PLOTCS(0.2, 0.9, PTITLE)
C
CALL CTRMAG(12)
CALL PLOTNC(0.2, 0.845, 248)
CALL PLOTCS(0.23, 0.845, 'Observed anomaly')
CALL POSITN(0.45, 0.85)
CALL JOIN(0.55, 0.85)
CALL PLOTCS(0.6, 0.845, 'Calculated anomaly')
C
CALL PCSCEN(0.5, 0.5, 'Distance km')
CALL CTRORI(90.0)
CALL PCSCEN(0.15, 0.675, 'Anomaly mGal')
C
CALL CTRORI(0.0)
CALL PCSCEN(0.5, 0.15, 'Distance km')
CALL CTRORI(90.0)
CALL PCSCEN(0.15, 0.325, 'Depth km')
CALL CTRORI(0.0)
C
CALL GREND
C
RETURN
END
C**
C**  SUBROUTINE PLOT2(PLPLT, NBODY, Z0PLT, NLOADS, DFPLT, ZDPLT,
1      NLayer, X, ANMPLT, NPTS, RSAMP, IOBS, NOBS, XOBS, OBS,
2      PTITLE, TE4KM)
C**
C**  ~~~~~
C**  Subroutine Plot2 generates a plot of the deflected
C**  lithosphere and the theoretical and observed gravity
C**  anomalies.
C**
C**  CHARACTER PTITLE*50
C
C  DIMENSION ANMPLT(2048), DFPLT(2048), PLPLT(5,2048), X(2048)
C  DIMENSION OBS(100), XOBS(100), ZDPLT(5), Z0PLT(5)
C  DIMENSION NBODY(5)

```

```

C*  PLOT ANOMALY
XMIN = 0.0
NPTSPT = NPTS
C
IF (IOBS .NE. 2) XMAX = (REAL(NPTS - 1)*RSAMP) / 1000.0
C
C*  CHECK RANGE OF OBSERVED VALUES
IF (IOBS .GT. 0) THEN
  DO 10 I = 1, NOBS
    IF (XOBS(I) .LT. XMIN) XMIN = XOBS(I)
    IF (XOBS(I) .GT. XMAX) XMAX = XOBS(I)
10  CONTINUE
  END IF
C
DO 20 I = 1, NPTS
  X(I) = (REAL(I - 1)*RSAMP) / 1000.0
  IF (IOBS .EQ. 2 .AND. X(I) .GT. XMAX) THEN
    NPTSPT = I - 1
    GO TO 30
  END IF
20  CONTINUE
C
30  AMIN = 1.0E+10
  AMAX = -1.0E+10
C
DO 40 I = 1, NPTSPT
  IF (ANMPLT(I) .LT. AMIN) AMIN = ANMPLT(I)
  IF (ANMPLT(I) .GT. AMAX) AMAX = ANMPLT(I)
40  CONTINUE
C
IF (IOBS .GT. 0) THEN
  DO 50 I = 1, NOBS
    IF (OBS(I) .LT. AMIN) AMIN = OBS(I)
    IF (OBS(I) .GT. AMAX) AMAX = OBS(I)
50  CONTINUE
  END IF
C
AMIN = AMIN - (AMAX - AMIN) * 0.05
AMAX = AMAX + (AMAX - AMIN) * 0.05
C
C*  INITIALIZE GHOST0
CALL PAPER(1)
CALL PSPACE(0.2, 0.8, 0.55, 0.8)
CALL MAP(XMIN, XMAX, AMIN, AMAX)
CALL BORDER
CALL SCALES
C
IF (IOBS .GT. 0) THEN
  CALL PTPLT(XOBS, OBS, 1, NOBS, 248)
  END IF
C
CALL CURVEO(X, ANMPLT, 1, NPTSPT)
C
C*  PLOT BODY/DENSITY CONTRASTS
ZMIN = 1.0E+10
ZMAX = -1.0E+10

```



```

C      DO 70 ILOAD = 1, NLOADS
C      DO 60 I = 1, NBODY(ILOAD)
C      PLPLT(ILOAD,I) = (PLPLT(ILOAD,I) + Z0PLT(ILOAD)) / 1000.0
C      IF (PLPLT(ILOAD,I) .LT. ZMIN) ZMIN = PLPLT(ILOAD,I)
C      IF (PLPLT(ILOAD,I) .GT. ZMAX) ZMAX = PLPLT(ILOAD,I)
C
C      60 CONTINUE
C      70 CONTINUE
C
C      DO 90 ILAYER = 1, NLayer
C      DO 80 I = 1, NPTSPT
C      Z = (ZDPLT(ILAYER) - DFPLT(I)) / 1000.0
C      IF (Z .LT. ZMIN) ZMIN = Z
C      IF (Z .GT. ZMAX) ZMAX = Z
C      80 CONTINUE
C      90 CONTINUE
C
C      ZMIN = ZMIN - (ZMAX - ZMIN) * 0.05
C      ZMAX = ZMAX + (ZMAX - ZMIN) * 0.05
C
C      PLOT DENSITY CONTRAST BOUNDARIES
C      CALL PSPACE(0.2, 0.8, 0.2, 0.45)
C      CALL MAP(XMIN, XMAX, ZMIN, ZMAX)
C      CALL BORDER
C      CALL SCALES
C
C      DO 110 ILOAD = 1, NLOADS
C      CALL POSITN(X(1), PLPLT(ILOAD,1))
C      DO 100 I = 2, NBODY(ILOAD)
C      CALL JOIN(X(1), PLPLT(ILOAD,I))
C      100 CONTINUE
C      CALL JOIN(X(1), PLPLT(ILOAD,NBODY(ILOAD)))
C      110 CONTINUE
C
C      CALL BROKEN(10, 10, 10, 10)
C      CALL POSITN(XMIN, 0.0)
C      CALL JOIN(XMAX, 0.0)
C      CALL FULL
C
C      DO 130 ILAYER = 1, NLayer
C      Z = (ZDPLT(ILAYER) - DFPLT(1)) / 1000.0
C      CALL POSITN(X(1), Z)
C      DO 120 I = 2, NPTSPT
C      Z = (ZDPLT(ILAYER) - DFPLT(I)) / 1000.0
C      CALL JOIN(X(I), Z)
C      120 CONTINUE
C      130 CONTINUE
C
C      ANNOTATE PLOT
C      CALL PSPACE(0.0, 1.0, 0.0, 1.0)
C      CALL MAP(0.0, 1.0, 0.0, 1.0)
C
C      CALL CTRMAG(17)
C      CALL PLOTCS(0.2, 0.9, PTITLE)

```

```

C      CALL CTRMAG(12)
C
C      CALL PLOTCS(0.2, 0.855, 'Elastic thickness of lithosphere')
C      CALL PLOTNF(0.57, 0.855, TE4KM, 1)
C      CALL PLOTCS(0.6, 0.855, 'km')
C
C      CALL PLOTNC(0.2, 0.825, 248)
C      CALL PLOTCS(0.23, 0.825, 'Observed anomaly')
C      CALL POSITN(0.45, 0.83)
C      CALL JOIN(0.55, 0.83)
C      CALL PLOTCS(0.6, 0.825, 'Calculated anomaly')
C
C      CALL PCSCEN(0.5, 0.5, 'Distance km')
C      CALL CTRORI(90.0)
C      CALL PCSCEN(0.15, 0.675, 'Anomaly mGal')
C
C      CALL CTRORI(0.0)
C      CALL PCSCEN(0.5, 0.15, 'Distance km')
C      CALL CTRORI(90.0)
C      CALL PCSCEN(0.15, 0.325, 'Depth km')
C      CALL CTRORI(0.0)
C
C      CALL GREND
C
C      RETURN
C      END
C**
C**
C** SUBROUTINE REFLCT(ARRAY, N, N2)
C** ~~~~~
C** Subroutine Reflct simply reflects
C** a 1D array about its endpoint.
C**
C**
C** IMPLICIT REAL*8(A - H,O - Z)
C
C      DIMENSION ARRAY(2048)
C
C      DO 10 I = N + 1, N2
C      J = N - (I - N)
C      ARRAY(I) = ARRAY(J)
C      10 CONTINUE
C
C      RETURN
C      END
C**
C**
C** SUBROUTINE WAVE1D(WAVE, N, SAMP)
C** ~~~~~
C** Subroutine Wave1d calculates the wavenumber
C** values for each array element after the FFT
C** has been calculated.
C**

```



```
C**  IMPLICIT REAL*8(A - H,O - Z)
C
C    DIMENSION WAVE(2048)
C
C    PIE = 4.0D0 * ATAN(1.0D0)
C    DN = DFLOAT(N)
C
C*   CLEAN ARRAY WAVE
C    DO 10 I = 1, N
C      WAVE(I) = 0.0D0
C    10 CONTINUE
C
C    DO 20 I = 1, N / 2 + 1
C      K = I - 1
C      WAVE(I) = 2.0D0 * PIE * DFLOAT(K) / (DN*SAMP)
C    20 CONTINUE
C
C    DO 30 I = N / 2 + 2, N
C      K = N - (I - 1)
C      WAVE(I) = 2.0D0 * PIE * DFLOAT(K) / (DN*SAMP)
C    30 CONTINUE
C
C    RETURN
C    END
```