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EVOLUTION OF THE YORKSHIRE, SOLE PIT AND
EAST MIDLAND BASIN SYSTEM, U.K.

by

Anthony David George Dixon

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A thesis submitted for the degree of Doctor of Philosophy
at the Department of Geological Sciences, University of Durham.



- 9 MAR 1990

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ABSTRACT

The objective of this study is to examine the thermo-mechanical evolution of the Yorkshire(Cleveland), Sole Pit and East Midland Basins, Southern North Sea using theoretical models of basin formation(subsidence) and basin destruction(inversion).

Subsidence occurs in response to a driving tectonic force and is amplified by the input of sediments, which impart a load on the lithosphere. The form of subsidence varies depending on the degree of crustal and sub-crustal involvement. In order to isolate this driving tectonic subsidence the loading effect of the sediments is removed by backstripping. Intrinsic to the accurate modelling of basin formation using this method are firstly, the presence of a complete sedimentary sequence representing the maximum load on the basement and secondly, a normal and representative compaction trend.

Subsidence in the Yorkshire, Sole Pit and East Midland Basins was terminated in the late Cretaceous-early Tertiary by inversion. This inversion is demonstrated to have been controlled by pre-existing structures and accommodated differentially within the Yorkshire and Sole Pit Basins in the form of basement uplift and shortening. A significant proportion of the sediments was removed by this uplift. This is quantified by studying compaction trends and is used to reconstruct the basin configuration prior to inversion to facilitate modelling of basin formation.

The patterns of subsidence appear to conform well to those predicted by a model of simple lithospheric stretching with a rapid initial subsidence followed by more gentle thermal and flexural subsidence. Superimposed on this background subsidence are discrete events which appear to be related to periods of active faulting or increases in regional loading(eustatic). Subsidence, like inversion, occurs differentially within the fault bounded margins of the Yorkshire and Sole Pit Basins. The relationship between faults at different crustal levels is complicated by stress partitioning by Permo-Triassic salt horizons, yet it does appear that reactivation of Carboniferous and older structures has influenced the geological evolution of these basins.

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ENCLOSURE BOREHOLE LOCALITY MAP.(MAP 1)

CHAPTER 1

INTRODUCTION

The Yorkshire, Sole Pit and East Midland Basins make up three separate structural units within the western margin of the continental Southern North Sea Basin (figure 1.1). The main area of study is bound to the north by the approximate trend of latitude $55^{\circ}N$, to the west by the English Pennines, to the south by the London Brabant Platform and to the east by the trend of longitude $2.5^{\circ}E$ (figure 1.2). Within these bounds lies a complex development of basins which subsided and inverted differentially, and which represent the variable localised structural responses to regional tectonic stresses in the continental lithosphere.

The region has been the subject of much geological interest, particularly in recent years as exploration has intensified. This introduction will outline the general structure, stratigraphy and sedimentology but the reader is referred to the following contributions for further information. For the onshore Yorkshire and East Midland Basins; Tate and Blake, 1876; Lees and Cox, 1937; Arkell, 1947; Falcon and Kent, 1950; Jeans, 1973; Smith, 1974; Hemingway, 1974; Neale, 1974; Kent, 1974, 1980. For the offshore Yorkshire, Sole Pit and East Midland Basins; Dingle, 1971; Ziegler, 1977, 1978, 1981, 1987; Glennie and Boegner, 1981; Van Hoorn, 1987. Additionally, much geological data, particularly stratigraphic data in the form of publicly accessible borehole records, are held at the Department of Energy, London. The latter forms the major and comprehensive data source for this research (map 1). From map 1, it can be seen that this provides a high level of constraint on the geological development of the basins, which facilitates study of the area as a whole.

1.1. General Geology.



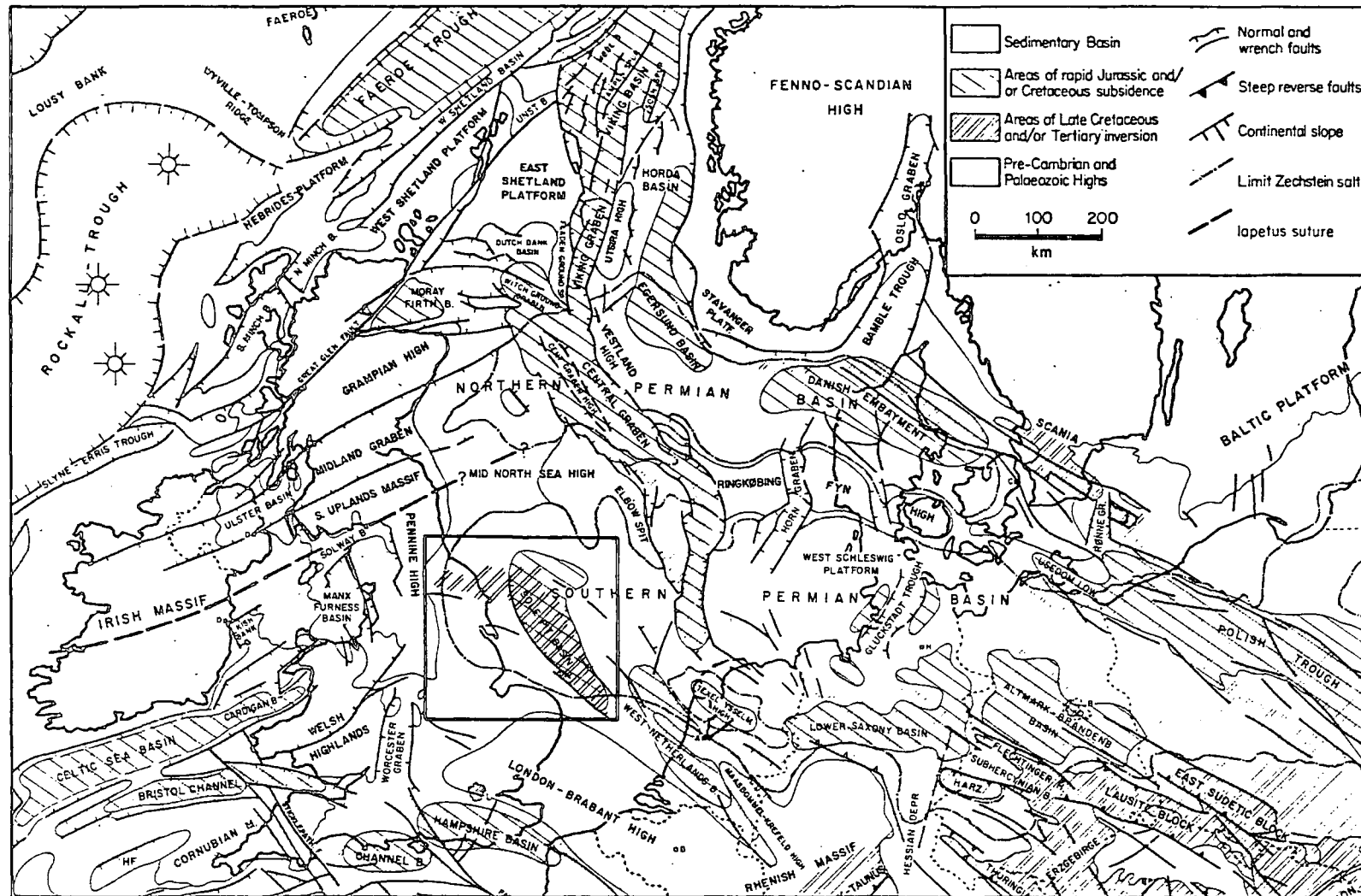


Figure 1.1. Regional geology of north-west Europe including the extent of the study area. (from Glennie, 1984)

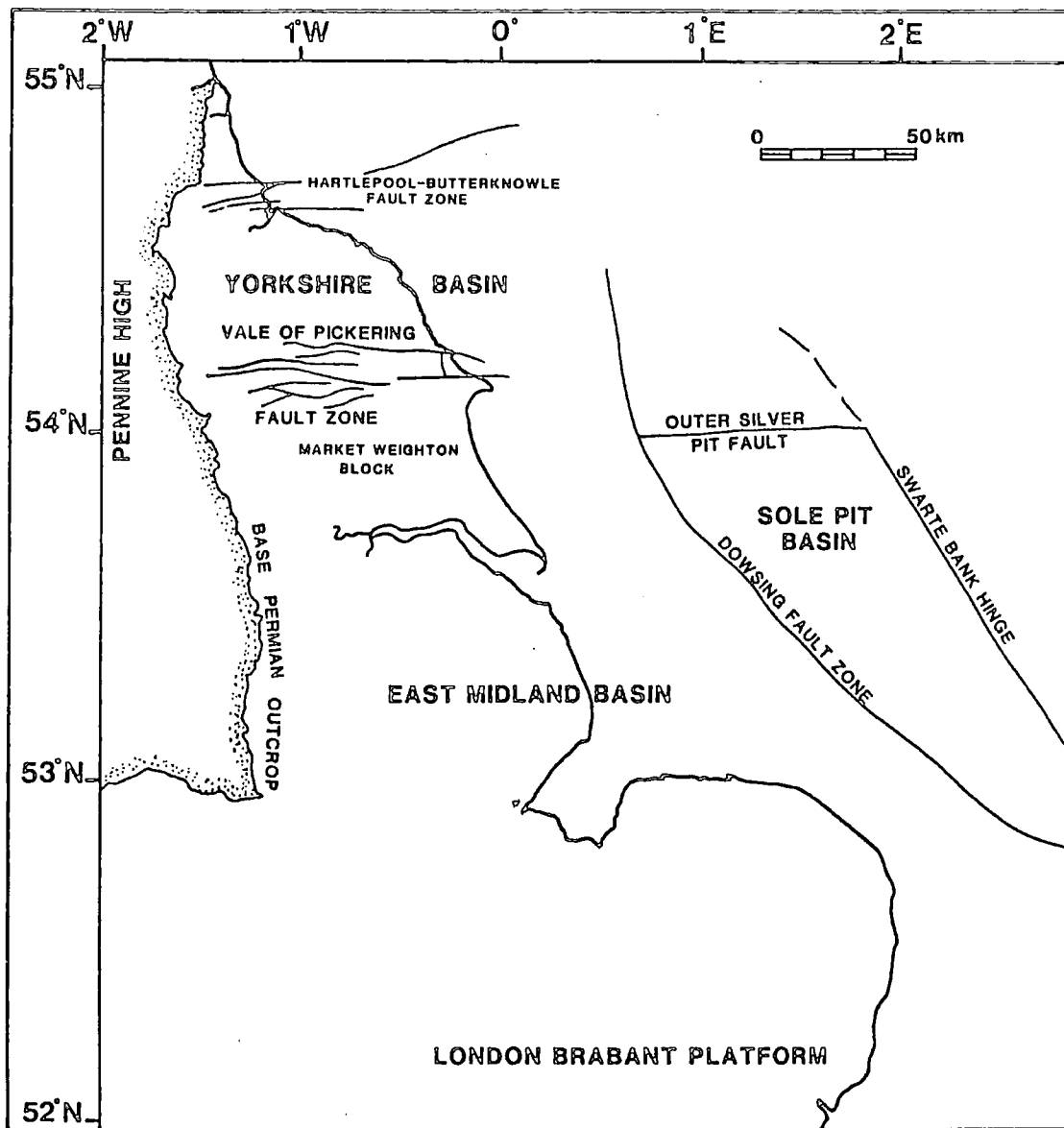


Figure 1.2. Major tectonic features and relative positioning of the Yorkshire, Sole Pit and East Midland Basins.

The study area contains three main basins separated by a number of discrete fault zones and structural highs (figure 1.2). The fault zones have had significant control on the relative positioning of the basins and the major structural events to affect them.

The Yorkshire, Sole Pit and East Midland Basins were initiated in the late Palaeozoic on a basement comprised mainly of Carboniferous sediments (figure 1.3). In the south of the region, Lower Palaeozoic to Pre-Cambrian meta-sediments and intrusives form the basement (figure 1.3). The basins subsided from the Permian to the end of the Cretaceous (figure 1.4). The sedimentological relationships between the basins are similar (figure 1.4), but each subsided differentially causing large variations in sedimentary thicknesses. Present sedimentary thicknesses are of the order of 1.1-2.5 km in the Yorkshire Basin, 0.8-2.5 Km in the East Midland Basin, and 2.5-3.4 km in the Sole Pit Basin. These differences not only represent the differential subsidence but also the magnitude of inversion which has removed a proportion of Jurassic and Cretaceous sediments from the Yorkshire and Sole Pit Basins specifically.

Rifting in the North Sea is believed to have commenced in the Permian to early Triassic (Sclater and Christie, 1980; Glennie, 1984). Onset of subsidence is marked by the Rotliegendes sandstones which thicken offshore towards the centre of the Southern North Sea Basin. Major flooding of the area by the Zechstein sea occurred before deposition in a mainly non-marine, continental environment in the Triassic (Warrington, 1974). Coarser and more sandy Triassic deposits in the Yorkshire and East Midland Basins suggest the close proximity of a hinterland source area, whilst sediments become more shaley eastwards including some marine incursions eg. Muschelkalk (Rhys, 1974; Anderton et al, 1979). The Rhaetian marked the change from a continental to a marine environment that was to continue for the majority of the subsidence history of the basins. The Yorkshire and

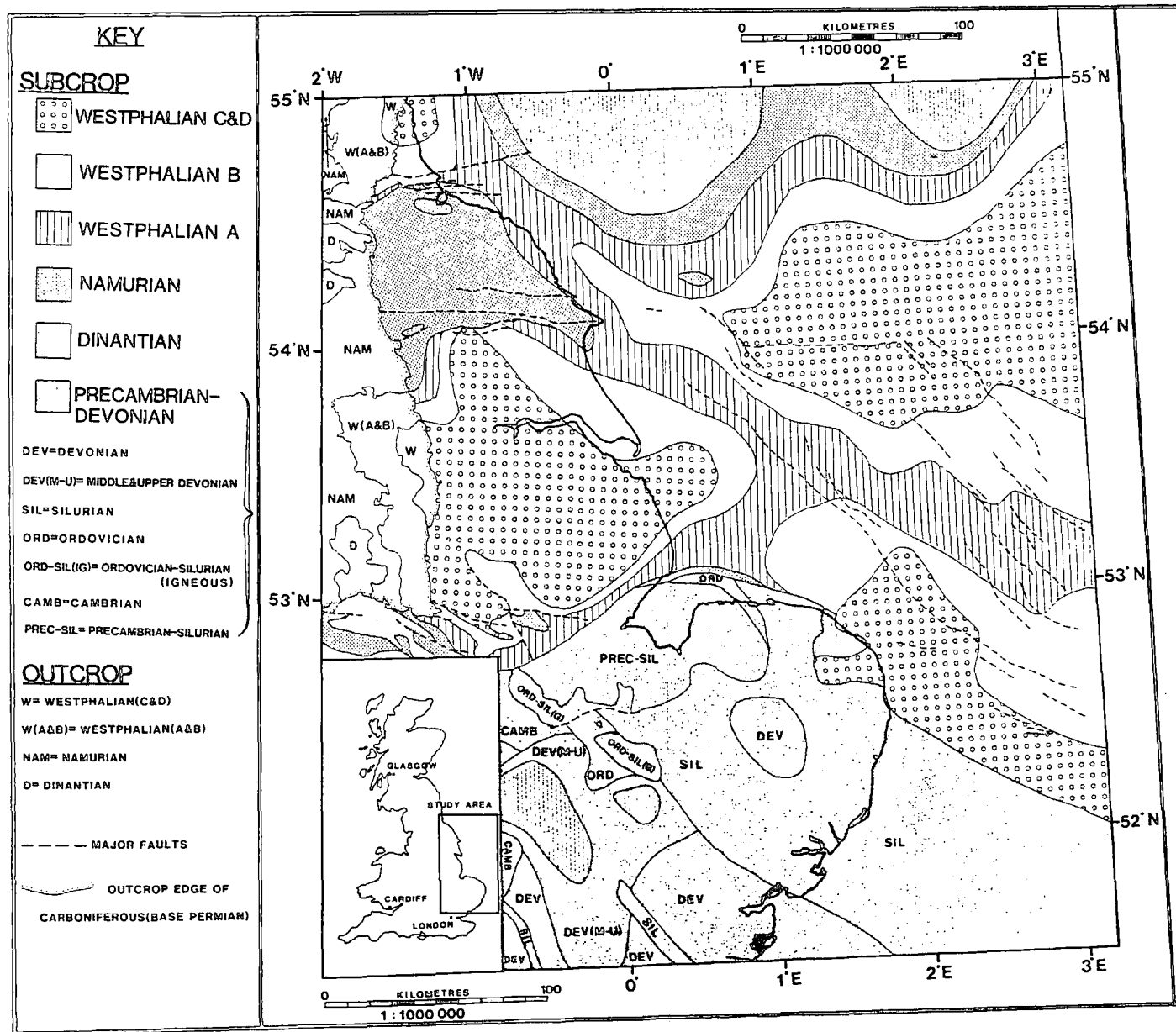


Figure 1.3. Pre-Permian basement map of the Yorkshire, Sole Pit and East Midland Basins

		YORKSHIRE BASIN	EAST MIDLAND BASIN	SOUTHERN NORTH SEA BASIN	
	TERTIARY	Cleveland Dyke	? ?	? ?	T
CRETACEOUS	MAASTRICHTIAN				CRETACEOUS
	CAMPANIAN				
	SANTONIAN				
	CONIACIAN			CHALK GROUP	
	TURONIAN				
	CENOMANIAN	CHALK	CHALK		
	ALBIAN	Red Chalk Spilton Clay	Red Chalk Carleton Suttonby Marl Skewness Clay Fullby Bodo		
	APTIAN				
	BARREMIAN		Toohey Bodo	CROMER KNOLL GROUP	
	HAUTERIVIAN				
JURASSIC	VALANGINIAN		Claxby Ironstone Spilby Sandstone		JURASSIC
	RYAZANIAN	Speeton Clay			
	TITHONIAN		Spilby Sandstone Kimberidge Clay		
	KIMMERIDGIAN	Kimberidge Clay		HUMBER GROUP	
	OXFORDIAN	Amphill Clay Corallian Limestone Oxford Clay	Amphill Clay Oxford Clay		
	CALLOVIAN	Hackness Rock Kellaways Cornbrash	Oxford Clay Kellaways Cornbrash		
	BATHONIAN		Blisworth Clay Great Oolite/Sandy Bodo Upper Estuarine Series		
	BAJOCIAN	Scalby Formation Scarborough Formation Cloughton Formation Eller Beck Formation Saltwick Formation Dogger	Lincolnshire Limestone Grantham Formation Dogger	WEST SOLE GROUP	
	AALENIAN				
	TOARCIAN	Blea Wyke Beds striatulus Shale Peak Shale Alum Shale Jel Rock Grey Shale			
	PLIENSCHACHIAN	Cleveland Ironstone Stalthea Formation Ironstone Shale	mudstone Marlstone Rock mudstone Pecten Ironstone mudstone	LIAS GROUP	
	SINEMURIAN	Pyritic Shale Siliceous Shale	Frodingham Ironstone mudstone/limestone Hydraulic limestone		
	HETTANGIAN	Calcareous Shale			
TRIASSIC	RHAETIAN	Rhaetic	Rhaetic	Winterton Formation	TRIASSIC
	NORIAN				
	CARNIAN	Keuper Shale	Keuper Shale	Kouper	
	LADINIAN			Muschoalkalk	
	ANISIAN	Upper Bunter Shale Bunter Sandstone Lower Bunter Shale Saliferous Marl evaporites	Bunter (Sherwood) Sandstone conglomerates Lower Bunter Shale	Upper Bunter Shale Bunter Sandstone Lower Bunter Shale Saliferous Marl evaporites	
	SCYTHIAN				
PERMIAN		Upper Magnesian Limestone evaporites	evaporites Upper Magnesian Limestone Middle Marls	Upper Magnesian Limestone evaporites	PERMIAN
		Lower Magnesian Limestone Marl Slate	Lower Magnesian Limestone Marl Slate	Lower Magnesian Limestone Marl Slate	
		Yellow Sandstone	Yellow Sandstone	Yellow Sandstone	
				Raillogend Sandstone	

Figure 1.4. Regional stratigraphy of the Yorkshire Basin, East Midland Basin, and offshore Southern North Sea Basin, including the Sole Pit Basin (after Rhys, 1974, Kent, 1980, Woollam and Riding, 1983)

Sole Pit Basins began to subside differentially in the Lower Jurassic with respect to the East Midland Basin. In the Middle Jurassic, rifting and basin flank uplift occurred in the Central North Sea (Leeder, 1983) producing source lands which fed delta systems to the north and south. This resulted in the Brent deposits in the Northern North Sea and the Middle Jurassic deltaic deposits characteristic of the Yorkshire Basin (figure 1.4). Much of the post-Lower Jurassic sedimentological data has been removed from the Sole Pit Basin by erosion. Subsidence continued into the Upper Jurassic to Lower Cretaceous, which appears to have been a period of fault controlled subsidence in the Yorkshire Basin (Jeans, 1973; Kent, 1974). This marked the end of differential subsidence and the onset of regional subsidence and deposition of the chalk in the Upper Cretaceous. Coincident with this is a marked rise in eustatic sea-level (Hays and Pitman, 1973; Vail et al, 1977; Pitman, 1978; Hallam, 1984). Late Cretaceous to early Tertiary compression associated with Alpine Orogenic plate collisions caused inversion, uplift and cessation of subsidence. Tertiary sediments are preserved over the London Brabant Platform (see Chapter 5, section 5.5) and a west-northwest to east-southeast Tertiary dyke, the Cleveland Dyke, transects the Yorkshire Basin.

1.2. Aims and Objectives.

Before assessing the objectives of this thesis, how they can be achieved and the specific peculiarities of the three above basins that warrants this research, the following points outline the main reasons why this study addresses the evolution of all three basins as opposed to one individual basin in the same context-

1. The extent of the basins forms the majority of the UK sector of the Southern North Sea Basin and hence research into their local and regional evolution is of interest to industry and academia alike.
2. The main data base, ie. published borehole records, provides comprehensive



coverage of all three basins.

3. The basins have a similar sedimentological evolution and have not been individual, subsiding units for their entire existence.
4. They are identified as three individual basins but neighbour each other and share the same major structural features. These basins have evolved within the main Southern North Sea Basin. Modelling their development may have important consequences for understanding the regional mechanisms controlling basin evolution.
5. Similarly it is important to study each basin's individual evolution and to assess how regional tectonic deformation is accommodated locally.
6. Identifying regional and/or compartmentalised deformation has important consequences for understanding the mechanisms of, for example, basin formation and basin inversion.

Despite much work in this study area, qualitative and quantitative modelling of the detailed local and regional forms of subsidence has not been accomplished. Many recent studies of the evolution of basins have addressed the problems of basin formation, and in particular, the application of theoretical models of basin formation mechanisms (basin kinematics) to real geological examples. However, all of these studies have been applied to areas where the present sedimentological configuration represents the entire record of subsidence. Therefore, the inverted Yorkshire and Sole Pit Basins, and to a lesser extent the East Midland Basin, provides a situation where the present sedimentological configuration not only records some of the subsidence history but also the intensity of basin destruction. This research assesses how basin formation modelling can be applied to inverted basins.

The overriding objective of this thesis is to provide a comprehensive analysis of the evolution of the Yorkshire, Sole Pit and East Midland Basins, including their pre-, syn-, and post-subsidence development. Within this title, a number of specific problems will be addressed. Basin analysis involves the integration and application of multiple data sets and techniques for furthering understanding of the structural and sedimentological evolution of a basin or basins. Utilized in this basin analysis study are field data, remote sensing data and techniques, seismic data, petrophysical borehole data, stratigraphic borehole data, and thermo-mechanical modelling techniques for application to basin formation and inversion. These data and techniques are employed to provide valuable information about the evolution of the basins, and also so that the applicability of such methods can be assessed with respect to the particular geological problems being addressed.

This study addresses four main topics:-

1. The application of a multidisciplinary approach for analysis of the tectonic, structural and sedimentological evolution of the Yorkshire, Sole Pit and East Midland Basins.
2. The application of theoretical models for basin formation to the observed development of the Yorkshire, Sole Pit and East Midland Basins.
3. The quantitative and qualitative analysis of basin inversion and its affects on the structural evolution of the Yorkshire, Sole Pit and East Midland Basins.
4. Modelling of the detailed burial history and subsequent maturation potential of hydrocarbon source rocks in the Yorkshire, Sole Pit and East Midland Basins. That is, the economic significance of the three aforementioned research topics.

Chapter 2 constitutes an appraisal of the potential and applications of remote

sensing for lithological and structural mapping in the Yorkshire Basin. The results are correlated with studies of basins of similar age, structure and sedimentology in Southern England, namely the Wessex and Weald Basins. The East Midland Basin was not studied due to unavailability of remote sensing data but its subdued geomorphology and lack of structural deformation relative to the Yorkshire Basin makes its study less appropriate. The Sole Pit Basin was not studied as it is completely submerged. Lithological mapping is shown to be relatively unsuccessful but the results do provide an interesting insight into the applicability of different satellite systems for such studies in the UK environment. Lineament analysis provides good results for detecting the regional and local structural grain within basins and for identifying previously unrecognised fracture systems. They constitute a useful additional component for integration with other data sets eg. field data, seismic data, to establish a comprehensive and detailed appraisal of the structural evolution of the area.

To date no research has been done into how the tectonic, structural and sedimentological evolution of the Yorkshire, Sole Pit and East Midland Basins, both collectively and individually, can be accommodated into a theoretical model for basin formation. Basin formation models have been developed to isolate and explain the tectonic forces that initiate subsidence (Sleep, 1971; Falvey, 1974; McKenzie, 1978; Royden et al, 1980, 1983; Royden and Keen, 1980). The reasoning behind and implications of these models will be discussed briefly in Chapter 4. It is established that McKenzie's (1978) model is the most applicable to observed geological subsidence histories in intra-cratonic and rifted basins. The model assumes that subsidence is initiated by lithospheric stretching, extension or attenuation. This is a mechanism readily explained and observed by stress imparted on the lithosphere by plate tectonics. The parameter β quantifies the amount of stretching, and is constant throughout the lithosphere. The observed subsidence in the intra-cratonic Yorkshire, Sole Pit and East Midland Basins is

correlated with McKenzie's model for uniform lithospheric stretching.

McKenzie's model predicts that the driving tectonic subsidence of the basement, initiated by lithospheric stretching, will constitute two main components; an initial, instantaneous fault controlled subsidence during rifting, followed by a regional, exponentially decreasing subsidence in response to lithospheric cooling and thermal re-equilibration. To isolate the driving tectonic subsidence in the basins the affect of sedimentary loading, which imparts an additional component of basement subsidence, must be compensated for (Watts and Ryan, 1976; Steckler and Watts, 1978). Then, comparisons can be made with the theoretically modelled tectonic subsidence curves. This creates a major problem if one wants to employ such a method to the Yorkshire, Sole Pit and East Midland Basins. Erosion due to basin uplift and inversion has removed a significant component of the syn-rift and post-rift sediments. The present load imparted by the sediments on the basement is therefore not the maximum. Consequently, the driving tectonic subsidence observed in the basins will be non-representative of the mechanism of basin formation and will be severely truncated.

To accomodate for this and to provide a quantitative analysis of some of the deformation associated with basin inversion, a detailed study of the amount of sediment removed from the area was considered imperative. Chapter 3 describes the detailed procedure employed. Previous workers (Marie, 1975; Hemingway and Riddler, 1982) have attempted to predict the regional maxima of sediment lost. However, because of the large area being studied and the structural and sedimentological variations within it, a more detailed appraisal of the local and regional amounts of removed overburden was warranted. This was done so that basin formation modelling techniques would be applied to stratigraphic sequences that had been individually compensated for the magnitude of deformation in that specific area. Physical changes eg. porosity, in sediments during compaction are

both depth and lithologically dependent. Using sonic velocity logs, interval transit time and porosity data were collected to produce observed compaction trends for a large suite of formations and lithologies. These were compared to predicted compaction trends and a finite value of uplift was quantified.

This procedure has another application. The sedimentary load computed by backstripping is calculated using sediment density variations from the porosity curve. In inverted basins the normal porosity curve has been offset, which will introduce errors into such a calculation. Compensating for the amount of uplift allowed the observed porosity curves to be reset prior to backstripping.

Thus, the observed tectonic driving subsidence in the Yorkshire, Sole Pit and East Midland Basins is assumed to be representative of their pre-inversion subsidence history. Chapter 4 describes the basin formation modelling carried on the study area using over 170 boreholes. The observed tectonic subsidence was modelled to isolate the significance of mechanical and thermal subsidence during basin formation. This reflects the relative influences of the brittle and ductile components (crustal and sub-crustal) of the lithosphere during stretching and extension. Recent studies (Royden and Keen; Royden et al; op. cit.) have predicted, from observations within basins, that lithospheric stretching may be depth-dependent and not uniform. This will be revealed in the form of the observed tectonic subsidence curves, and the nature and magnitude of extensional, fault controlled subsidence in the basin. To account for this, a depth-dependent stretching model was applied to the data.

The results imply that the theoretical tectonic subsidence curves for simple, uniform lithospheric stretching correlate well with the majority of subsidence curves in the Yorkshire, Sole Pit and East Midland Basins. The form of the curves is consistent across the three basins. It predicts a significant rapid initial subsidence in the late Permian to early Triassic followed by more gentle, thermal-type

subsidence to the end of the Cretaceous. The secondary stage of subsidence is punctuated by a number of small subsidence events. These are analysed with relation to specific additional pulses of lithospheric or crustal extension and eustatic sea-level fluctuations. Not only do the tectonic subsidence curves closely fit the theoretical model, but also the regional distribution of sediments reflects the characteristic syn-rift and post-rift stages of subsidence. This study is supplemented by seismic data (British Petroleum) which reveals some of the structural controls on basin formation. Simple calculation of extension from fault offsets is found to be similar to that predicted by the model (β).

Lithospheric flexure is not accounted for in the modelling but its effects on the observed subsidence are discussed. Application of the depth-dependent stretching model was largely unsuccessful. However, severe inversion, specifically in the Sole Pit Basin, makes the correlation between the predicted and observed tectonic subsidence difficult.

Chapter 5 investigates further, the deformation effects of inversion. The total basement uplift (removed overburden) recognised in Chapter 3 is one component of the localised crustal deformation in response to large scale lithospheric compression and shortening. The form of the inversion in the study area is modelled and the contributions of total uplift, tectonic uplift and lithospheric/crustal shortening are quantified and appraised. These results are assessed with respect to their regional distribution and relationship to the major structural controls on the basins. The local and regional accommodation of stress during basin inversion is investigated using the above data, field examples of the brittle accommodation of fault reactivation, mapped faults, and lineament or fracture patterns from remote sensing analysis.

The data, methods and results from the above research are integrated into a study of:-

1. The potential of the methods used to hydrocarbon exploration.
2. The maturation potential of hydrocarbon source rocks in the basins.

Although remote sensing methods have been used to define structural traps from lineament analysis and hydrocarbon see pages from geobotanical mapping, its applicability in the context of this study has not been considered. Chapter 6 implements data from Chapters 3, 4 and 5 to assess the detailed burial and hence thermal history of specific source rocks in the Yorkshire, Sole Pit and East Midland Basins. The study is a two-fold appraisal of:-

1. The maximum burial depth of source rocks.
2. The time and temperature burial history of source rocks.

The results assess the economic significance of source rocks in the study area and stress the importance of reconstructing both the original basin configuration prior to inversion, and the detailed thermal evolution of the lithosphere during basin formation.

Chapter 7 outlines the major conclusions of this thesis. Appendices C3 and C4 represent regression analyses of porosity data for Chapter 3 and backstripped tectonic subsidence curves for Chapter 4 respectively.

CHAPTER 2

SATELLITE REMOTE SENSING AND BASIN ANALYSIS

2.1 Introduction.

Basin analysis is interpreted as a multidisciplinary study which utilizes all the tools available that may contribute to the greater understanding of the evolutionary history of a basin. These include geological fieldwork, geophysical techniques such as seismic, gravity and magnetic surveying and more recently remote sensing. Integration of such data sets provides a substantial basis for the structural and sedimentological evaluation of a sedimentary basin.

Remote sensing has traditionally been regarded as a tool by which reconnaissance or preliminary geological surveys can be made. As techniques and systems improve, remote sensing is becoming a vital tool in frontier exploration for both hydrocarbons and minerals (Feder and Penfield, 1985; McCoy et al, 1986; Crawford, 1986; Rowan et al, 1974; Blodget et al, 1978; Goetz et al, 1985). The limitations of remote sensing for basin analysis relate principally to the types of sensor available, the type of basin that is being studied (passive margin, intra-continental), the degree of structural deformation of the basin and the environmental setting which will control such things as vegetation and drainage.

The following discussion highlights the advantages and limitations of remote sensing for basin analysis in the British Isles.

Optically processed Seasat Synthetic Aperture Radar (SAR), Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) imagery together with digitally processed Seasat SAR and TM imagery were utilised in a study of their

potential for lithological and structural mapping in three major onshore Late Palaeozoic to Tertiary basins of England, namely the Yorkshire (Cleveland) Basin, Wessex Basin, and Weald Basin (figure 2.1). These basins have similar geological histories, with subsidence from Permian (Triassic in the Weald Basin) to Upper Cretaceous-Lower Tertiary and subsequent inversion and uplift which has resulted in partial destruction of the original basins. The aim of this study is to appraise the structural and lithological characteristics displayed in the imagery and critically assess the results with respect to the relative benefits they lend to the understanding of the geological development of each basin.

2.2 Objectives.

- A. To investigate the suitability of various satellite systems for basin analysis in the U.K.
- B. To investigate the application of digital processing techniques for enhancement of geological features.
- C. Examine imagery for lineaments and determine their significance:-
 - mapped faults
 - unmapped faults
 - topographic lineaments eg: hills, ridges or valleys which may or may not be geologically significant.
 - other lineaments eg: vegetation contrast, drainage alignment.
- D. Analyse lineament/fracture pattern in the context of the tectonic setting of the basin.

It has been shown that remote sensing data from various satellite systems have

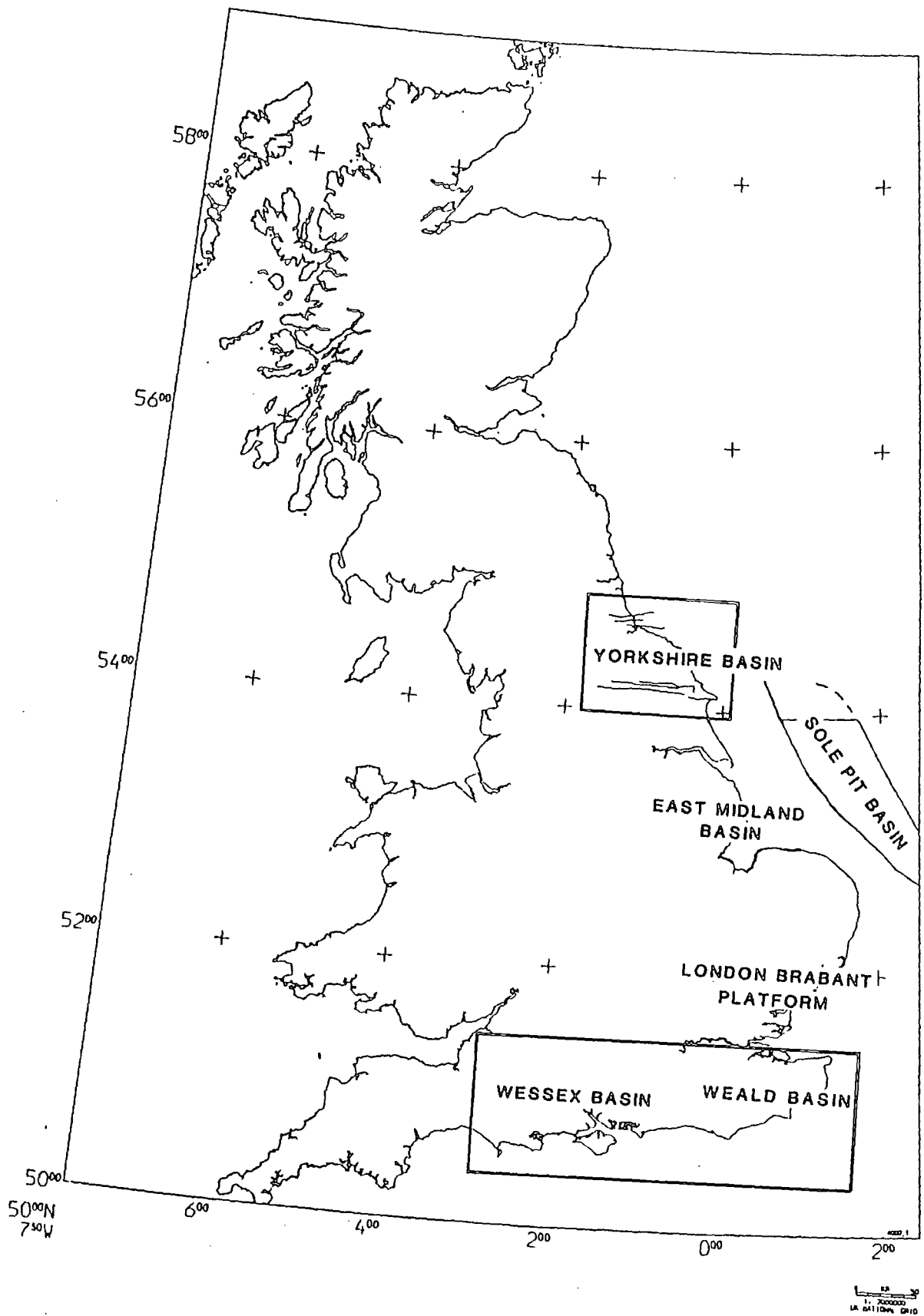


Figure 2.1. Relative positions of late Palaeozoic-Mesozoic basins investigated in geological remote sensing study.

considerable potential for geological studies in a variety of terrains at both local and regional scales (Vincent 1980, Elachi 1980, McDonald et al 1978, Ford 1980, Blom and Elachi 1981). Accordingly, the following results assess the potential for both large scale, regional studies, using selected subscenes from optical and particularly digital images. The potential of each satellite system to highlight geological and geomorphological features will also vary due to their different specifications. Important differences include their relative resolutions, the wavelength they are monitoring and whether the system is active ie. transmits and receives its own energy source (Seasat SAR), or passive ie. receives reflected radiation (Landsat).

In order to further the knowledge of the structure of the three basins, and to experiment with digital processing techniques for enhancing geological structures, a comprehensive lineament analysis of each area, using the optical and digital data, was undertaken. Analysis involves measuring lineament frequencies, lengths and orientations, and comparisons are made between the various data sets. Lineament maps are thoroughly screened eg. for roads, and conclusions drawn in careful consideration of the postulated tectonic evolution of each basin. In sedimentary basins, large and small scale lineaments occur such as faults, joints, folds, shear zones and lithological contrasts. Blanchet (1957) considered the large scale features to have been generated at, or below the level of the basement and that small scale features were probably controlled by and directly related to basin structure. Berger (1985) described the potential of remote sensing for identification of lineament fracture patterns which are the manifestation of reactivated structures during basin formation and destruction. The reactivation of structures in time has been suggested to be important to the development of the Yorkshire, Weald and Wessex Basins (Melville and Freshney 1982, Dewey 1982, Whittaker and Chadwick 1984). Major basement related structures have been identified in the images sampled.

Basin analysis requires that one not only attempts to recognise and interpret geological events within an individual basin but also correlates them with neighbouring basins in a regional tectonic context. This study researches the potential for remote sensing in the Yorkshire, Wessex and Weald Basins of the north-east, south and south-east of England respectively (figure 2.1). Other basin analysis techniques such as backstripping (Chapter 4), are also used to correlate the geological history of the Yorkshire Basin (in particular its thermo-mechanical evolution) with other basins such as the Sole Pit, East Midland, Wessex, Weald and Central North Sea Basins. Integration of such techniques enhances understanding of the local and regional geological evolution of an area.

The data from all satellite systems employed in this study were used to identify and enhance major and minor structures in the basins, and to examine the potential of the remote sensing techniques as a tool for understanding the tectonics of relatively undeformed, structurally simple sedimentary basins.

2.3 Satellite Systems and Data Used.

The three satellite systems used are:

1. Seasat Synthetic Aperture Radar (SAR)
2. Landsat Multispectral Scanner (MSS)
3. Landsat Thematic Mapper (TM)

Imagery from these particular satellite systems is used because they are readily available to the academic fraternity and provide comprehensive coverage of the onshore and offshore United Kingdom

2.3.1. Seasat SAR.

The Seasat 1 satellite was launched in 1978 to an 800km altitude and gave

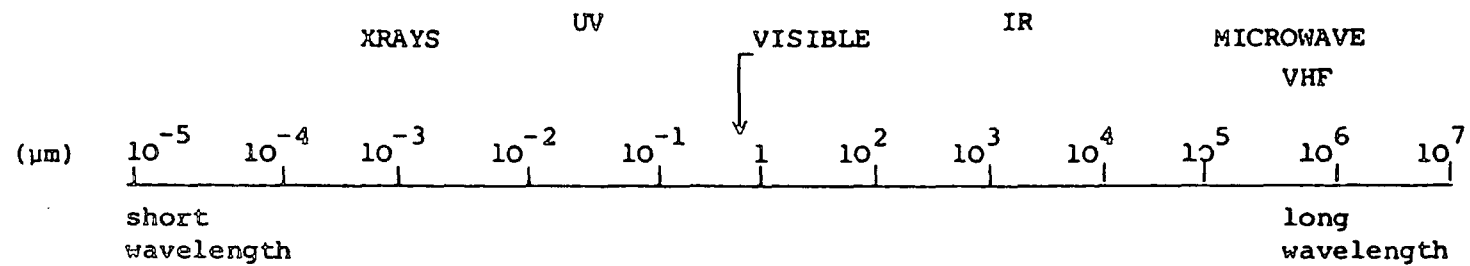
continuous coverage, independent of the weather, of both land and sea at a spatial resolution of 25m. The Seasat system actively transmitted microwave radiation (figure 2.2) and measured the response from the target media. This response is related to two sets of parameters; one concerning the nature of the terrain, and the second concerning the characteristics of the system itself.

Terrain parameters include di-electric properties of the medium, surface roughness and topography. Of these surface roughness is the most significant in determining the nature and intensity of the backscattered radiation. Surface roughness can be measured at various scales, eg. micro-relief, to large scale topographic variations. Rough surfaces and corner reflectors eg. cliffs, ridges, give good returns in all directions, whereas smooth surfaces act like a mirror and reflect radiation strongly but not necessarily back to the satellite sensor.

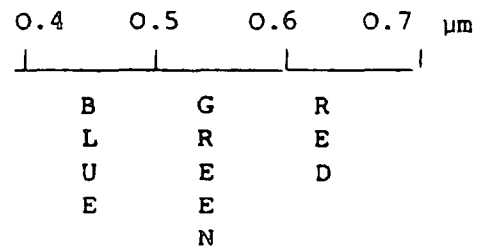
System parameters include the look-direction and incidence angle of the radar. A major control on the response is the relative positioning of the satellite (look-direction) with respect to topographic trends, such that lineaments perpendicular to the look- or illumination direction are preferentially selected, whilst those close or parallel to it are suppressed. This can obviously introduce a bias into a structural interpretation. To alleviate this problem digital images combining a number of look-directions have been used.

The interactions of the above parameters results in a characteristic spectral signature or texture that can be identified, mapped and interpreted on the image.

Interpretation is based on the tones and their textures, the context in which they appear in the image and their temporal variations. These may or may not be geologically significant, particularly in areas like the three basins concerned which are both well cultivated and vegetated terrains. McDonald et al (1978) said that although vegetation may obscure lithological and structural features, it may also



$1\mu\text{m} = \text{one micrometre} = 10^{-6}\text{m}$
 UV = ultraviolet IR = infrared



Visible spectrum from approx 0.4 to 0.7 μm .

Figure 2.2. Schematic representation of electro-magnetic radiation defined by wavelength

enhance them by geological preference or selectivity. This is assessed in both lithological and structural analyses of the study areas. Much of the information extracted from the images is based on the regional textural variation of tone and shape. The data is considered in the light of previous geological knowledge and experience.

Optically and digitally processed Seasat images are used and interpreted on a regional and local scale ^srepectively.

2.3.2. Landsat MSS

The Landsat MSS system was in orbit at 900km (variable), recorded reflected radiation between the visible and near infra-red part of the spectrum and gave a spatial resolution of about 80m. Reflected radiation was measured in 4 bands within the spectral range (0.5-1.1 μ m).

Optical images only were used, including a winter acquired scene of the Wessex and Weald Basins, which enhanced lineaments due to the low sun angle, and a summer colour composite image of the Yorkshire Basin area.

2.3.3. Landsat TM

The Landsat TM system orbiting at 705km, recorded spectral data (figure 2.2) in 6 bands at a resolution of 30m, and a thermal band at 120m resolution. Thus it provided more detailed spectral information than the MSS system, at a significantly higher spatial resolution. Data used includes an optically processed image of the Weald Basin and a digitally processed image of the Isle of Wight.

2.4. Geological Remote Sensing in the Yorkshire Basin.

The Yorkshire Basin formed on Carboniferous basement and subsided from Permian to Upper Cretaceous - Lower Tertiary times, after which, major base-

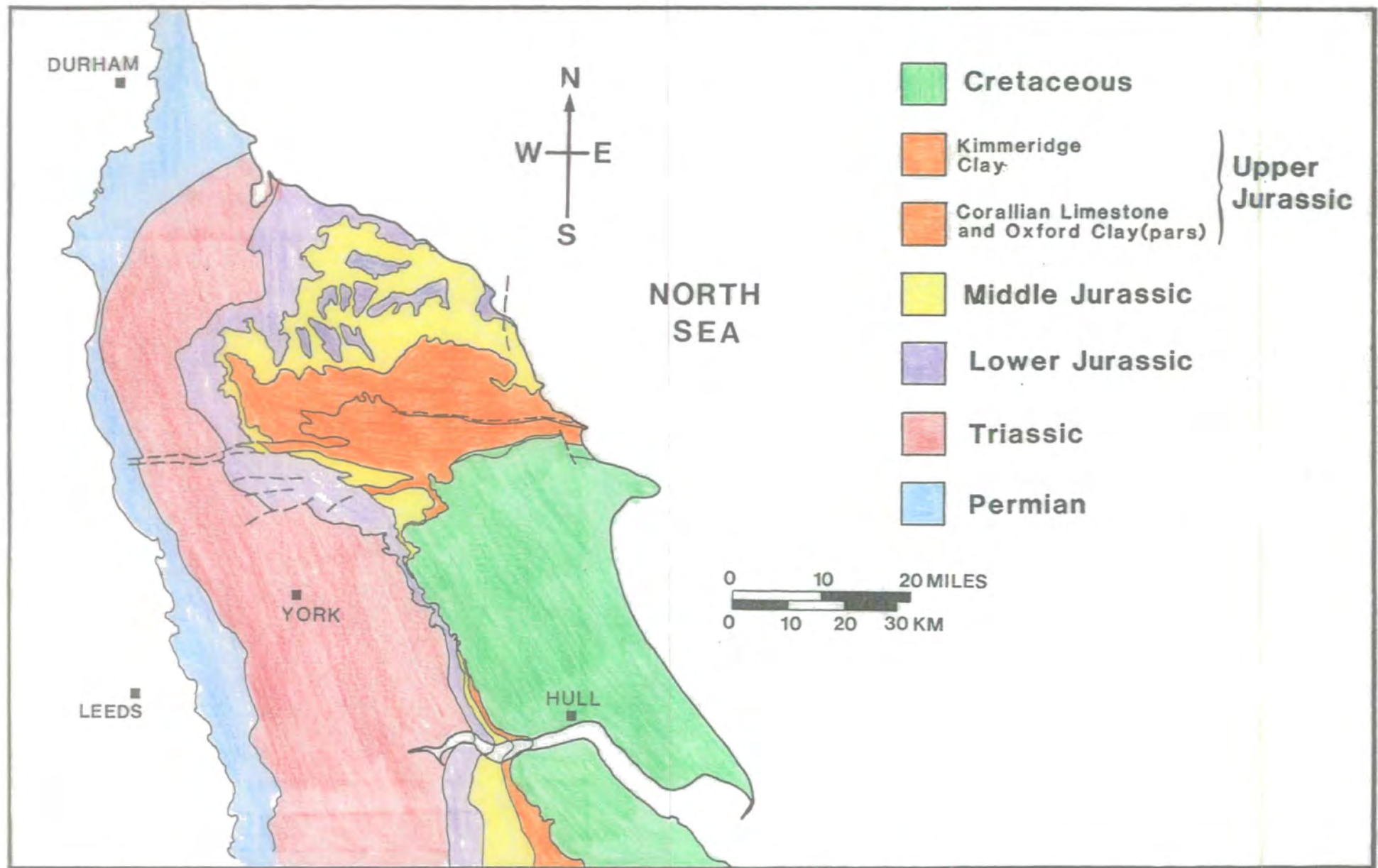


Figure 2.3. Geological map of the Yorkshire Basin.

ment uplift by inversion took place resulting in the present geological situation illustrated in figure 2.3 (Hemingway, 1974; Kent, 1980a). The general younging of exposed sediments towards the southern margin of the basin is postulated to reflect a deformation gradient during inversion within the basin. This may be reflected in the geographical positioning and intensity of the structures identified in the satellite imagery. Three major geomorphological provinces occur, namely the North Yorkshire Moors, Chalk Wolds and surrounding lowlands.

Textural or geomorphological units and lineaments identified in the imagery are assessed with respect to their structural and sedimentological significance in the Yorkshire Basin, and their tectonic significance regionally.

Optical Seasat and Landsat data and digital Seasat data were used in the study of the structure and lithology of the area.

Figure 2.4 shows a Landsat MSS colour composite image of the Yorkshire Basin. The image displays little detail to enable classification of structural and lithological features. Two main image units can be distinguished, the heather vegetated tops of the moorland (1 in figure 2.4) and the surrounding low lying areas (2 in figure 2.4).

The Seasat SAR imagery, described below, includes a regional analysis of the optical mosaic of the UK and a subscene from the north of the area, including both moorland and lowland, the location of which is outlined in figure 2.5. The locally abrupt geomorphological features of the Yorkshire Basin, including the expansive upland of the North Yorkshire Moors and relative lowland areas such as the Vale of Pickering and Vale of York were expected to yield good results from the Seasat SAR imagery (as compared with those from analysis of the Wessex and Weald Basins below), due to the strong response from slopes and changes of relief to the radar.

2.4.1. Optical Seasat SAR Imagery

Figure 2.6 represents the geological interpretation of the optical Seasat SAR mosaic. An interesting lineament pattern is established and a number of textural units identified, which may have geological significance. Four major units are identified.

- A. Unit 1 in figure 2.6 occupies a central area of high relief, characterised by strong (bright) returns from the steep vale sides, some shadowing of inclines facing away from the north-easterly look direction and a speckled light grey tone, characteristic of the natural moorland vegetation. This unit is typically underlain by Middle Jurassic sandstones and shales (figure 2.3). Figure 2.7 illustrates the characteristic vegetation and geomorphology of unit 1 in the field in the Yorkshire Basin.

To the south of unit 1, a sub-unit labelled 1a in figure 2.6 is identified. Unit 1a, although occupying relatively high ground, contrasts with the deeply incised topography associated with unit 1 on the moors, and coincides with a gradual change in texture to a more consistent mid grey tone. This unit forms a shallow plateau at the southern extent of the North Yorkshire Moors and it stretches from the coast in the east to the western limit of unit 1, where it turns southwards, enclaving unit 2 and apparently linking (in a textural and geomorphological sense) with unit 3 (figure 2.6). This sub-unit is consistent with the approximate outcrop of the Oxfordian (Corallian) limestones, although its southern extension appears to correspond to the outcrop of the Lower Jurassic to Oxfordian sediments, as they approach the basin margins at the Market Weighton Axis (figure 2.3). Figure 2.8 illustrates the characteristic vegetation and geomorphology of unit 1a in the field. Its contrast with unit 1 in figure 2.7 is clear.

- B. Unit 2 comprises an area of lowland with respect to units 1, 1a and 3 by which

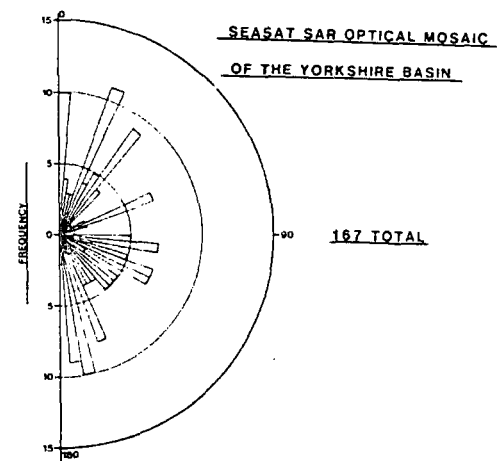
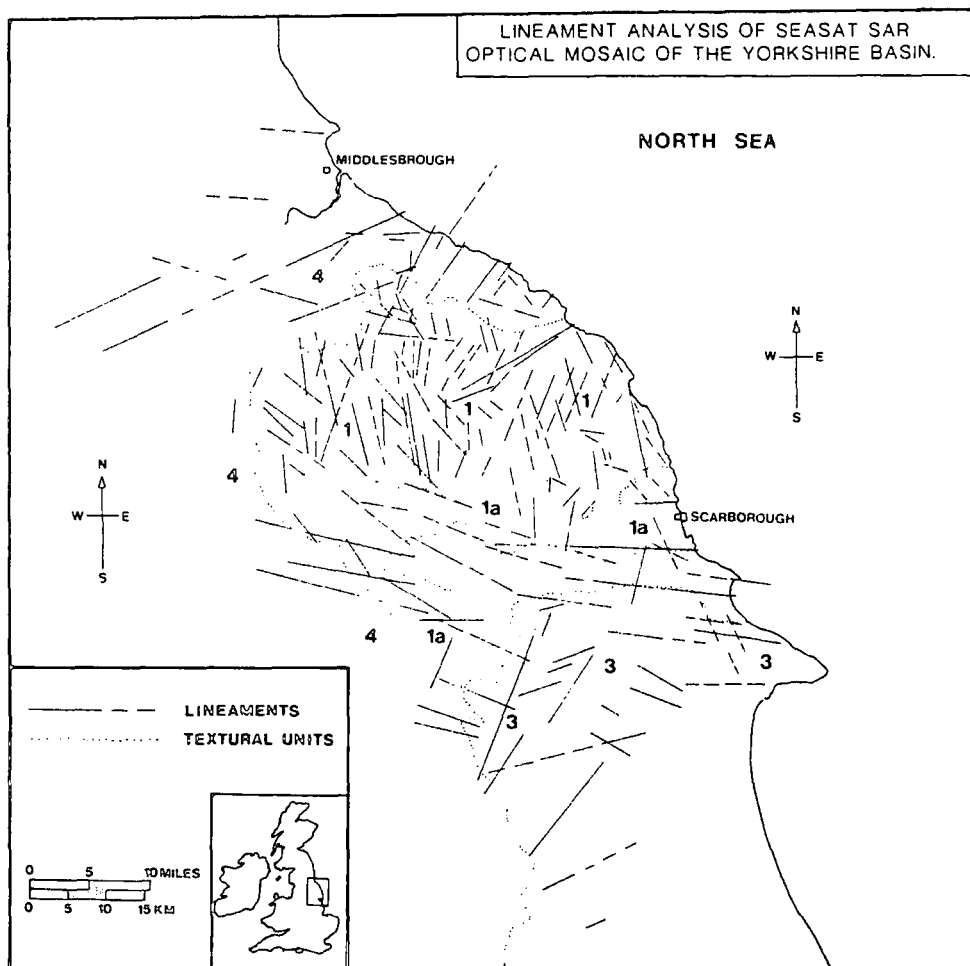


Figure 2.6. Lineament analysis and mapped textural units from optical Seasat SAR image of the Yorkshire Basin.

it is enclosed except for its coastal side. It displays a mid-grey tone which is very consistent through the whole extent of the unit and is due to the lack of internal geomorphology or relief. Its boundaries are thus represented by both a change in relief and texture with the surrounding units. Some subtle but extensive, east-west trending lineaments are detectable in unit 2 (figure 2.6) despite its low relief and quite extensive drift cover. These are also identified in the digitally processed data (figure 2.11). Unit 2 corresponds to the outcrop (subcrop) of the Kimmeridge Clay in the Vale of Pickering, which the unit defines (figure 2.3). This is illustrated in figure 2.9, which is taken from the low-lying, Kimmeridge Clay underlain Vale of Pickering looking south-westwards towards the uprising Chalk Wolds (unit 3 in figure 2.6).

C. Unit 3 (figure 2.6) is characterised by positive relief with respect to unit 2, although its boundary with unit 1a is difficult to distinguish, as discussed above. Dark tones and a strong agricultural overprint (fields) typify unit 3 which can be followed southwards to the Wash and East Anglia. Unit 3 corresponds to the outcrop of the Chalk (figure 2.3) and defines the Chalk Wolds of South Yorkshire and Lincolnshire. Its contrast with unit 2 is illustrated in figure 2.9.

D. Unit 4 (figure 2.6) in the western and northern margins of the area, contrasts strongly with the neighbouring high ground of units 1, 1a and 3. This unit is typified by a poor topographic response with medium to light grey tones. It has a diffuse but reasonably well cultivated, agricultural appearance. This unit corresponds to the outcrop of Lower Jurassic and Permo-Triassic sediments of, amongst other areas, the Vale of York in the west and South Teesside in the north (figure 2.3).

Detailed lithological mapping, such as that described in the Weald Basin below (section 2.10) , is not possible in the Yorkshire Basin using optical Seasat SAR imagery. However the results do depict major lithological contrasts which can be

classified in accordance with geomorphological, textural and tonal variations in the imagery.

2.4.2. Lineament Analysis

The lineament map and rose diagram (figure 2.6) display geologically significant trends with a high concentration of shorter lineaments being confined to the higher, geomorphologically distinct North Yorkshire Moors area (unit 1 in figure 2.6) and a smaller concentration of generally longer east-west trending lineaments expressed in the imagery to the north and south. This is probably due to a combination of a number of factors, including lithological contrasts, topographic expression of fractures and drift cover. It may also represent some tectonic variation within the area. The lineaments and their importance to the tectonic interpretation of the Yorkshire Basin will be discussed in section 2.5.

2.4.3. Digital Image Processing in the Yorkshire Basin

An attempt was made, using image processing techniques to improve the geological content of the satellite imagery. The subscene imaged (figure 2.5) includes the contrasting lowlands of South Teesside and the Vale of Pickering with the uplands of the North Yorkshire Moors. The subscene has been separated into two images, figure 2.10 enclosing Teesside and the northern extent of the moors and figure 2.11, enclosing the majority of the North Yorkshire Moors, the Vale of Pickering and part of the Chalk Wolds. Similar textural units to those on the optically processed images are identified and a number of faults/ lineaments become more identifiable (figures 2.10 and 2.11). Generally the digitally processed images provide more precise relationships between tone and texture which allow more precise recognition and interpretation of the geological features. Figure 2.10 displays little textural variation, the majority of the image depicting the relatively flat dipping, low lying Lower Jurassic and Permo-Triassic sediments similar

to unit 4 in figure 2.6. The feather edge of unit 2 in figure 2.6 is evident in the southern part of figure 2.10. Figure 2.11 displays much more information due to the contrasts between the geomorphological terrain represented in the image. Particularly evident are a number of discrete regions;

- A. Labelled 1 in figure 2.11 and corresponding to unit 1 in figure 2.6 for optical images. Figure 2.7, again, is the equivalent geomorphological unit in the field.
- B. Labelled 2 in figure 2.11 which corresponds with unit 1a in figure 2.6 but which is more readily identified as a distinct unit in the digital images. Figure 2.8 is the equivalent geomorphological unit in the field.
- C. Labelled 3 in figure 2.11 which corresponds to unit 2 in figure 2.6.

Additional units are evident in the image (figure 2.11) but the greater ability for lineament discrimination particularly in the centre-west part of the image has resulted in the dissection into smaller units, of the larger scale units identified in figure 2.6. These small units have been recognised but not individually classified in terms of real geology.

A number of digital image processing techniques were applied to the data, including directional filtering (figure 2.12), pseudoclabouring (figure 2.13) and median filtering (figure 2.14). The two former techniques are found to rid the original image of much of its geological information. Directional filtering (figure 2.12) produces no additional information and tends to remove textural variation and leave a resultant image depicting high frequency variations in the data. Pseudoclabouring (figure 2.13) assigns specific grey tone levels to a specific colour. Although a simplistic classification of the image into comparable units with the raw data (figures 2.10 and 2.11) is accomplished (figure 2.13b), more detailed mapping of textural and geomorphological units and lineaments is not possible due to a loss of information under a 'noise' of colour. The median filtered images (figures 2.14a and

2.14b) are, like figures 2.10 and 2.11 more successful for identifying geologically relevant features due to the clear expression of geomorphology and texture.

The black and white (grey tone) images, as has been discussed, are more successful at discriminating lithological and structural features due to the recognition of units by textural and geomorphological changes. However, these images are also more successful for discriminating features since the human brain can more easily perceive black and white information than colour, which is a more complex function.

2.5 Interpretation of Results for the Yorkshire Basin

From the lineament map and rose diagram (figure 2.6) it is clear that there is a concentration of NNW-SSE and NNE-SSW lineaments within unit 1, the uplifted North Yorkshire Moors area, in the centre of the Yorkshire Basin. Most of the lineaments correlate with topographic and drainage features (figures 2.11 and 2.14) characteristic of this particular area. They may reflect a fracture pattern that was initiated during north-south directed compression, associated with major changes in plate motions that occurred in the Upper Cretaceous- Tertiary (Livermore and Smith, 1986). This event caused inversion and uplift in many post-Carboniferous basins in Europe including the Wessex and Weald Basins discussed below. The affects of this deformation in the Yorkshire Basin are discussed in Chapters 3, 4, 5 and 6. As this was the last major phase of deformation to affect the Yorkshire Basin, the lineaments seen in the imagery are believed to represent the expression of reactivated, basin forming faults and/or a primary fracture pattern initiated during inversion.

An attempt to orientate both previously mapped structures and those detected on satellite imagery into a tectonic stress regime during inversion and compression is depicted in figure 2.15a and 2.15b.

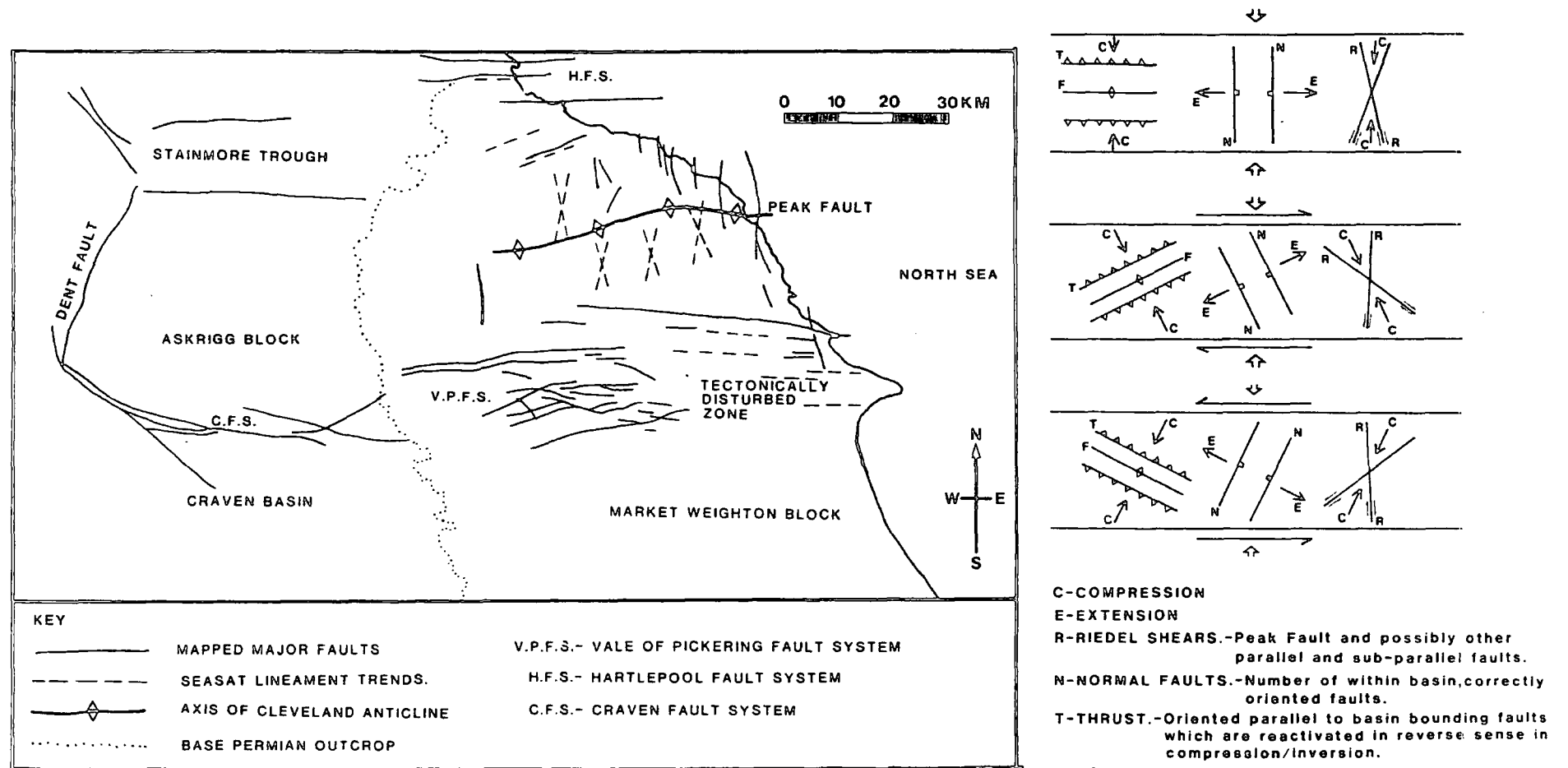


Figure 2.15. Tectonic interpretation of integrated lineament analysis and mapped faults in the Yorkshire Basin.

The Peak Fault (figure 2.15a), postulated to have significant sinistral strike slip offset, other mapped young NNE-SSW and NNW-SSE faults along the coastline (figure 2.15a), and the observed lineament orientations within the central area of the basin, are consistent with expected normal and strike slip fault trends in such a compressional regime (figure 2.15b). The amount and orientation of regional strike slip (transpression or transtension) is uncertain but will affect the relative orientations of the intrinsic fault and fold pattern (figure 2.15b). Furthermore, the Cleveland Anticline, the major basin wide fold, transects the North Yorkshire Moors with an east-west axial trend (figure 2.15a), consistent with the postulated fold patterns in figure 2.15b.

In the north and south of the area, a number of east-west orientated lineaments are mapped in the satellite imagery, some of which are expressed through a cover of glacial drift in the Vale of Pickering (figure 2.11, 2.13 and 2.14). These lineaments coincide with the known orientation of important basin faults in the Vale of Pickering Fault Zone and Hartlepool and Butterknowle Faults to the north. The former downfault the Kimmeridge Clay and bound the lowland of the Vale itself from the surrounding topographic highs. Thus, some of the lineaments form boundaries to lithological/textural units as well as depicting known fault structures. The approximately east-west orientated faults and lineaments are extensive both in the images and geological maps and were important in the development and destruction of the area as a basin. These lineaments are not strongly depicted in the radar images when compared with for example, the Purbeck-Isle of Wight fault in the Wessex Basin (figure 2.16) which was reactivated during inversion to form a distinct monoclinical structure. This is clearly defined in Landsat MSS, TM and Seasat SAR imagery (figures 2.23-MSS, 2.36-TM and 2.24, 2.26, 2.28, 2.30 and 2.34-Seasat SAR). The Vale of Pickering Faults do not appear to have played a major role in accommodating shortening, inversion and uplift in the basin by reactivation, and, as seen in figures 1.4 and 2.3, they are still in a high state of

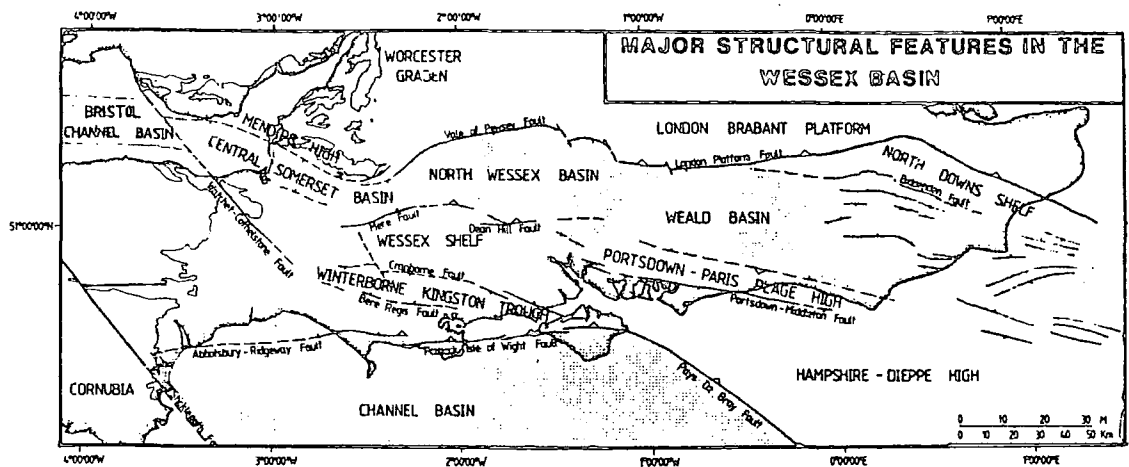


Figure 2.16. Structural features of the Wessex and Weald Basins
(after Lake, 1985).



Figure 2.17. Lineament analysis of Landsat TM imagery (after Lake et al, 1984).

extension. However, to the north, the similarly orientated Hartlepool and Butterknowle Faults (figure 2.3 and 2.15), which link directly to the Carboniferous basement and were important during Carboniferous basin evolution, are in much less extended states and may have played important roles in the structural and sedimentological evolution of the Permian-Recent Yorkshire Basin. Similarly, the east-west trend of the larger scale lineaments is found to extend into the Pennine area to the west in the Seasat SAR mosaic image, and it is inferred that basement faults with this orientation eg. Craven Fault System (figure 2.15a) have had a major influence on basin evolution. Thus, east-west trending faults in the Permian and younger sediments are the manifestation of these major basement fault systems, the detailed relationship between which will be discussed in more detail in succeeding chapters.

2.6 Geological Remote Sensing in the Wessex Basin.

The intra-cratonic Wessex Basin of Southern England developed on deformed Palaeozoic basement comprising shallow southward dipping Variscan thrusts offset by NW-SE late Variscan wrench faults (Stoneley, 1982; Chadwick et al, 1983). These structures were reactivated and played a major role in controlling the succeeding evolution of the area (figure 2.16). Optical images covering the majority of the basin were analysed together with a smaller subscene of the Isle of Wight for digital image processing. The onshore area of the Wessex Basin is well vegetated and gently undulating.

2.6.1. Lineament Analysis

Lineament analysis of the Wessex Basin using Landsat TM, Landsat MSS and Seasat SAR optical images is displayed in figures 2.17, 2.18 and 2.19 respectively. Each lineament was classified by length and orientation and the results presented in rose diagrams (figure 2.20- TM and MSS clear and subtle lineaments after Lake

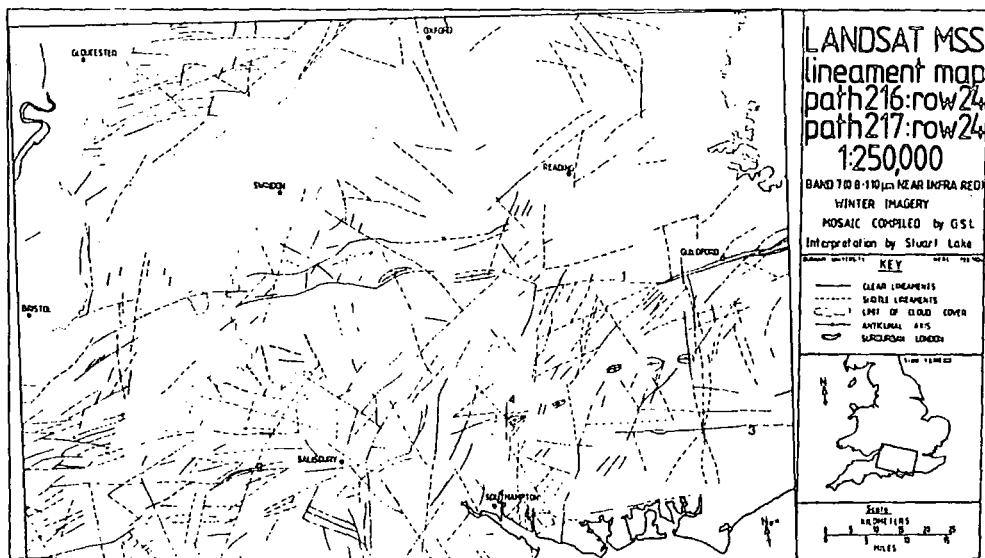


Figure 2.18. Lineament analysis of Landsat MSS imagery (after Lake et al, 1985)

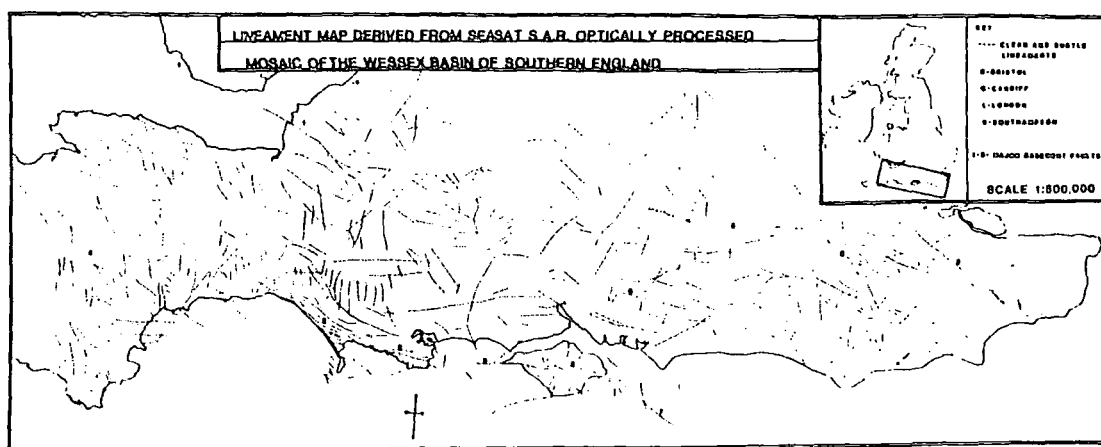
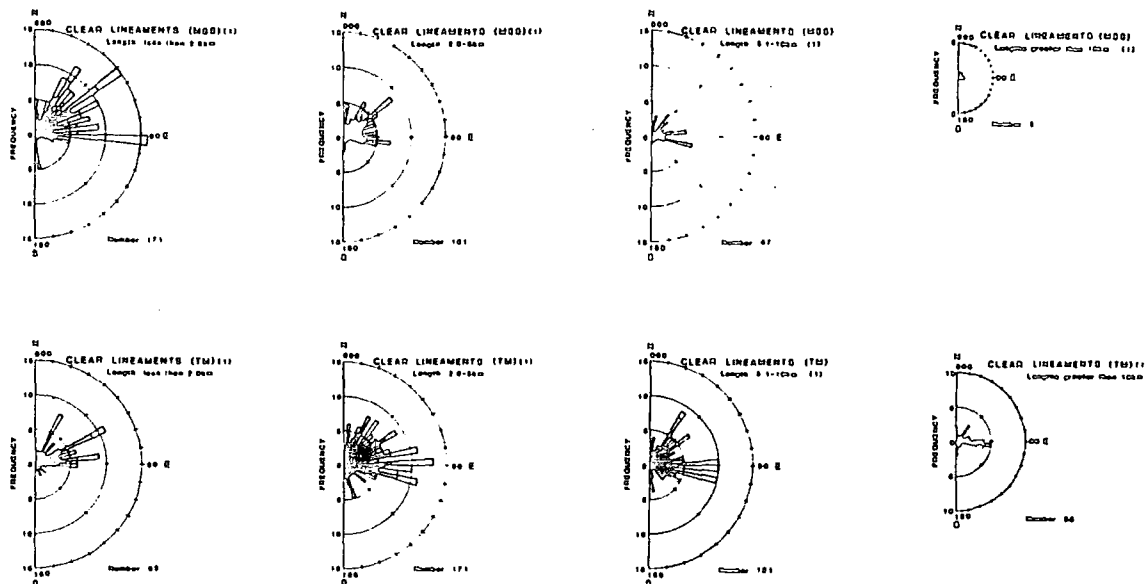
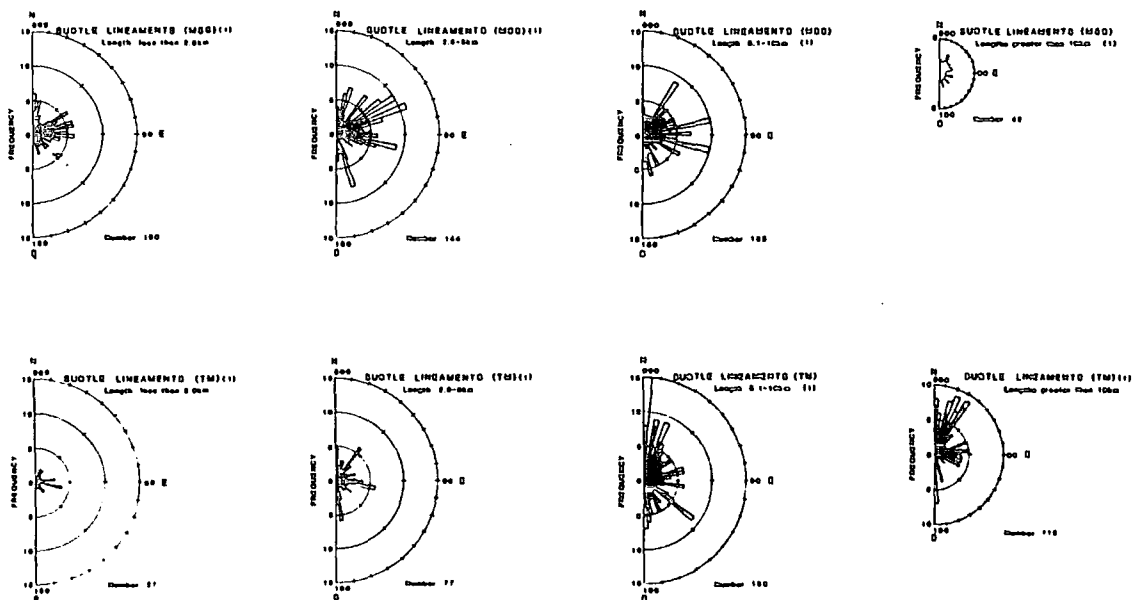


Figure 2.19. Lineament analysis of Seasat SAR imagery of the Wessex and Weald Basins.



Analysis of clear lineaments from MSS and TM data.



Analysis of subtle lineaments from MSS and TM data.

Figure 2.20. Landsat TM and MSS lineament orientations for the Wessex Basin.

et al 1984, figures 2.21 and 2.22- Seasat SAR after Dixon et al, 1985)

Four manifestations of lineaments were recorded in the study area, (which for the TM and MSS data includes parts of the Weald Basin, figure 2.1).

These are vegetation changes about some linear feature, incised fractures along faults and joints forming valleys, sudden topographic changes such as fault scarps and ridges, and offshore lineaments formed by a response to sea surface topography (Zimmerman 1985) which relate to sea-bed topography.

2.6.1A. E-W Trending Lineaments

E-W trending lineaments are perhaps the most significant in the basin as they parallel the trends of the folds, faults and thrusts in the Variscan basement. Lake et al (1984) noted (figure 2.17) that lineaments 1 and 2 correspond to E-W trending listric growth faults caused by backthrusting along shallow southward dipping Variscan thrusts (Chadwick et al 1983) and that lineament 3 (figures 2.17 and 2.18) corresponds to a major fault bounding a basin high, the Portsdown-Paris Plage ridge (Taitt and Kent 1958). Lineaments 3 and 8 in figure 2.19, from the Seasat SAR optical mosaic, correspond to the Purbeck Isle of Wight disturbance, which is related to a major Late Palaeozoic thrust fault (Stoneley 1982). This was subsequently reactivated both in a normal sense during Mesozoic subsidence and extension and in a reverse sense during Tertiary uplift and inversion (compression). This particular lineament is well defined in both Landsat MSS and Seasat SAR imagery (figure 2.23- Landsat colour composite and figure 2.24 - Seasat piecewise linear stretched digital image). Rose diagrams for the TM and MSS imagery (figure 2.20) and the Seasat SAR mosaic (figure 2.21) indicate that the longer lineaments show a preferred east-west orientation. Their significance can be appreciated by comparison of the mapped image lineaments with the major structures in figure 2.16.

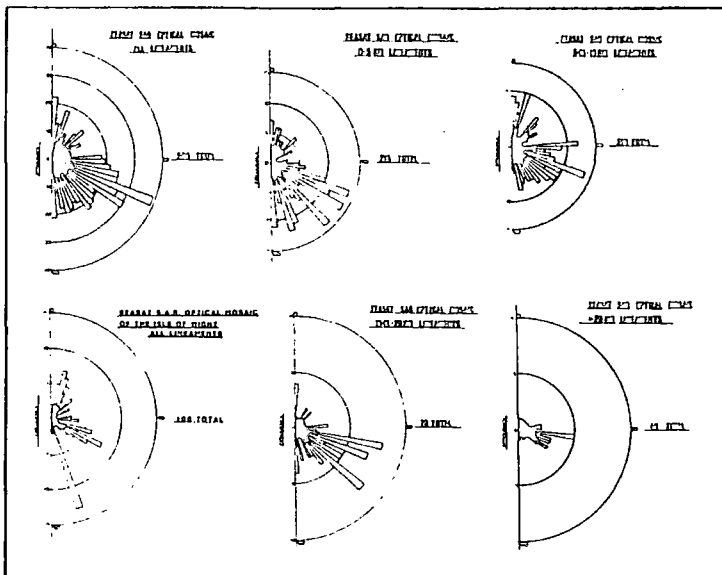


Figure 2.21. Seasat SAR lineament orientations for the Wessex Basin.

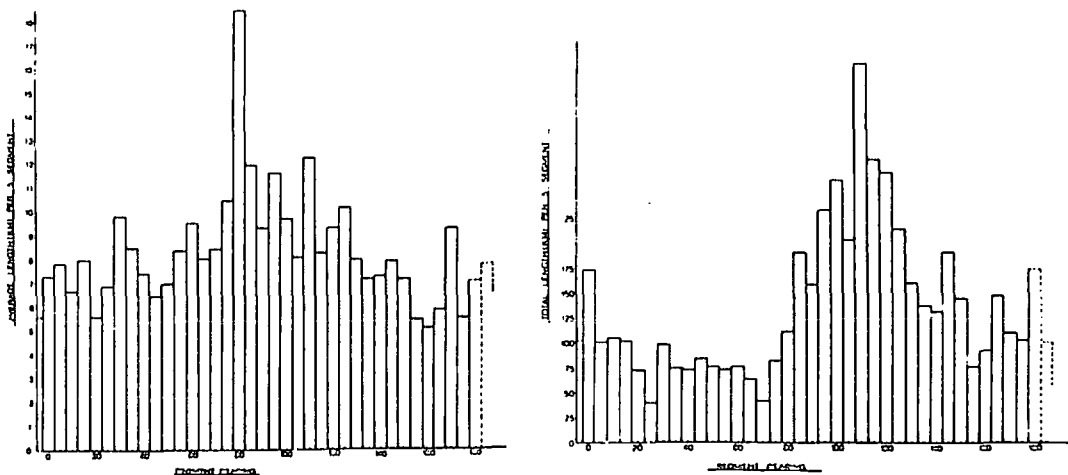


Figure 2.22. Histogram analysis of lineaments from Seasat SAR for the Wessex and Weald Basins.

2.6.1B. NE-SW Trending Lineaments

This trend is enhanced predominantly by the MSS and TM images (figures 2.17, 2.18 and 2.20). Seasat imagery does not preferentially record this trend (figures 2.19, 2.21 and 2.22). Nevertheless, this trend represents late Variscan structures which are part of a northeast-southwest northwest-southeast conjugate wrench pair (Hancock 1983, Bevan 1984 - see section 2.7 figure 2.26).

2.6.1C. NW-SE Trending Lineaments

This is a late Variscan trend and as discussed above forms one half of a wrench pair identified in the Wessex Basin. MSS and TM images do not clearly display this trend (figures 2.17, 2.18 and 2.20) due to the azimuth of the sun angle being parallel to this trend and hence suppressing any such orientated structures. Nevertheless, the Seasat SAR imagery recognises the presence of structures with this orientation (figures 2.19, 2.21 and 2.22). Notable lineaments in the Seasat data (figure 2.19) are numbered 1, 2, 4, 5 and 7 and correspond to major basement faults or thrusts reactivated in the overlying sedimentary cover. Lineament 1 appears to correspond to the postulated line of the Variscan Front (Shackleton 1984), whereas lineament 7 corresponds to the Pay de Bray Fault (figure 2.16) and is picked up as an offshore lineament trend in the English Channel due probably to response to sea-bottom topography and/or sediment transport direction and currents (Zimmerman 1985).

2.6.1D. N-S Trending Lineaments

These are thought to be Caledonian and Pre-Caledonian in age and correlate with structures such as the Malvern line and Worcester Graben (Kellaway and Welch 1984). Although abundant in all data sets and imagery (figures 2.16 to 2.22), they have probably not been important controls on basin formation.

2.7 Isle of Wight Subscene

The Isle of Wight, an area of relatively complex geology within the Wessex Basin, was chosen as a site for a more detailed analysis of digitally processed data to appraise its potential and any advantages that can be gained by working on a smaller scale, with data that could be manipulated to extract maximum lithological and structural information.

The Isle of Wight (figure 2.25) is split structurally in two by the Purbeck Isle of Wight Disturbance, the northern half characterised by flat lying Tertiary sediments on a relatively thin Mesozoic sequence, and the southern half by a thick Mesozoic sequence.

The youngest succession of Cretaceous strata are exposed in two WNW-ESE trending en echelon monoclines, which represent the surface expression of fault/thrust reactivation in the basement (Stoneley 1982). They formed during Late Cretaceous-Early Tertiary compressional phases, during which the Wessex Basin was inverted and uplifted.

The digital and optical Seasat images of the Isle of Wight (figures 2.26 and 2.27) display similar NNE-SSW and NNW-SSE trends, which are consistent with a conjugate shear pair recognised by Bevan (1984) in Landsat imagery and in the field. In both the digital and optical images (figure 2.26 and 2.27) the east-west orientated en echelon monocline, characteristic of the area and mentioned above (figure 2.23 and 2.24) is recognisable. Significantly, this major structural feature is mappable in the immediate easterly offshore area (figure 2.26). To the west, its continuation is mappable but is less evident (figure 2.28) and is known to continue offshore as the link between the Isle of Wight and Purbeck Disturbances (Stoneley 1982, Lake 1985).

The imagery for the Isle of Wight clearly show two texturally distinct provinces

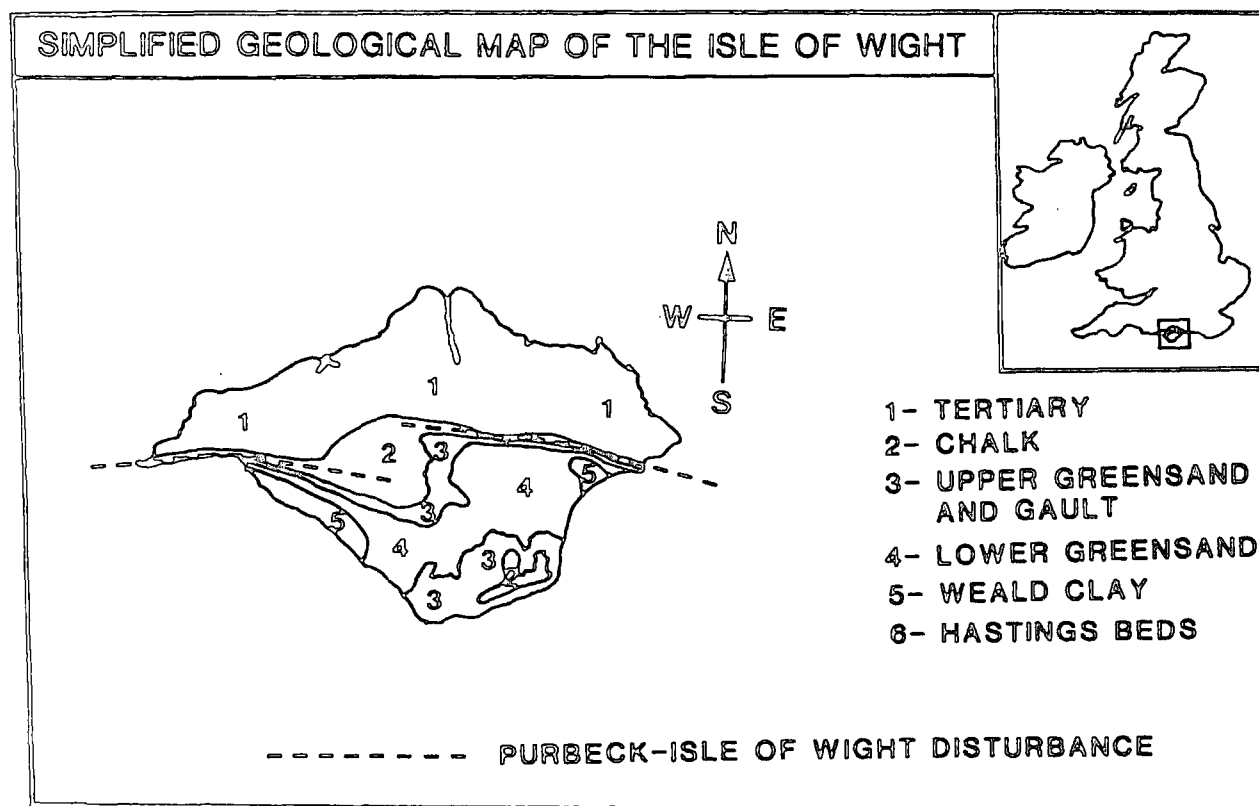


Figure 2.25. Geological map of the Isle of Wight, Wessex Basin.

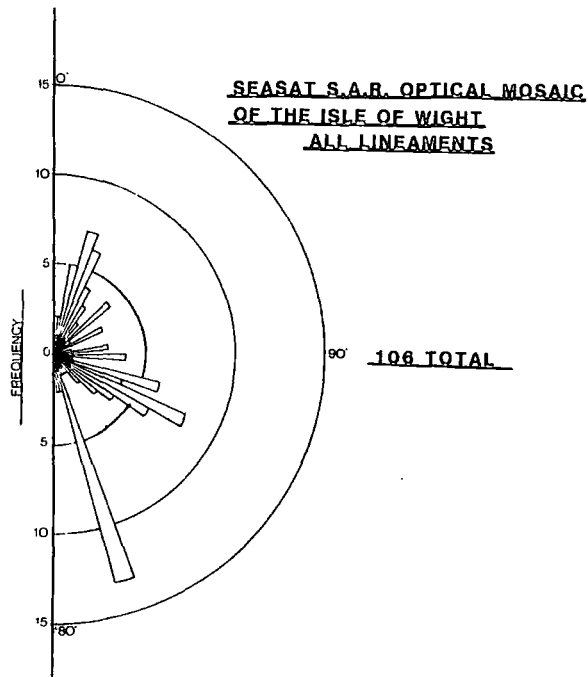
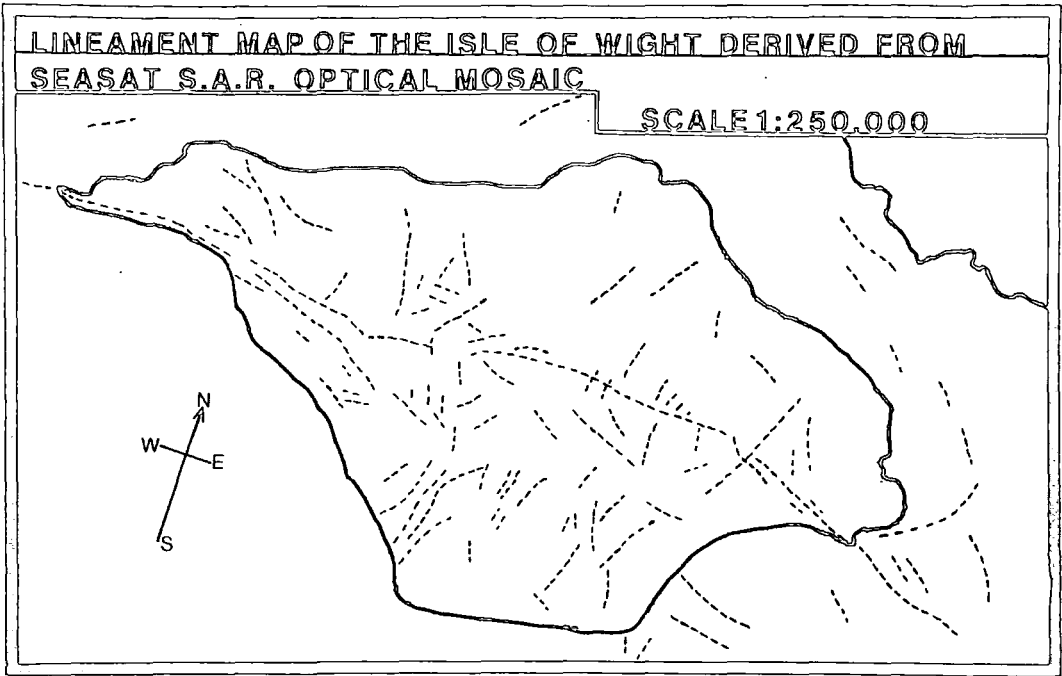


Figure 2.27. Lineament analysis of optical Seasat SAR image of the Isle of Wight.

(figures 2.23, 2.26 and 2.28), the more incised, uplifted (inverted) southern province with a greater intensity of lineaments due to increased drainage features and the relatively monotonous (texturally) northern province due to non-uplifted (non-inverted) flat lying sediments.

bf 2.8. Hue, Saturation Intensity Transformation (HSI).

Most of the data gives poor results for lithological discrimination eg: compare figure 2.25 with figures 2.23, 2.24, 2.26 and 2.28. Daily (1983) has shown that use of the Hue Saturation Intensity (HSI) transformation, in terrains of moderate relief and sparse vegetation, is beneficial for enhancing structural and lithological features. Radar images eg: Seasat, can be split into a low frequency component related to tonal variations in vegetation and lithology, and a high frequency component representing sloping targets facing the radar. By assigning hue (colour) to the former and intensity (brightness) to the latter, the resultant images can considerably enhance structural and lithological features. This transformation was implemented on 2 areas within the Isle of Wight subscene:-

1. Isle of Wight - a general appraisal of the whole image (figures 2.29, 2.30 and 2.31).
2. Culver Cliff - the transformation is performed on a subscene of the Isle of Wight (figures 2.32, 2.33, 2.34 and 2.35).

2.8.1. Isle of Wight

Figures 2.29 and 2.30 represent the two input components of the HSI transformation and figure 2.31 the final output image. The two major provinces mentioned earlier are fairly clearly depicted by spectral variations in the resultant image (figure 2.31) and as these two areas are lithologically and structurally distinct the transformation may be regarded as having some success.

However, any more detailed lithological or structural analysis is not possible.

2.8.2. Culver Cliff

A similar conclusion can be drawn from the second image analysed using the HSI transformation. The objective was to enhance the on and offshore continuation of the Isle of Wight-Purbeck disturbance. Figures 2.33, 2.34 and 2.35 represent the Hue, Intensity and final image respectively. The fault/ disturbance is evident as continuing offshore but detection is not enhanced by this particular image processing technique. Less complicated image processing such as directional filtering (figure 2.33) are apparently more beneficial to geological analysis of this particular area.

2.9 Perspective Image Processing

A further processing technique called perspective was utilised. This combines two specific image types, one a 3 band colour image and one a single band grey tone image. The resultant image is viewed in perspective from any specifiable orientation (north, south) or elevation angle (90° , 45°).

The two images used are described below:-

1. TM image of the Isle of Wight (figure 2.36).

Figure 2.36 is the colour input of the transformation and represents a 3 band colour composite of the Isle of Wight which it has been geometrically rotated to the same orientation as the second image (figure 2.37) as each pixel must be matched to its equivalent on the other image. The TM image was used to provide a colour input response from the natural response of vegetation to lithological and/or structural variation.

2. Seasat SAR Isle of Wight (figure 2.37).

Figure 2.37 is the grey tone input of the transformation. The Seasat image was used to provide a grey tone response that would be dependant on both geomorphological variations (structures) and textural variations which may be lithologically dependent.

The resultant image (figure 2.38) was viewed from the south at 45° elevation angle and it was hoped that it would provide a three-dimensional view of the area, enhancing the combined spectral and geological/geomorphological variation in the area. However, the results are disappointing, as seen in figure 2.26, and it is postulated that this is primarily due to the response of the TM data to cultural (agricultural) noise, distortion during the geometric reorientation of the images and inappropriate selection of the input images.

2.10 Geological Remote Sensing in the Weald Basin.

The Weald Basin is similar geomorphologically to the Wessex Basin, being gently undulating and well vegetated. The basin formed in the Triassic and subsided until the early Tertiary, after which it was inverted to form the west plunging Weald Anticline with chalk escarpments on its northern, southern and western limbs and Lower Cretaceous sediments exposed in its core as illustrated in figure 2.39 (Allen, 1975; Anderton et al, 1979; Chadwick, 1985a; Smith, 1985).

Lineament analysis of the basin from Seasat data was carried out in a combined survey of the Wessex and Weald Basins (figures 2.19, 2.21 and 2.22). The results indicate that the two areas are tectonically linked. More detailed lithological and structural analysis of the Weald Basin is not greatly enhanced by the Seasat SAR data. However, it is found that due to the large scale of the Wealden structure and preferential weathering due to relative competency contrasts of the exposed sediments, a detailed lithological analysis can be achieved using Landsat TM data, including single band and colour composite images. Figure 2.40 is the

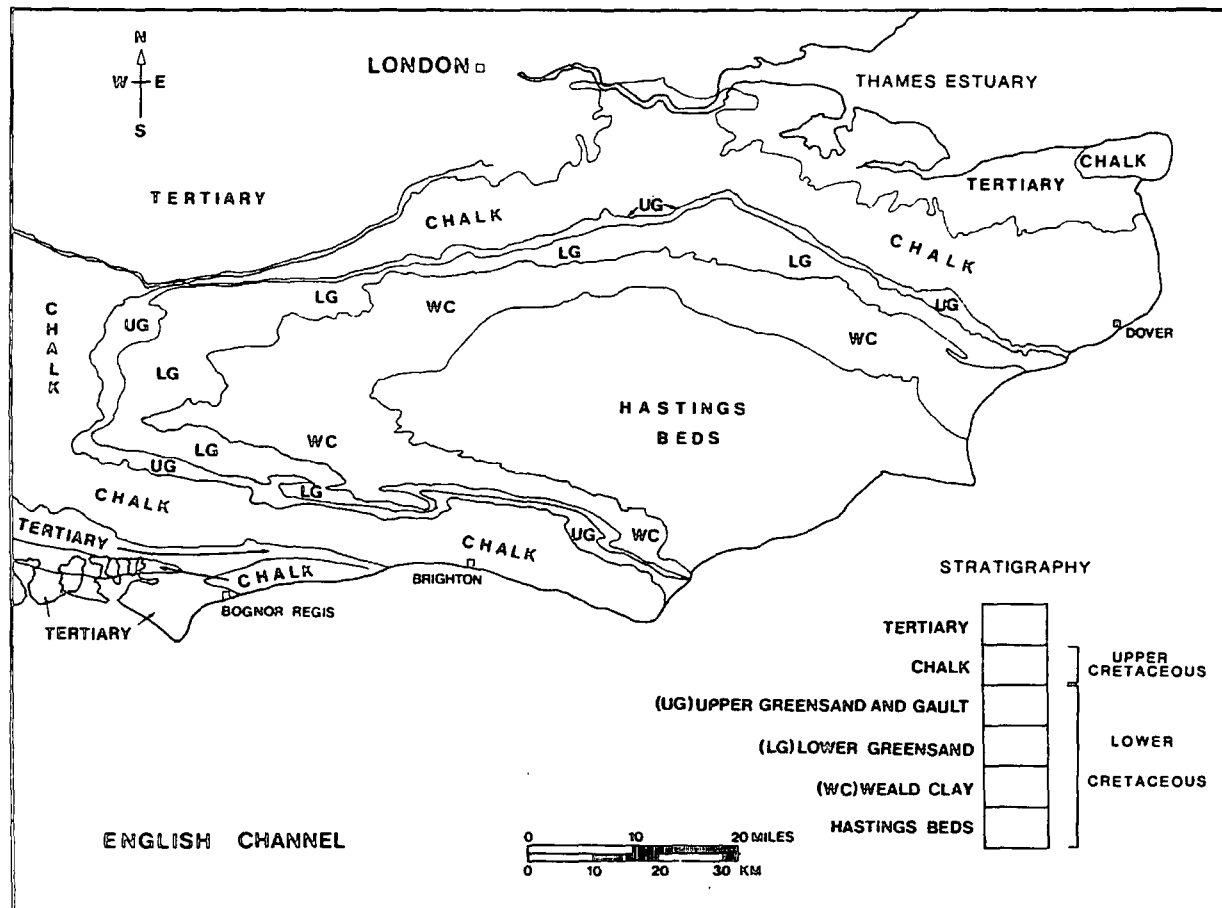


Figure 2.39. Geological map of the Weald Basin.

colour composite image used in the analysis. The image was studied and interpreted as objectively as possible. The classification of lithological units is based upon the textural and spectral variations in the image, each individual unit being identified using parameters such as topography, geomorphology, colour, tone, drainage features (patterns) and vegetation. It is immediately possible, from figure 2.40, to identify a number of unique geological units and the general geology of the area.

Six distinct units are identified (figure 2.41) and are discussed below.

Units 1, 3 and 6 show a distinct change in geomorphology and spectral signature from the intermediate units 2, 4 and 5. The former occupy relatively higher ground and show good, irregular drainage features corresponding to small hills and vales. Units 1 and 3 are similar in all respects and could, without a structural interpretation, be classified as the same unit. They typically are forested with little artificial agricultural features and are clearly distinguished from the surrounding units 2 and 4 by a spectral break, mappable along most of the boundaries, and by a change in slope, which in most areas is also well defined and coincides with the spectral change (figure 2.40).

Unit 6 is particularly distinctive to the south and west. It displays strong positive geomorphological characteristics, occupies high ground and appears reasonably well cultivated with little forestry (if any). Its specific spectral response on the colour composite image (figure 2.40) is yellow/red, and clearly defines its boundary with unit 5. For the most part, this boundary is also defined by an abrupt change in the slope manifested in a steep scarp face in the image. It is least clear in the west where the shallow plunge of the structure causes a more gentle geomorphological change. To the north the limb of the structure can be observed to have quite a substantial dip northwards which can account for the apparent thinning of some of the units (figures 2.40 and 2.41).

Unit 2 occupies low land and appears well cultivated. It has a distinctively 'quiet' or negative geomorphological signature in comparison to units 1 and 3 surrounding it and, as said previously, its boundary with the latter units coincides with a mappable change of spectral response and shape.

Units 4 and 5 in places are difficult to separate, particularly in the northern and southern areas. Unit 4 appears similar to unit 2, in spectral and geomorphological terms, and occupies low land relative to units 5 (where distinguishable) and 3, with which it has a clearly definable boundary.

Unit 5 in the north and south appears under the scarp face of unit 6 and is difficult to distinguish. In the west and south-west however, it does develop a significant spectral and geomorphological signature, which allows it to be distinguished from its neighbouring units. Here, it forms a shallow shelf below unit 6 and forms its own scarp at the postulated junction with unit 4 (figures 2.40 and 2.41). Its spectral signature is similar to unit 4, but it does show a positive relief and distinct geomorphological features within it which are in contrast to unit 4.

Structurally, we can also interpret the image (figure 2.40) as a westwardly plunging antiform. The north and south limbs are clearly defined by the repetition of each lithological unit and measurable dips confirm this hypothesis. In the south the chalk is observed to be either horizontal or shallowly dipping southwards. In the north dips recorded in scarps of units 3, 5 and 6 are apparently quite high to the north (figure 2.40). To the west, the closure of the structure can also be mapped (figures 2.40 and 2.41).

Analysis of these results thus show excellent correlation with the known geology in the area. The boundaries and units mapped coincide with major lithological changes in the area and the contrast in competencies of the different lithologies has enhanced lithological discrimination in the imagery. In the field we would find

that:

Unit 1 = Hastings Beds - sandstones (and clays)

Unit 2 = Weald Clay - clays and mudstones

Unit 3 = Lower Greensand - resistant sands, limestones, mudstones

Unit 4 = Upper Greensand - glauconitic sandstones

Unit 5 = Gault Clay - mudstones

Unit 6 = Chalk

The TM data has been shown to provide much detailed information for lithological mapping in the Weald Basin, facilitated by the large scale nature of the Wealden structure and well defined preferential erosion of the sedimentary formations.

2.11 Discussion

Optically processed Seasat SAR, Landsat MSS and TM, and digitally processed Seasat SAR and Landsat TM satellite imagery were utilised in a structural, lithological and tectonic analysis of the Yorkshire, Wessex and Weald Basins, U.K.

It has been shown that features identified in the imagery can be correlated with known and unknown geology in the basins and hence provide a useful tool for tectonic interpretation. Lake et al (1984) studied the potential of MSS and TM data for structural interpretation of the Wessex Basin but concluded, as did Dixon et al (1985), that the imagery may reflect an orientational bias towards certain structures in the basin. Although lineaments are visibly clearer and more abundant in the TM imagery it is felt that careful utilisation and analysis of multi-look Seasat SAR data, in conjunction with Landsat MSS and TM data, is

important in lithological and structural studies due to the strong response of the former to geomorphology and topography.

Large scale, regional studies using the optical images are found to give interesting results for structural/tectonic analysis of the Wessex Basin, and general structural and lithological/geomorphological mapping in the Yorkshire Basin. However, much of the information that could be interpreted geologically is found, for all three basins, not to greatly expand on known lithological and structural features. Lineaments from optical images in the Wessex and Weald Basins correlate well with postulated tectonic trends and many correspond to major mapped lithological faults and fractures. Lithological mapping using TM data in the Weald Basin displays the ability of this data to define detailed and precise spectral and geomorphological changes. Seasat SAR data in the Yorkshire Basin displays its potential for lineament detection and the broad classification of textural units which are found to correlate well with lithological units in the basin. Lineament analysis proves significant with respect to the structural architecture of the basin and its tectonic development.

Digital image processing techniques are used in the Yorkshire and Wessex Basins to attempt to enhance geological features. The results from the Weald TM analysis are felt to be the maximum that can be achieved. In the Wessex Basin, the Isle of Wight was chosen as an area that can be readily relatable to lithology and structural maps for correlation. In Yorkshire, a scene enclosing the majority of the mapped textural units was chosen to try and enhance their classification and any lineaments that are present.

Although the implementation of digital image processing techniques increases the number of identifiable lineaments compared to optical images and in places defines textural boundaries more precisely, it is felt that any processing after the initial enhancement of the original, raw image eg: by directional filtering; or

pseudocolouring, does not significantly improve the results or the quality of the imagery.

More advanced processing involving the integration of specific images, such as perspective and HSI transformations are also largely unsuccessful. In the case of the latter, it is felt that due to the widespread (100%) vegetation cover in the basins, much of which is artificial, ie. agricultural, the low frequency hue component is almost entirely masked by the 'cultural noise' and is not, as experienced in more successful attempts at implementing this transformation (Daily 1983), a primary response from naturally selective vegetation or exposed rock surfaces. Furthermore, large scale features such as lithological or vegetation contrasts are masked by high frequency variations associated with small drainage and topographic patterns.

In conclusion, the structures encountered in the satellite imagery have been shown to conform well with the known structural and tectonic formations of the respective areas and the British Isles in general. Major structural features, both exposed and concealed beneath sediments have been recognised and identified in all images. Landsat MSS and, in particular, TM data provide much detailed information, particularly related to lithological variations whereas Seasat, although displaying excellent potential for identifying many lineaments of various origins (faults, fractures, lithological boundaries, drainage features, joints and surface moisture variations), is of limited use for detailed lithological discrimination.

The primary drawback to the use of remote sensing in the terrains encountered above is the extent of cover/drift sediments which suppress all categories of geological expression in the immediate subsurface and also the lack of natural vegetation contrasts due to intense agricultural activity.

Satellite remote sensing provides little extra geological information than is

already known, particularly on the smaller scale encountered in digital images. Hence in the Yorkshire, Wessex and Weald Basins the potential of remote sensing techniques as a tool for frontier exploration are limited. Nevertheless, the results suggest that it has potential for regional tectonic correlation and large scale identification of texturally, possibly lithologically distinct units. These results provide a useful additional component for basin analysis studies in the British Isles, and in particular the Yorkshire, Wessex and Weald Basins.

CHAPTER 3

QUANTIFICATION OF UPLIFT AND REMOVED OVERBURDEN FROM THE YORKSHIRE, SOLE PIT AND EAST MIDLAND BASINS

3.1 Introduction.

Basin analysis involves the study of the whole geological evolution of a particular area, from the initiation of basin formation, to its structural evolution after subsidence has ceased. Basement uplift has caused the erosion and removal of variable amounts of Permian to Cretaceous sediments from the Yorkshire, Sole Pit and East Midland Basins. This period of partial basin destruction is analogous to similar events in other north-west European basins, although its magnitude and timing are not consistent (Kent, 1980a; Glennie and Boegner, 1981; Van Hoorn, 1987; Ziegler, 1987). Removal of sediments by basement uplift represents a significant event in the evolution of these basins and is one which therefore necessitates not only qualification, but also quantification.

The removal of sediments from a basin by basement uplift will hinder the study of the earlier subsidence history. Accurate appraisal of basement subsidence, sedimentary thicknesses, sedimentation rates and extension cannot be achieved if appreciable amounts of basin fill have subsequently been removed from the area. In particular, techniques such as backstripping, which isolates the driving tectonic subsidence by removal of the influence of the sedimentary load acting on the basement, requires that the maximum sedimentary load be accounted for. This method of study of the mechanisms of basin formation reveals much information about the evolution of a basin including the components of mechanical and thermal

subsidence, and extension in the crust and lithosphere.

Therefore, before an accurate appraisal of their subsidence history can be made, one must reconstruct the pre-uplift structural and sedimentological configuration of the Yorkshire, Sole Pit and East Midland Basins. This chapter outlines the possible methods for accurately predicting the amount of sediment lost in a basin, and proceeds to describe in detail how analysis of burial or depth dependent, physical sedimentary parameters in particular, can facilitate such a study.

The main benefits of this research are three fold:-

1. It permits the reconstruction of the original basin configuration and hence is an important tool for analysis of subsidence in inverted or uplifted basins.
2. The regional distribution and magnitude of basement uplift and corresponding removed sediment not only is a measure of the intensity of basin destruction, but also identifies the causal mechanisms of such crustal deformation eg. positive basin inversion (Chapter 5), diapirism, flexure.
3. Appraisal of the complete history of subsidence and uplift, both of which are facilitated by this study, permits more detailed modelling of the potential for hydrocarbon generation in the Yorkshire, Sole Pit and East Midland Basins, and in particular, the history of burial of potential source rocks (Chapter 6).

3.2 Methods of Quantifying Uplift.

The purpose of this chapter is to determine the amounts of sediment that have been lost in the study area, but not to deliberate at this stage, as to the possible causes of the uplift. This serves as the basis for the discussion on the causal mechanisms for uplift which follows in Chapter 5.

The amount of sediment lost in the Yorkshire, Sole Pit and East Midland

Basins can be estimated from the local and regional stratigraphic correlations (Kent, 1980b). However, a more appropriate and objective method is to compute the amount of sediment lost using an independent, measurable parameter, which can subsequently be correlated with the local and regional stratigraphy. This is particularly important in areas where substantial uplift has occurred over previously rapidly subsiding areas, such as the Yorkshire and Sole Pit Basins. Clearly, it would be difficult to predict original sedimentary thicknesses into a basinal area using data from marginal basins which do not necessarily display the same or even similar subsidence histories, and which have not been subjected to the same degree of inversion.

The three methods considered for an objective study of the uplift and removal of overburden are:

1. Fission Track Analysis.
2. Chemical Diagenetic Variations of Sediments with Depth.
3. Physical Diagenetic Variations of Sediments with Depth.

3.2.1. Fission Track Analysis.

Fission track analysis is a little used or, more appropriately, scarcely available technique which dates and quantifies thermal events that have been applied to a sediment, by analysis of minor trace elements such as apatite, zircon or sphene. It has been applied in economic geology as an exploration tool and is useful for detecting thermal events associated with rifting (Gleadow, 1978) and uplift (Green, 1986). Indeed, Green (1986) applied the method in north-west England and concluded that the rocks presently at or near the surface had once been at a temperature of 70 – 125° C prior to 60Ma ago, when uplift occurred.

The most plausible explanation for these high thermal values is believed to be

a heating event associated with the initiation of the Tertiary volcanic centres of north-west Britain. It is predicted that substantial amounts of sediment have been lost from nearby Mesozoic basins in the Solway Firth and Irish Sea (Ashley Price, pers. comm. 1986). The anomalous fission tracks are postulated to represent the cumulative effects of the aforementioned phenomena.

It may be that the results in Green's paper can be correlated, via fission track analysis of Yorkshire, Sole Pit and East Midland Basin sediments, to the uplift that occurred in the latter areas at, and around the same time, as the events described above (Kent, 1980a; Dewey, 1982). However, fission track data are not at present available and thus, the consequences of Green's work for the evolution of the study area are purely speculative.

3.2.2. Diagenetic Changes in Sediments with Depth of Burial.

Diagenesis refers to all those changes of a physical and mineralogical nature that occur within sediments immediately after deposition (eogenesis), up to the onset of metamorphism (mesogenesis), and due to uplift (epidiagenesis). Clearly, the burial history of a sedimentary basin will profoundly affect the style of diagenetic changes that occur with depth and time.

3.2.2A. Chemical Diagenetic Changes.

Chemical diagenetic changes with depth are well documented (Glennie, 1984b; Stow and Lovell, 1987), but the precise depth of those changes are not accurately known and tend to show a high degree of variation due to the influence of external factors not directly related to the burial depth, eg. formation fluid chemistry, lithology. For this reason, plus the unavailability of data for the offshore area, it is concluded that this is not a plausible alternative for calculating maximum burial depths attained by a sediment, and hence uplift in this specific area. Furthermore, Hemingway and Riddler (1982) carried out such a study in the Yorkshire Basin.

It is postulated that the reliability of results from chemical diagenetic changes, such as in the above study, are susceptible to higher palaeogeothermal gradients, which are very likely to occur during basin formation and rifting (McKenzie, 1978), or sudden influxes of heat associated with some anomalous thermal event. As the study areas display substantial subsidence since the Permian and form part of the North Sea graben system, a higher palaeogeothermal gradient may have occurred during subsidence and extension. Also, the Tertiary (Palaeocene) Cleveland Dyke, which transects the Yorkshire Basin from west to east, is a remnant of the anomalously high thermal event associated with the Tertiary volcanic centre to the north-west and whose effects were discussed briefly in section 3.2.1. Although, metamorphic effects of the dyke in the adjoining sediments are minimal (quarry near Great Ayton, this study), this does not preclude the possibility that the whole region was subjected to higher than normal temperatures.

The probability that palaeotemperatures were anomalously high, combined with the effects of epidiagenetic changes during uplift on the earlier diagenetic signatures, suggests results from research concerned with chemical diagenetic changes may be subject to considerable error. Nevertheless, they do provide a useful source for correlation with results from other quantitative studies of uplift.

3.2.2B. Physical Diagenetic Changes.

Physical or petrophysical diagenetic changes are determined by the reaction of the sediment to burial and compaction, and, in essence, can be classified as the variation of porosity and permeability with depth. Permeability is less dependent on the depth of burial than porosity, and is controlled by other factors, eg. clay content, cementation, which will not be discussed in this thesis. This study, is concerned with the primary porosity or total porosity variation with depth. This reflects the compaction trend of the sediment concerned, which is proportional to the amount of overburden and rates of subsidence and sedimentation. How

can one obtain a comprehensive data base that allows analysis of the variation of porosity with depth for representative stratigraphic sequences throughout the Yorkshire, Sole Pit and East Midland Basins?

Since the mid-late 1960's borehole logging techniques have been developed that have eliminated the need for continuous coring but still allowed detailed petrophysical investigation of the sediments present. Notably, three of the techniques developed have been used to measure various physical parameters of sediments, all of which can be translated to porosity and its variation with depth (Schlumberger, 1972, 1974 and 1979).

These logging techniques are:

1. Sonic Velocity Logs.
2. Density Logs.
3. Neutron Logs.

and will be discussed in more detail below (Section 3.3).

Exploration of the Southern North Sea basin (onshore and offshore) since the 1930's has resulted in a very comprehensive borehole coverage, much of which is now available to the general public at the Department of Energy, London. Thus, this data base provides not only much detailed stratigraphic information, but also (since the majority of boreholes have been completed since the late 1960's when exploration began to increase), a large amount of wireline logging data from sonic, density and neutron logs.

For the following reasons petrophysical analysis of the area was the method used for calculation of uplift and inversion:-

1. Released boreholes provide a large, comprehensive and accessible data base.
2. Boreholes provide detailed stratigraphic data for both onshore and offshore areas.
3. Many of the boreholes include logs for petrophysical analysis.
4. Data for fission track and chemical diagenetic analysis was not readily available or did not give good coverage, particularly offshore.
5. Measurement of the change of a physical parameter of a sediment with depth is relatively temperature independent as one is measuring primary compaction and burial features.
6. Fission track and chemical diagenetic data reflect the temperature history of a sediment and not necessarily its burial history.

Clearly, a combination of the three techniques (physical diagenesis, chemical diagenesis and fission track) will provide a very comprehensive investigation of the subsidence and uplift history, and a greater understanding of the relationship between the thermal and tectonic histories of the basins.

3.3 Measurement of Sediment Compaction Trends.

The reduction in porosity and increase in density with burial (compaction) has long been recognised as a common geological process that is quantifiable in different sediments (Athy, 1930; Hedberg, 1936). It is this relationship which forms the basis to this study of the Yorkshire, Sole Pit and East Midland Basins. Utilisation of borehole logs, mentioned previously and described in more detail below, leads to detailed calculation of the variation of porosity with depth and subsequent analysis of uplift and subsidence (Magara, 1968, 1976).

3.3.1. Petrophysics.

Archie (1950), defined this term as the physical properties of specific rock types or lithologies. Typically, petrophysical studies are concerned with well-log data acquisition and their detailed sedimentological interpretation. The techniques are also of more applied use in sedimentological and structural interpretation of geophysical data, such as seismic. The parameters that can be evaluated from borehole logs include porosity, permeability, sonic velocity or interval transit time, density radioactivity, resistivity, spontaneous or self-potential, fluid properties and capillary pressure.

This study is concerned specifically with porosity and the wireline logs that are implemented specifically for its calculation, namely sonic, density and neutron logs. Figure 3.1 and 3.2 outline the types of log signatures for various main lithological types and their potential and uses for the study of the physical nature of sediments.

Porosity can be defined in two ways:

1. Absolute Porosity (log derived) = Volume of Voids / Total Volume
2. Effective Porosity (lab. derived) = Volume of Interconnected Pores / Total Volume

As one needs to quantify compaction, and not permeability, one must isolate the absolute porosity which reflects total porosity loss due to burial.

3.3.2. Sonic Logs.

The sonic log (figure 3.1 and 3.2) measures the velocity of a compressional wave through a sediment (sonic velocity) or, in other words, the time it takes for the wave to travel per foot through the sediment (interval transit time, $\mu s/ft.$, $\mu s/m$).

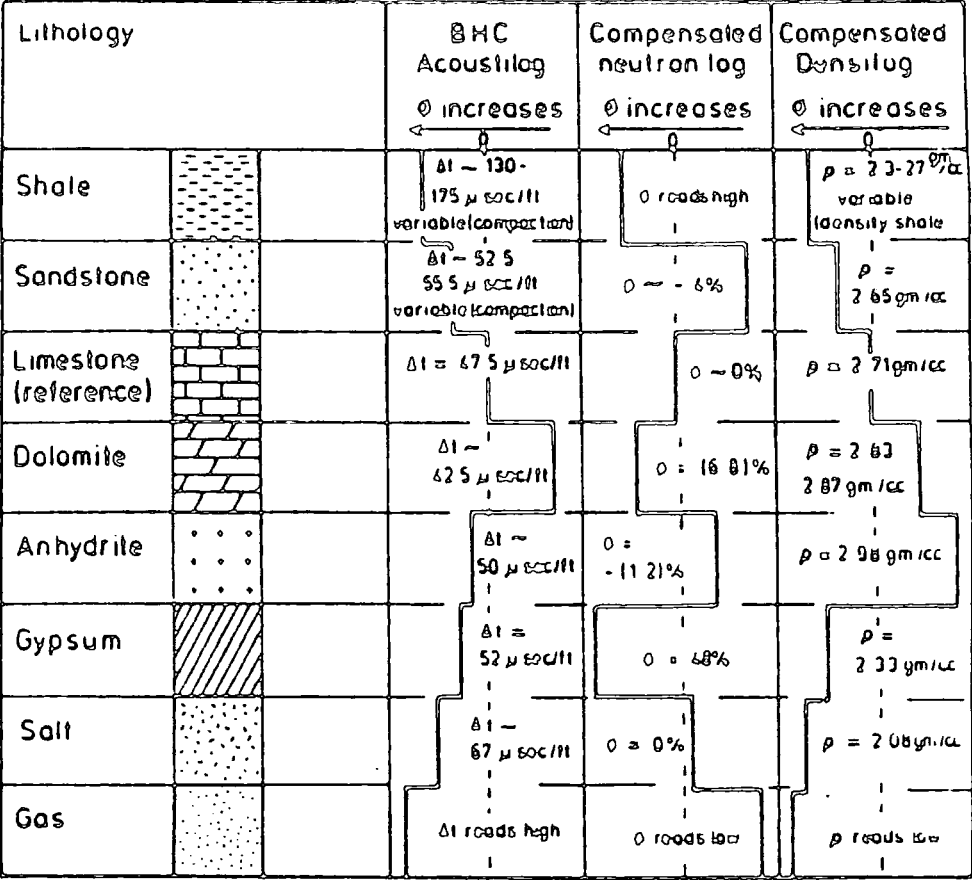


Figure 3.1. Characteristic lithological porosity log signatures.

LOG	Correlates on	Uses or Advantages
Sonic	Δt (dependent on lithology and porosity).	Good porosity correlation, useful in low resistivities. Provides Δt parameter measurement for identification of lithological markers.
Neutron	Hydrogen content of formation. Large shale response.	Good porosity correlation. Good in combination with other logs for gas detection. Provides ϕ_N parameter measurement for identification of lithological markers. Useful in cased holes. (Often run with Gamma Ray.)
Density	Formation density (dependent on lithology and porosity).	Chiefly useful for identification of lithological markers.

Figure 3.2. Summary of uses of sonic, density and neutron logs.

Porosity can be calculated from the Wyllie time average equation (Schlumberger, 1971).

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad 3.1$$

where ϕ is the resultant porosity, Δt is the measured transit time, Δt_{ma} is the transit time for the matrix ie. zero porosity, and Δt_f is the fluid (no sediment) transit time.

This can then be related to a depth function by equation 3.2.

$$\phi = \phi_0 e^{-cz} \quad 3.2$$

where ϕ is the observed porosity, ϕ_0 is the porosity at deposition, z is the depth of burial and c is a lithologically dependent constant. This defines porosity as an exponentially decreasing function with depth.

3.3.3. Formation Density Logs.

Density logs (figure 3.1 and 3.2) use a gamma ray source and measure the back-scatter which is proportional to the bulk density of the sediment. Similarly, porosity is defined by:

$$\phi = \frac{\rho_{ma} - \rho_{log}}{\rho_{ma} - \rho_f} \quad 3.3$$

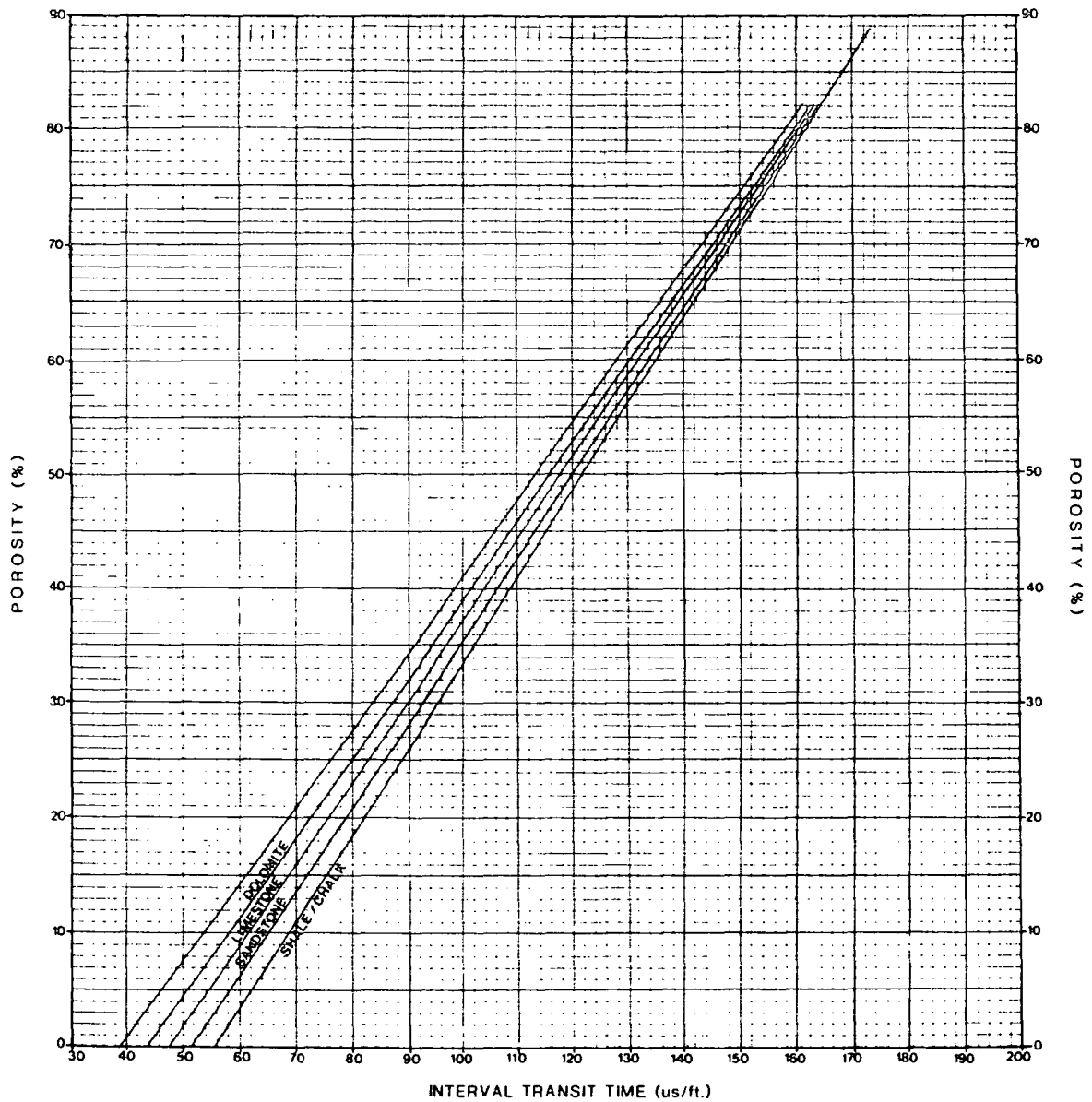
3.3.4. Neutron Logs.

Neutron logs bombard the sediment with neutrons which are responsive to hydrogen nuclei (measures H^+ ion concentration), which it detects as free water or hydrocarbons in pore spaces.

Porosity can be calculated from the above equations 3.1 and 3.2 or graphically (figures 3.3, 3.4 and 3.5) using

1. Single Plots. eg. Sonic log only (figure 3.3).

POROSITY EVALUATION FROM SONIC LOGS



Lithology	V_{ma} (ft./sec)	t_{ma} (us/ft.)
Sandstones	19500	51.3
Dolomites	23000	43.5
Limestones	21000	47.6
Chalk	18000	55.5
Shales	18000	55.5

Wyllie's Formula

$$\phi = \frac{t - t_{ma}}{t_i - t_{ma}}$$

Figure 3.3. Porosity evaluation from sonic logs (Schlumberger, 1979).

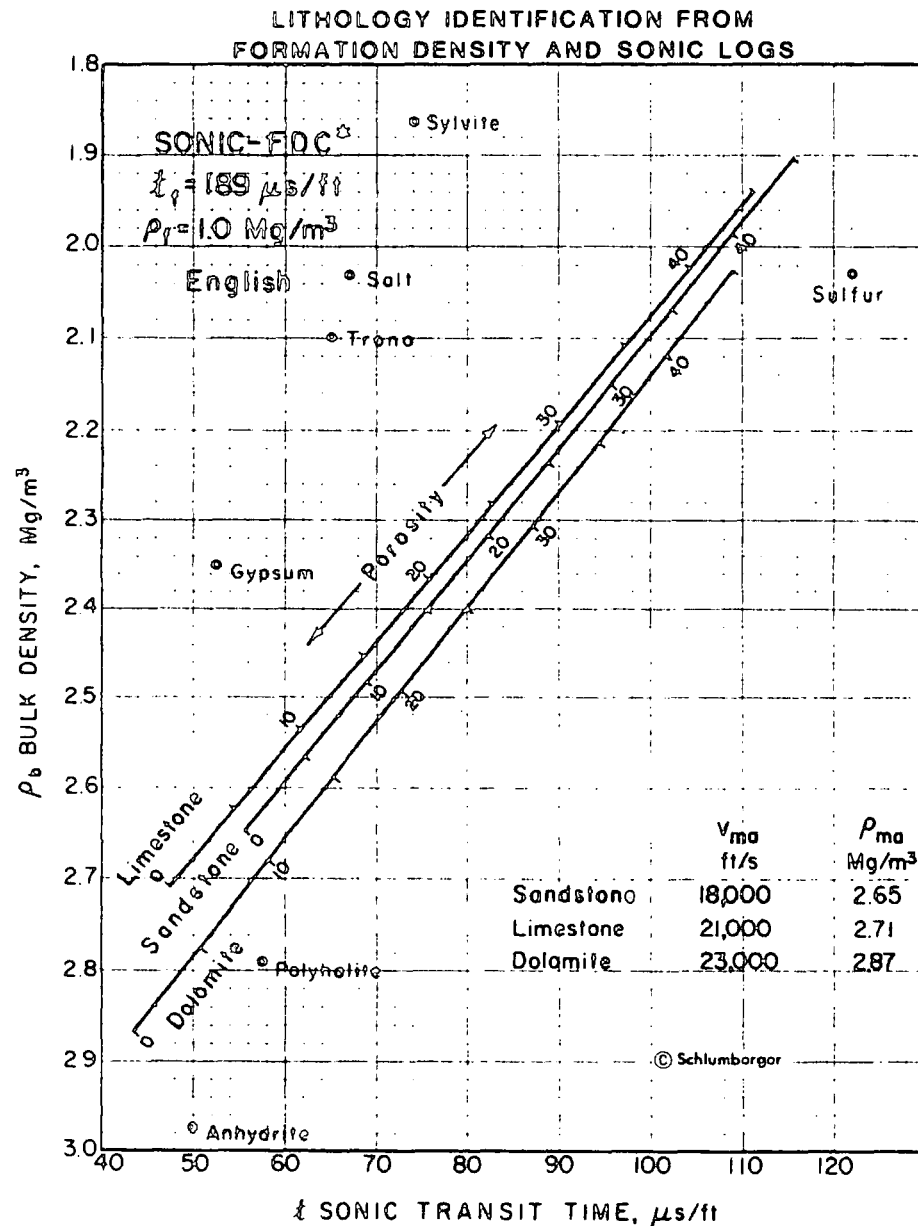


Figure 3.4. Cross-plot. Porosity evaluation from density and sonic logs

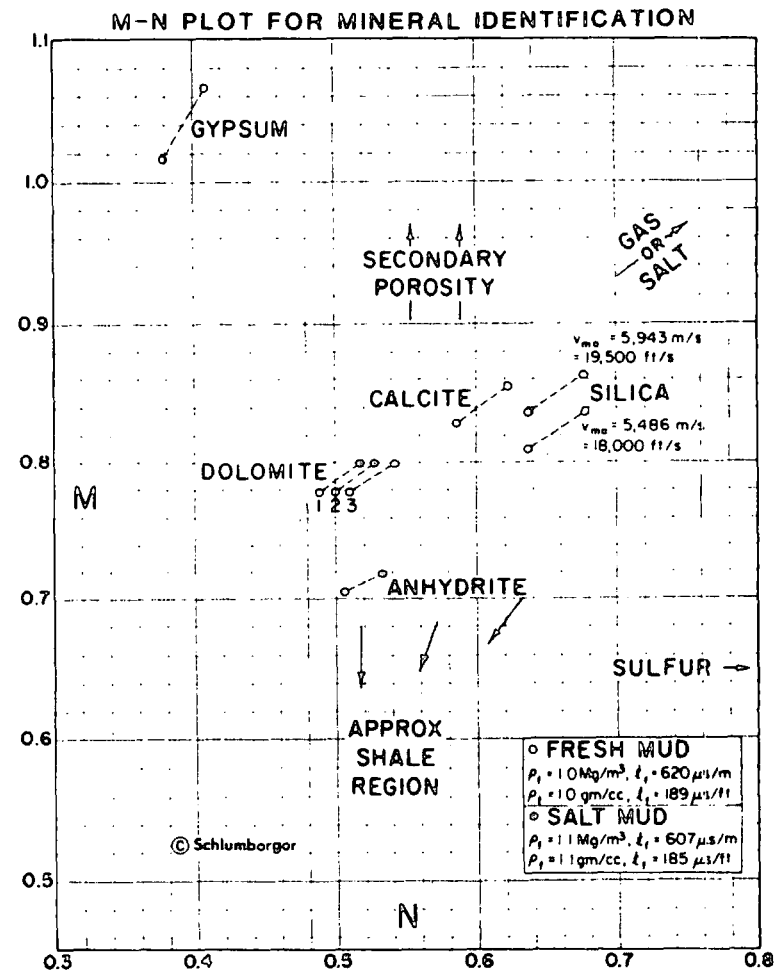


Figure 3.5. M-N Plot. Utilizes all three porosity logs for lithological discrimination.

2. Cross Plots. eg. Sonic and Density logs (figure 3.4).
3. M-N Plots. Use all three logs (figure 3.5).

One further method which can be utilised is to estimate porosity from sample cores and cuttings in the laboratory. This has been done in figure 3.6 and the results when compared with porosity determined from sonic logs shows fairly good correlation. However, the observed core porosities tend to be proportionately less than the sonic values since the former estimate the effective porosity and the latter the absolute porosity.

The use of cross plots (figure 3.4) and M-N plots (figure 3.5) is most beneficial for lithological determination. Lithological control was good in this study due to the availability of composite logs and therefore only single plots were utilised. However, porosity from both sonic and neutron logs are compared for two boreholes (figure 3.7a and b). The results show very good correlation, but for reasons outlined below, only sonic velocity logs, using single plots were utilised:-

1. Density and neutron logs tend only to be run in important (source or reservoir) formations and do not therefore give comprehensive coverage through the whole sedimentary succession.
2. Sonic logs are typically run through the whole or most of the borehole.
3. Density and neutron logs measure the total porosity of the sediments.
4. Sonic logs measure the primary porosity and tend to be unaffected by vugs and fractures. That is, sonic logs measure the compaction of sediments.
5. Neutron logs are unable to differentiate between free and bound water. Thus, in shales especially, the readings may be erroneous.
6. Sonic logs are strongly dependent upon porosity when the lithology is known.

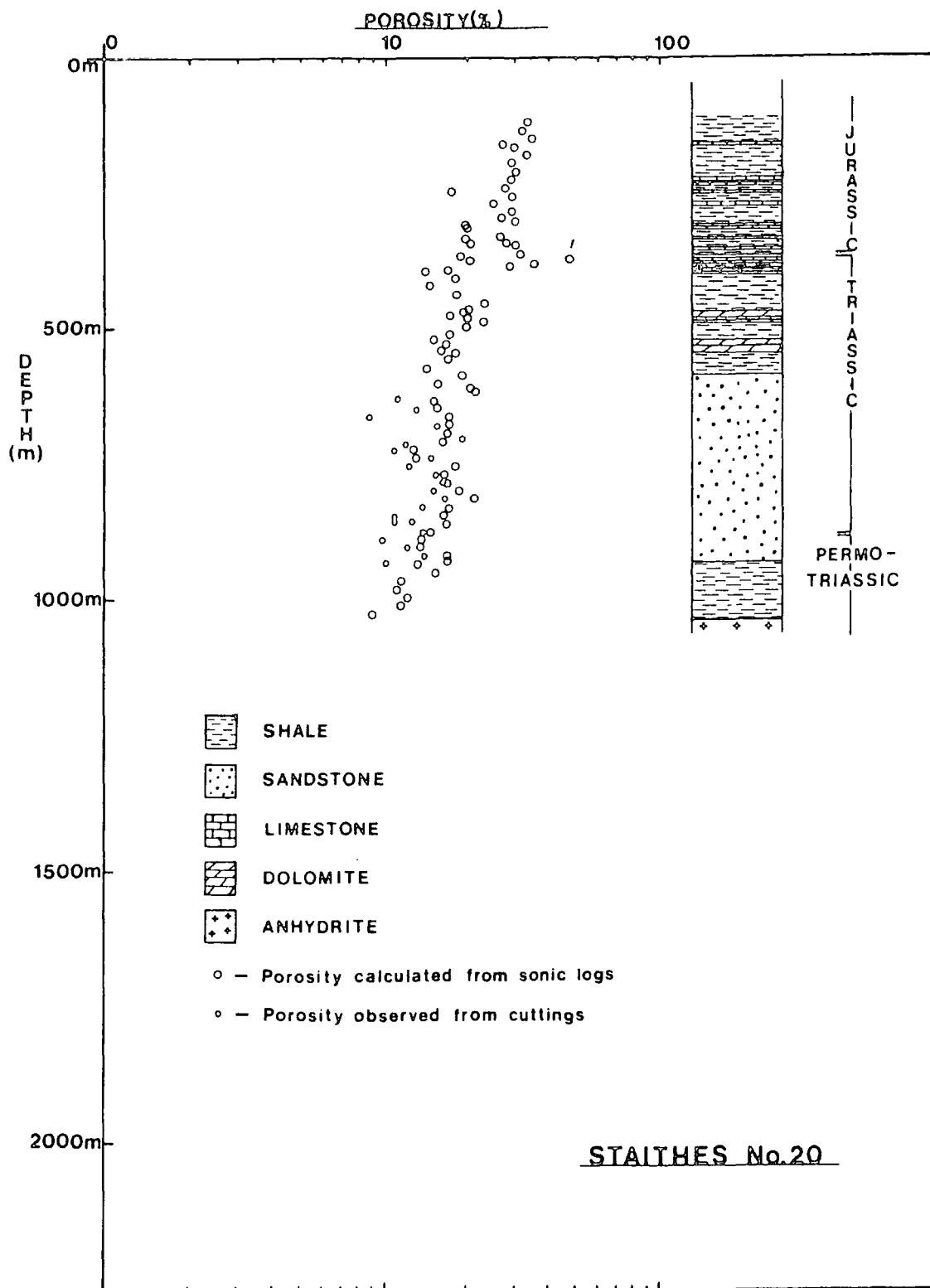


Figure 3.6. Comparison of observed porosity from cuttings and sonic logs for a borehole in the Yorkshire Basin (map 1).

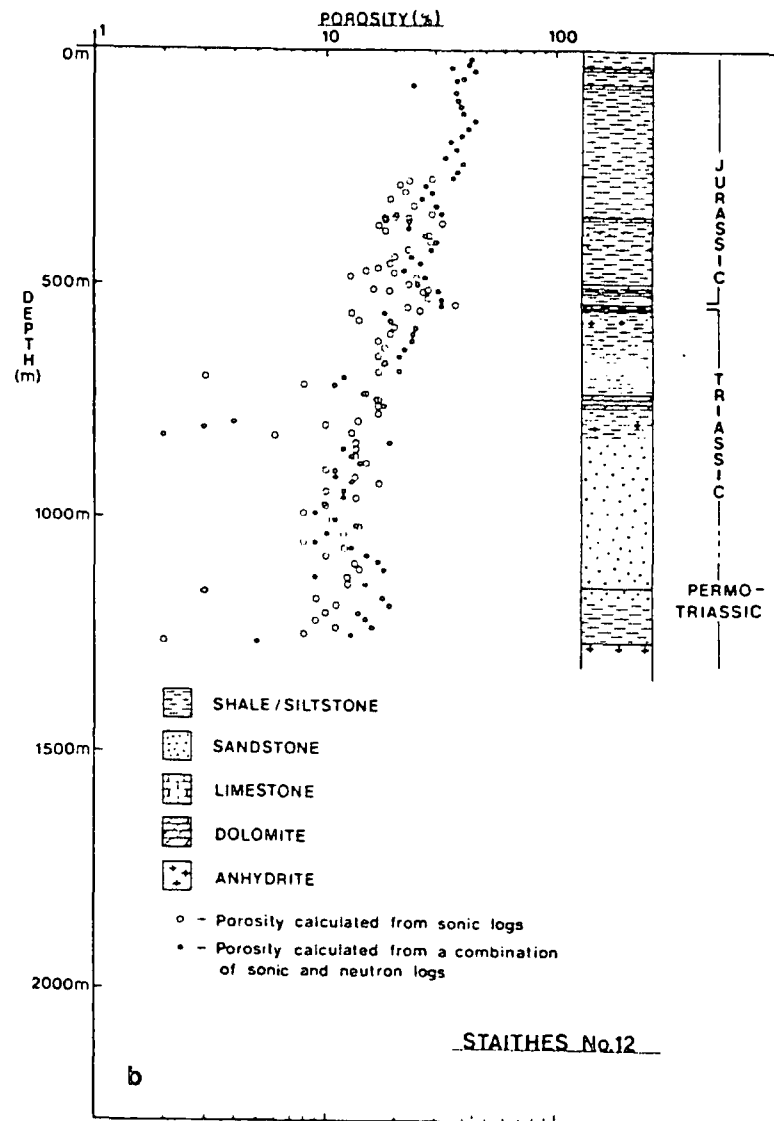
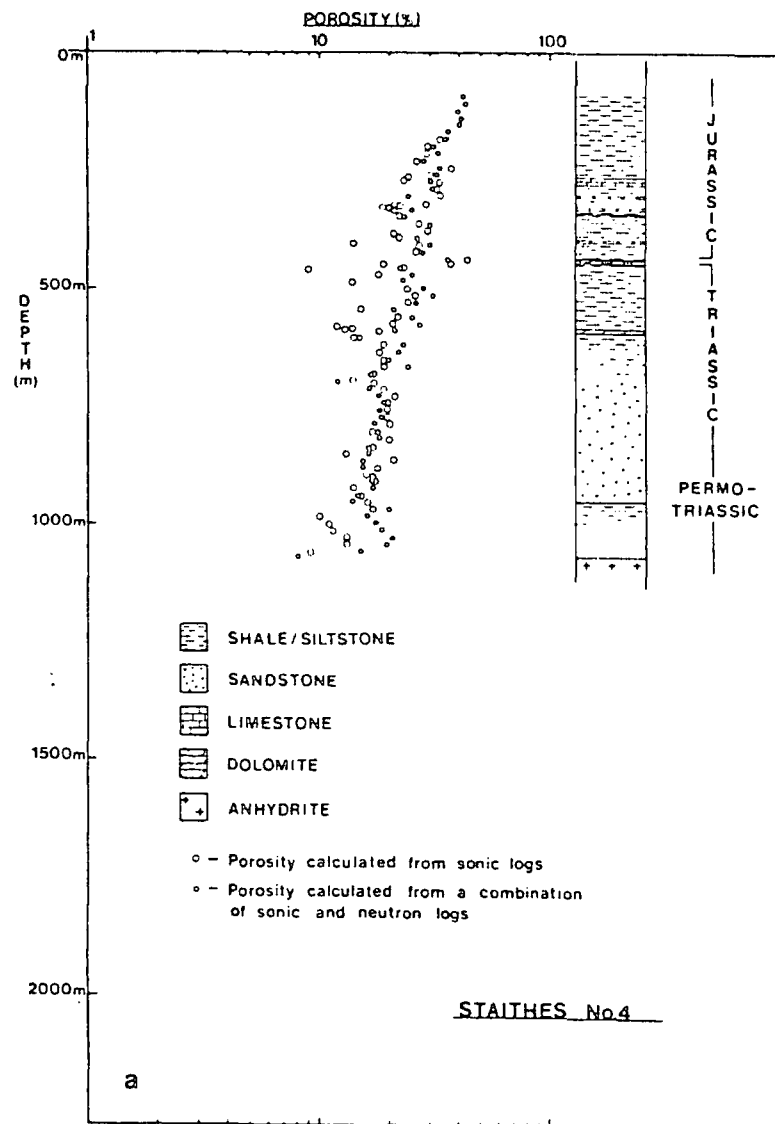


Figure 3.7. Correlation of porosity calculated using single and cross plots (figures 3.3, 3.4) for two boreholes in the Yorkshire Basin.

Most boreholes have composite logs which help give excellent correlation between lithology and the response on the wireline logs. Where lithological data is missing, utilisation of density, neutron and gamma-ray logs aids in lithological discrimination.

7. Sonic logs clearly detect overpressured sections.

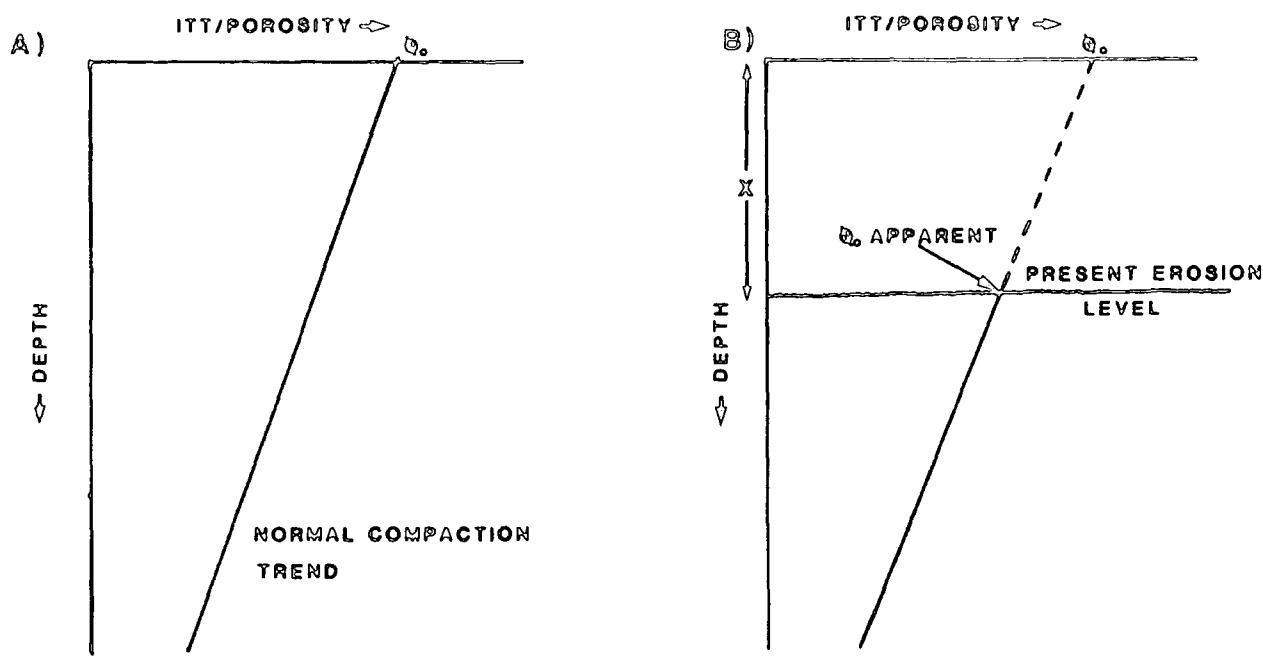
For the above reasons, the sonic log method was used to calculate porosity. It provides the most comprehensive, lithologically and burial dependent downhole porosity information.

3.4 Principles of the Relationship between Porosity/ Interval Transit Time and Depth of Burial.

Why do I need to evaluate the relationship between porosity/interval transit time and depth of burial in the context of this particular study?

1. Quantification of Uplift (this Chapter and Chapter 5).
 2. Quantification of Subsidence (Chapter 4).
- (a) Reconstruction of maximum sedimentary thickness using 1. above.
 - (b) The variation of porosity with depth affects the load of sediments on the basement. The technique of backstripping (Chapter 4) which isolates the driving tectonic subsidence in a basin, utilises the porosity:depth relationship to decompact the sedimentary sequence and remove the contribution from their load to the total subsidence in the area.

As has been stated (section 3.3 and figures 3.2 and 3.3), the variation of porosity and interval transit time with depth is quantifiable and lithologically dependent. However, the curves in figure 3.3 depict the values of porosity for interval transit time and vice versa, measured purely from sonic logs and inde-



x = UPLIFT OR SEDIMENT REMOVED.

Figure 3.8. Schematic representation of the method used to estimate uplift or removed overburden from sonic logs.

pendently of the depth of burial. We may expect each lithology to have or display a normal, depth dependent compaction trend which can either be calculated from boreholes in the study area, to obtain a trend characteristic to a particular basin, or from other studies of similar lithologies. In principle, the offset of the observed compaction trend (porosity/interval transit time: depth curve) from the normal or expected compaction trend is proportional to the amount of uplift that has occurred (figure 3.8).

Thus, the porosity:depth relationship can play an important role in the quantitative and qualitative analysis of both subsidence and uplift or inversion.

3.5 Lithological Variation in the Compaction Trends.

Sediments such as shale, chalk, sandstone and carbonates all compact in a similar fashion but due to the physio-chemical variation of the different matrices, the behaviour is not exactly the same. Where possible, therefore, each lithology must be treated independently. Figures 3.9.1 - 3.9.20 represent the variations of porosity and interval transit time with depth on a lithological basis for 78 boreholes throughout the Yorkshire, Sole Pit and East Midland Basins. Their geographical distribution is illustrated in map 1 and the relative positions of the various licensing blocks are illustrated in figure 3.10

Porosity and interval transit time data have been studied for sediments of Carboniferous to Cretaceous age in the study area. However, one problem in this particular region is that the computation of a normal compaction trend for sediments typical to these basins is hindered due to the probability that the majority of boreholes, at least in the Yorkshire and Sole Pit Basins, have undergone a substantial amount of uplift. Thus, the majority of sedimentary sections and their porosity/interval transit time:depth curves are at an elevated position with respect to their maximum burial depth (figure 3.8). They do not represent a

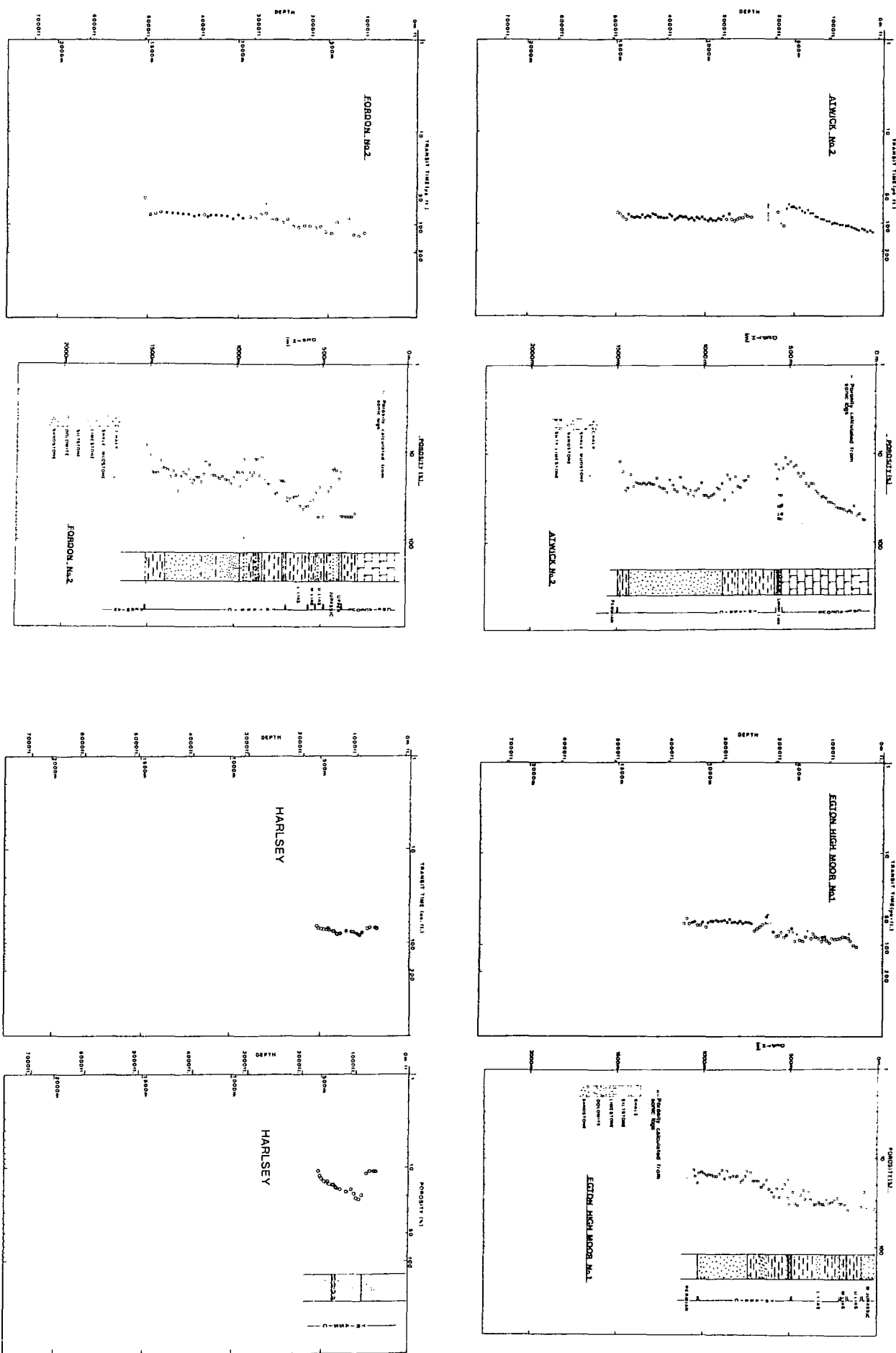


Figure 3.9.1 Figure 3.9.1 - 3.9.20 Compaction trends from analysis of sonic logs

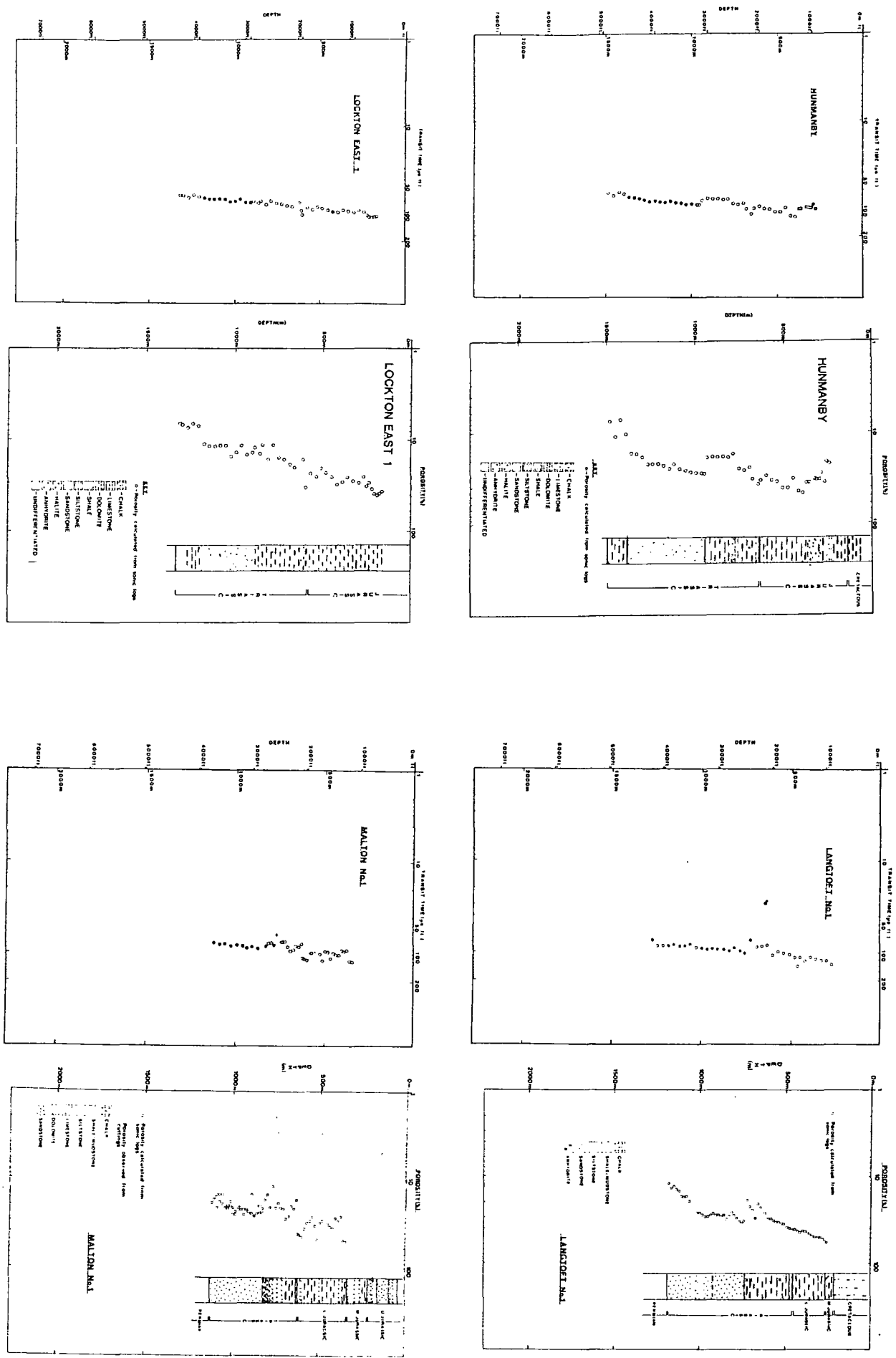


Figure 3.9.2

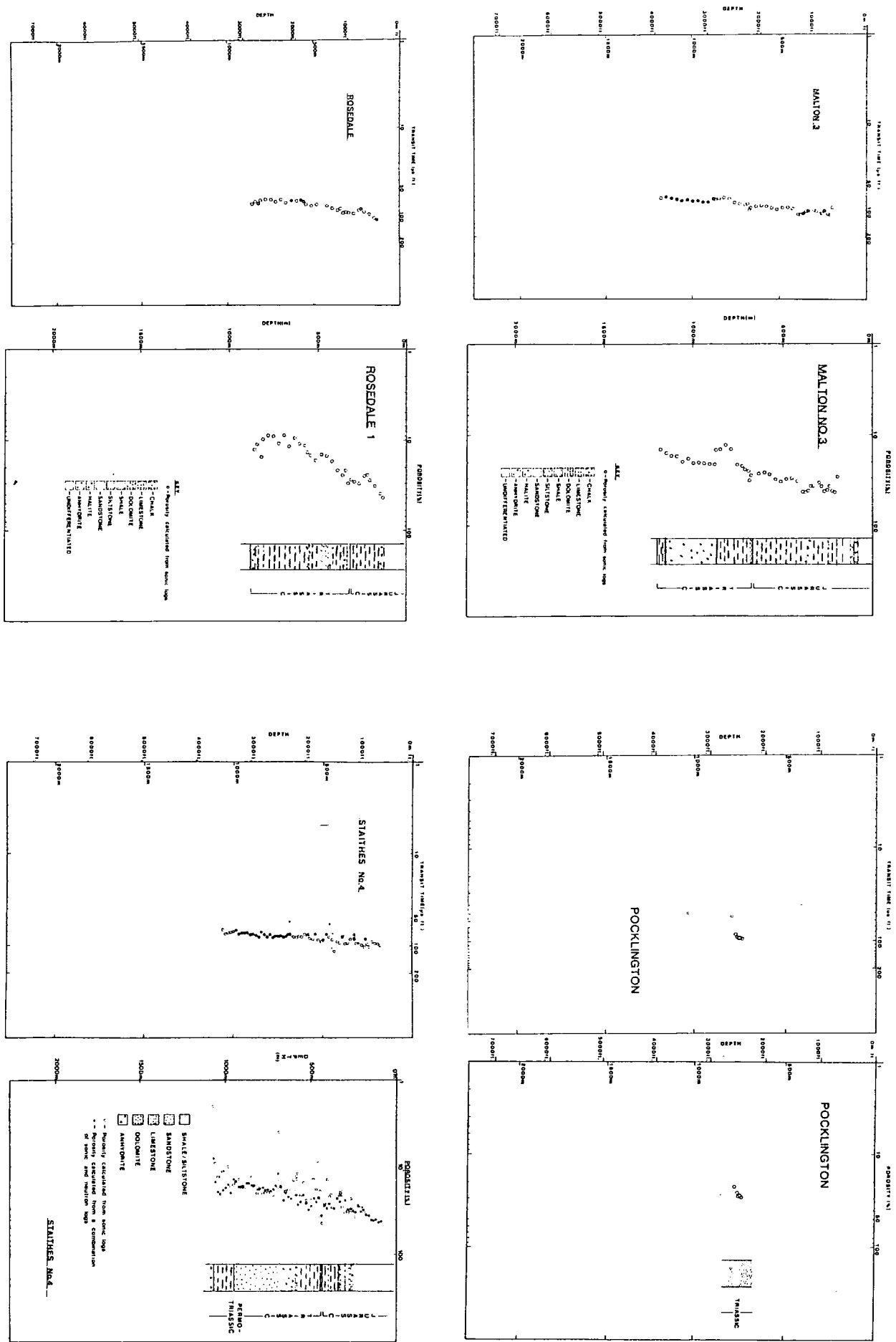


Figure 3.9.3

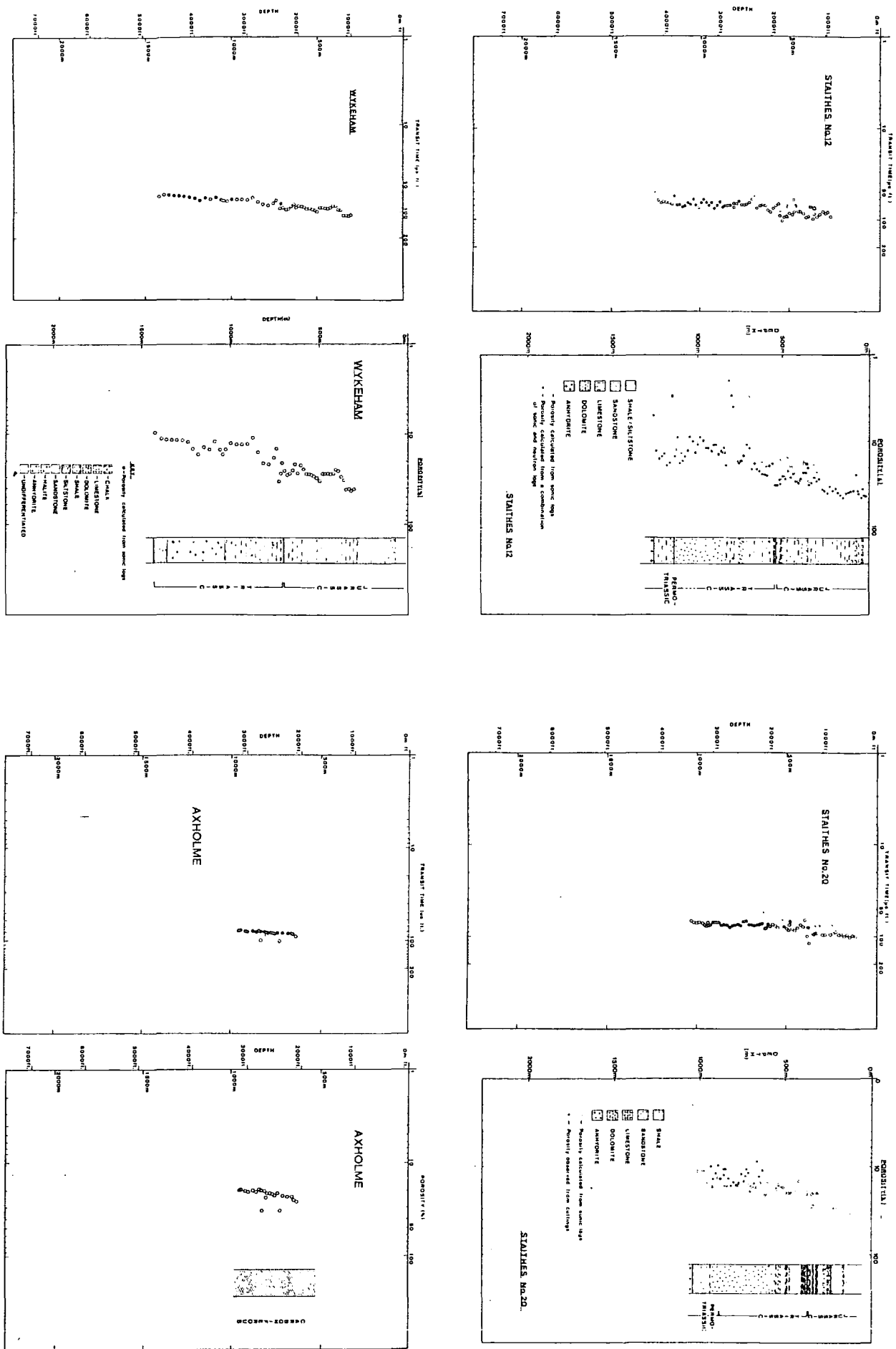
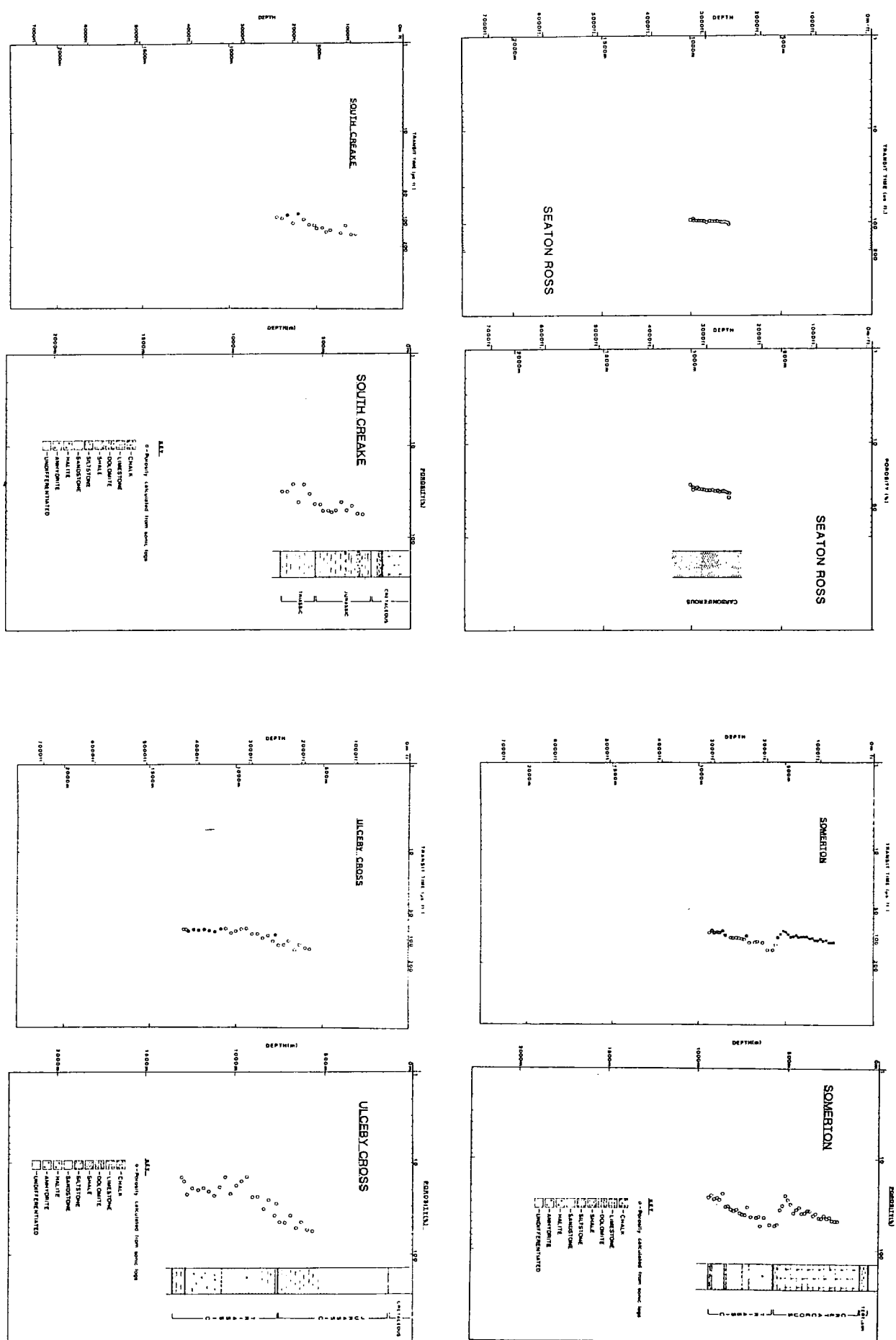


Figure 3.9.4



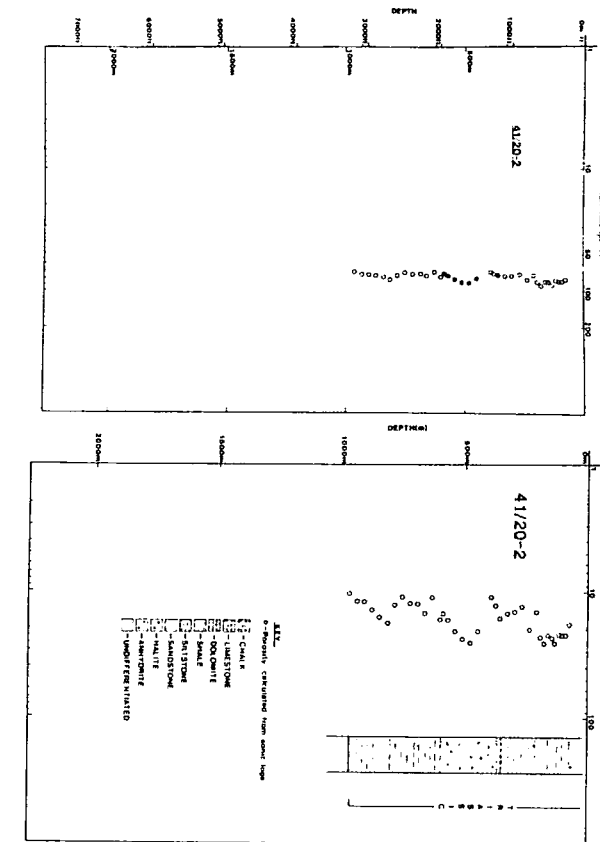
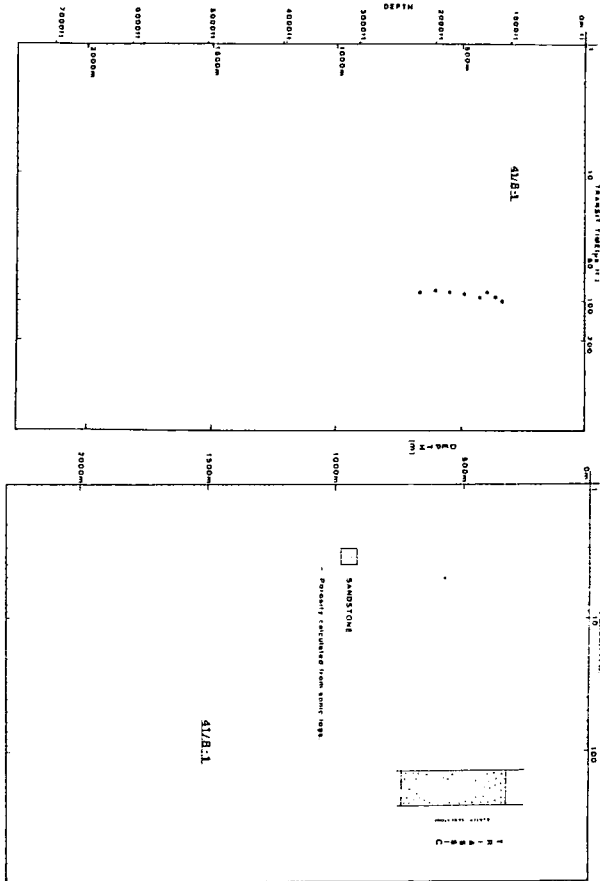
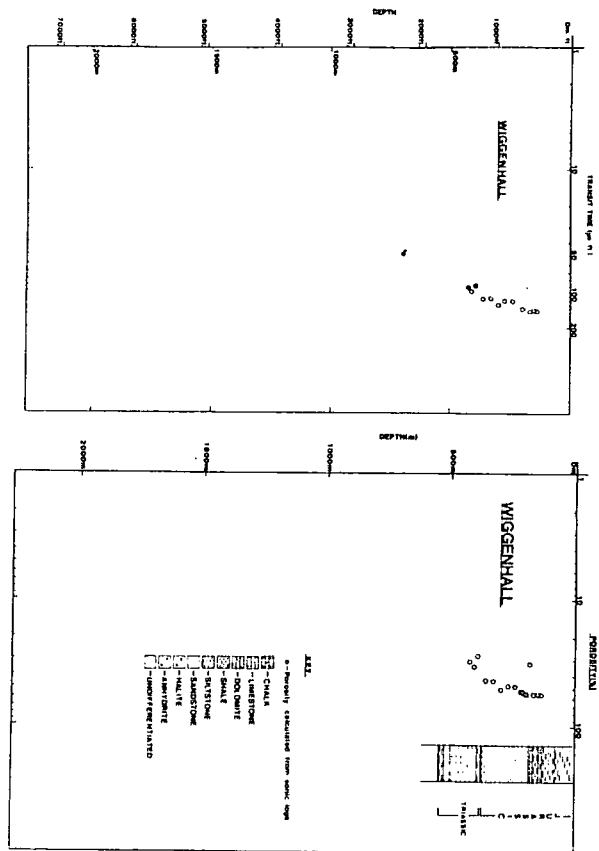
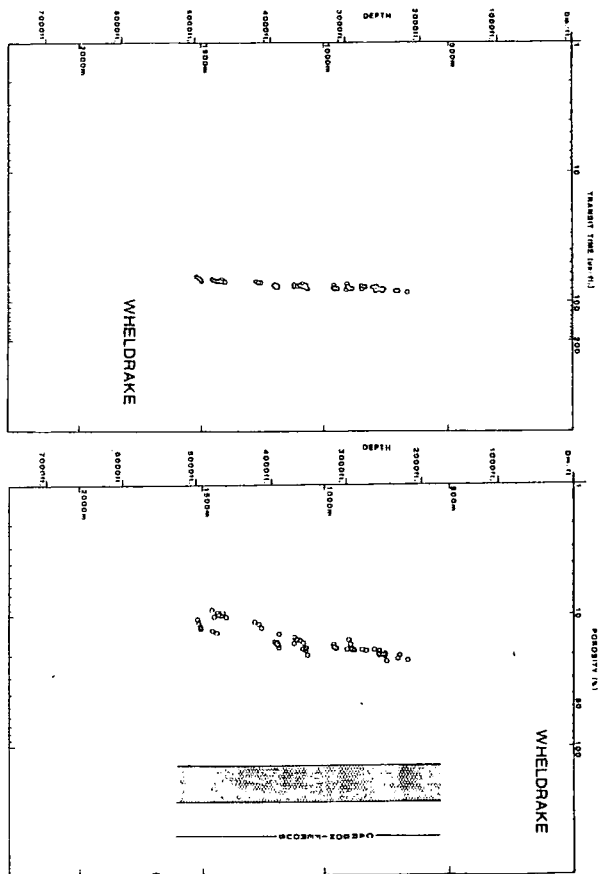


Figure 3.9.6

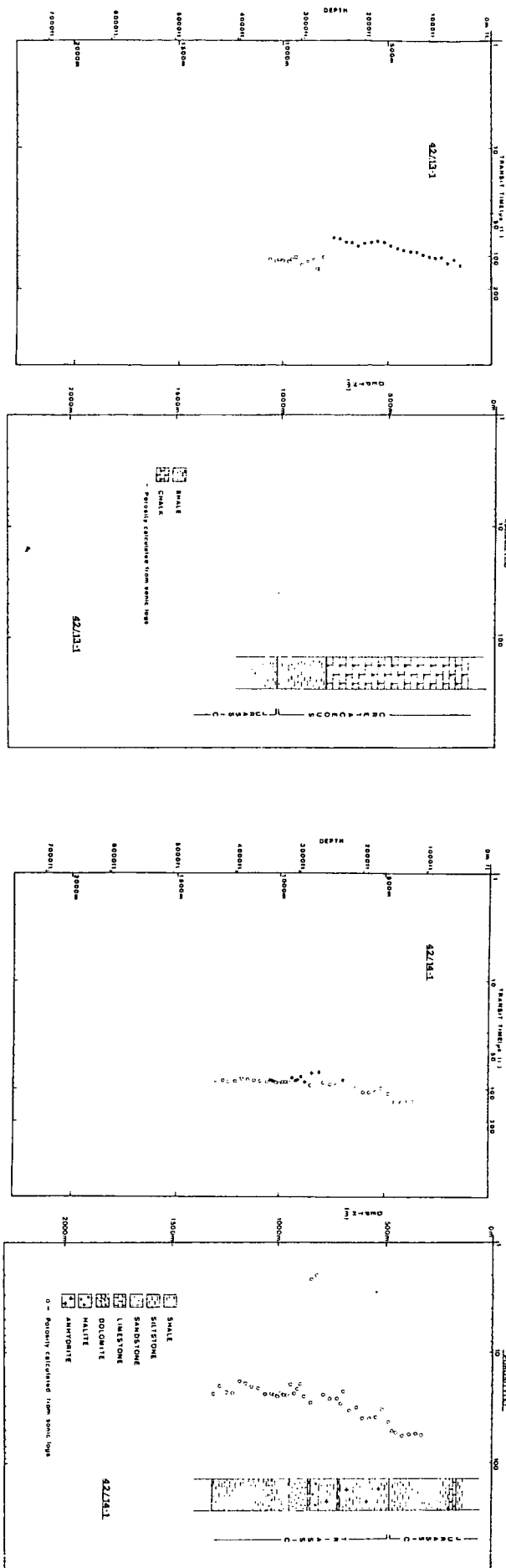
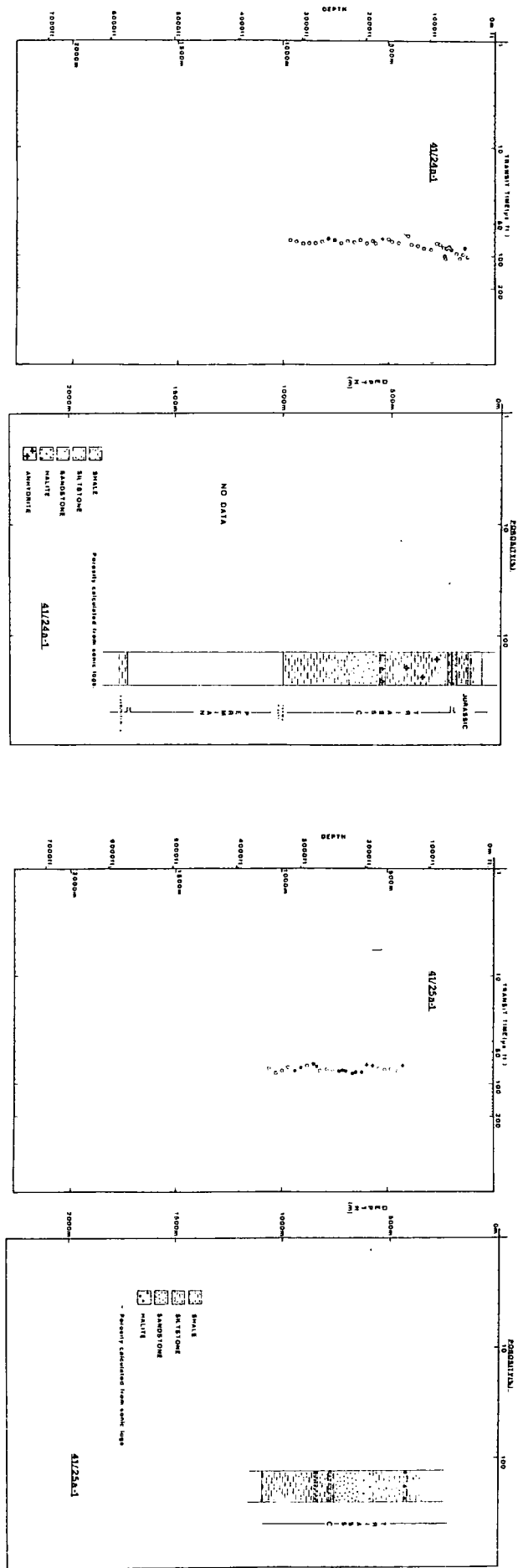


Figure 3.9.7

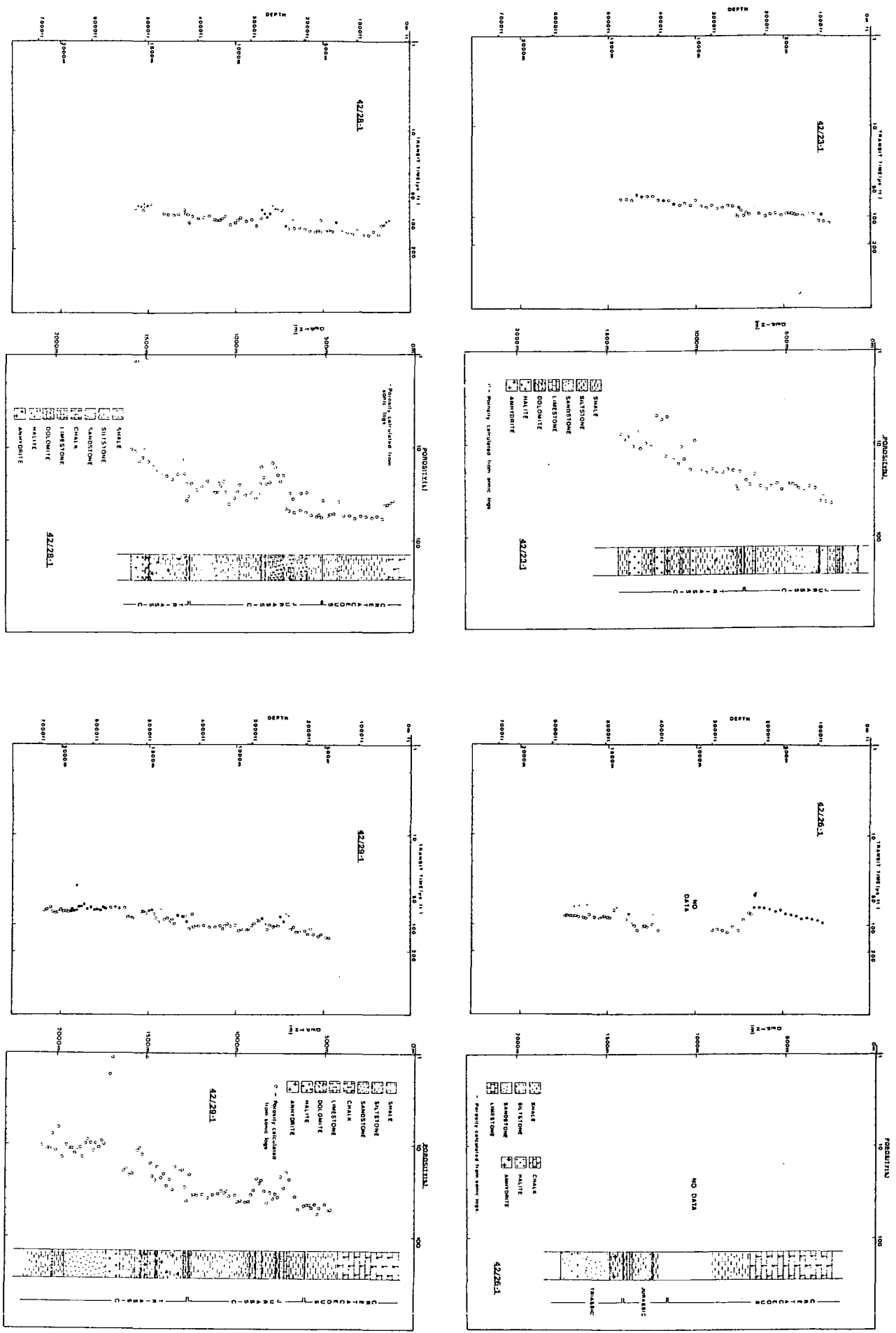


Figure 3.9.8

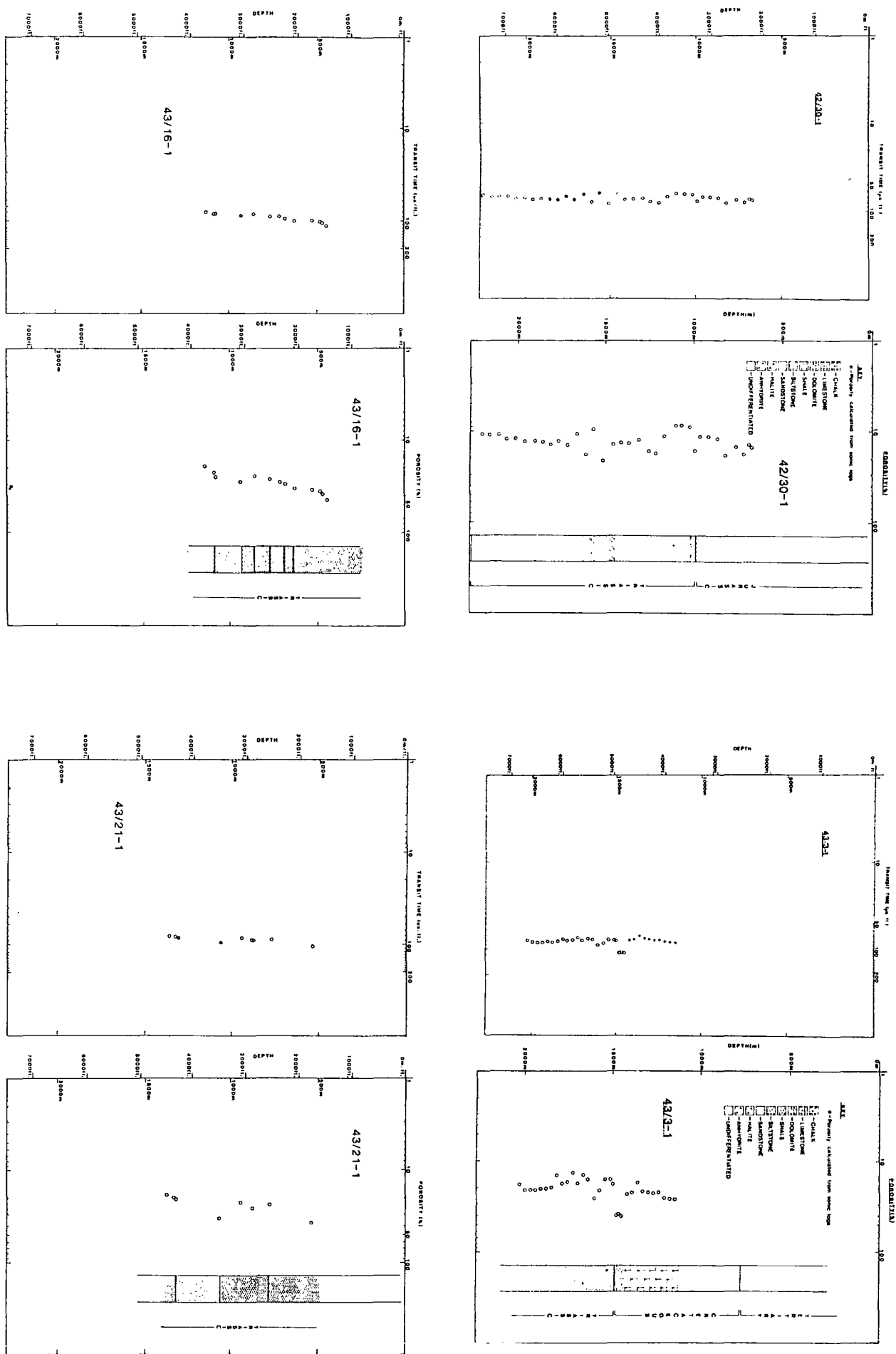


Figure 3.9.9

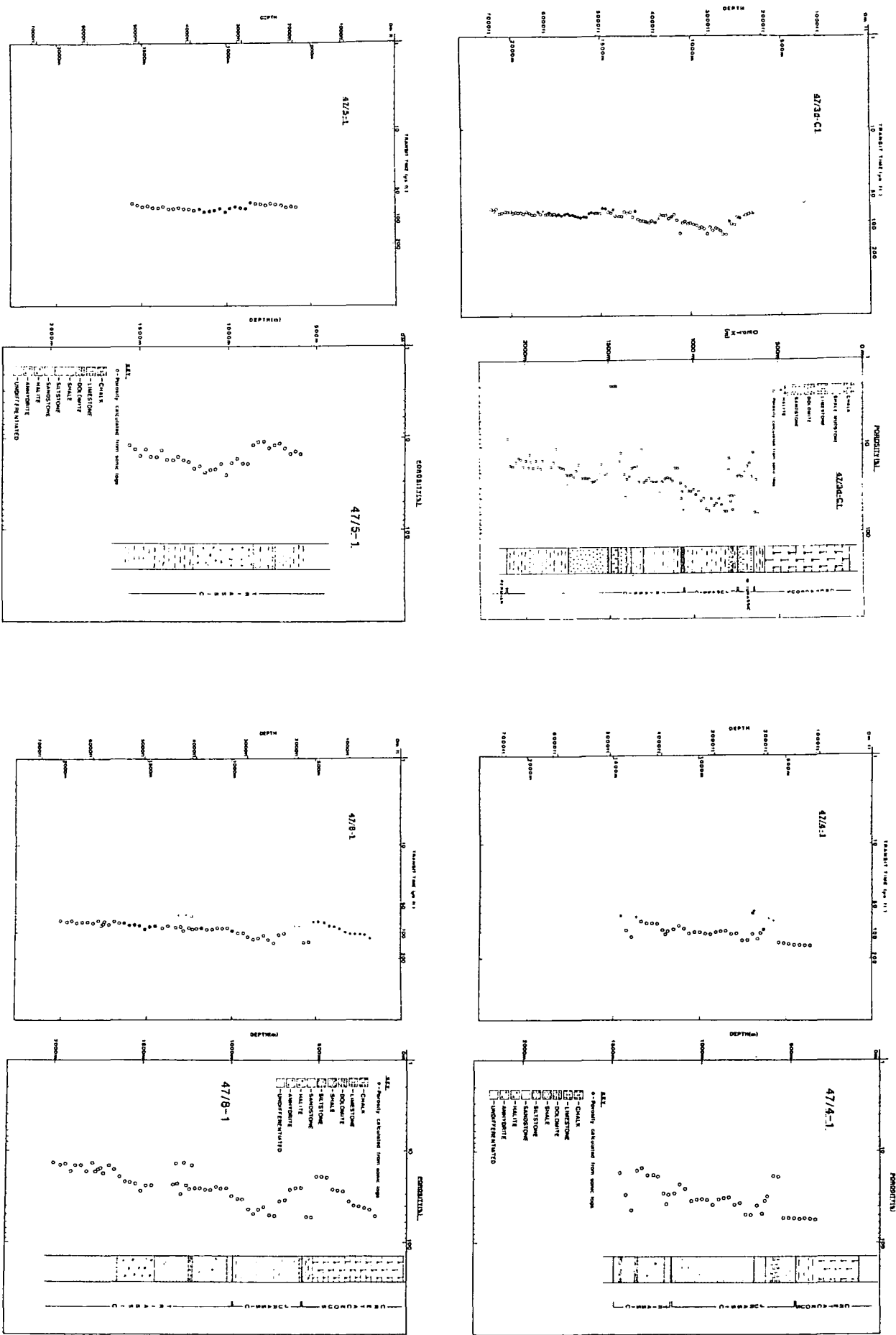


Figure 3.9.10

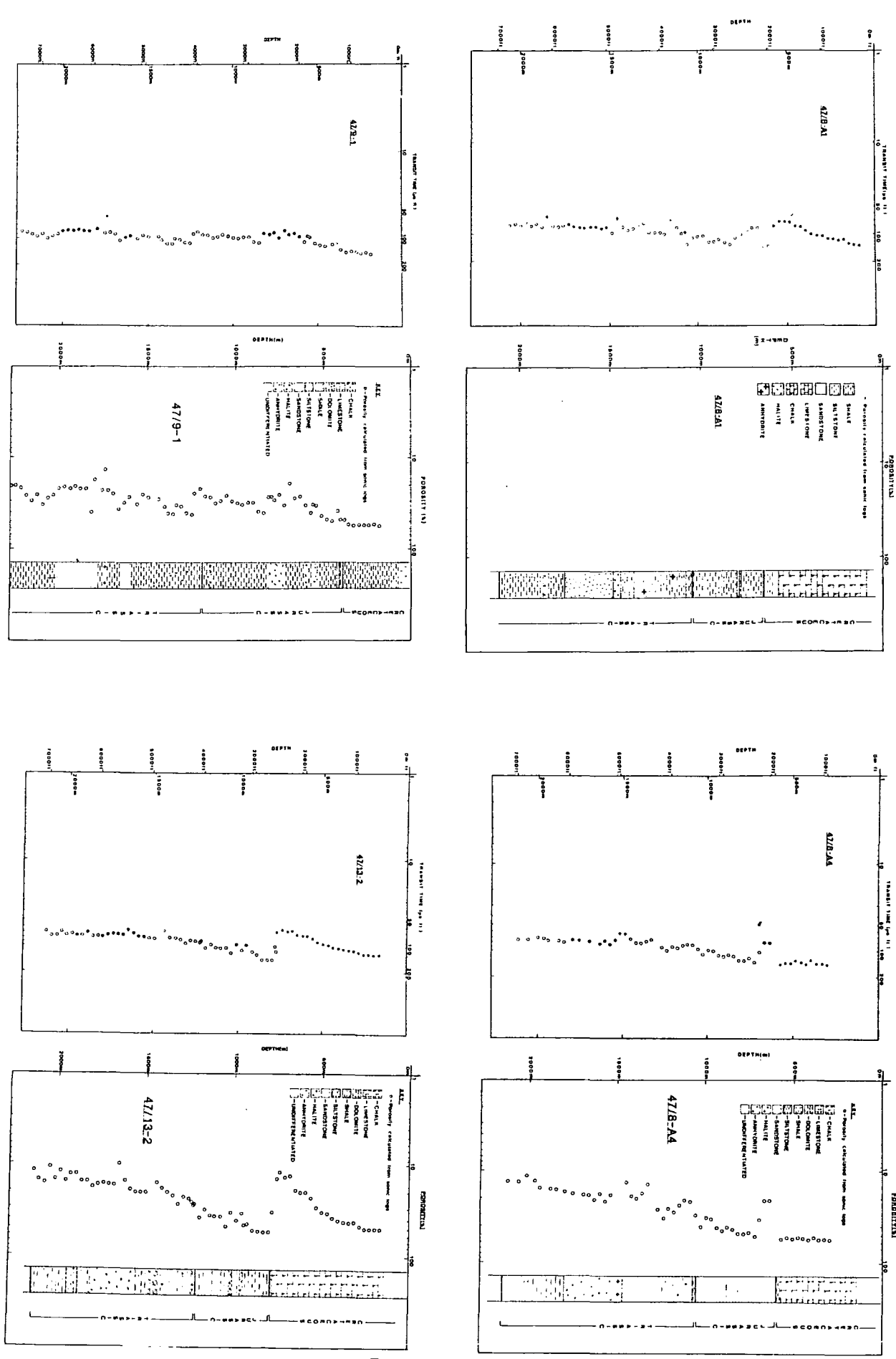


Figure 3.9.11

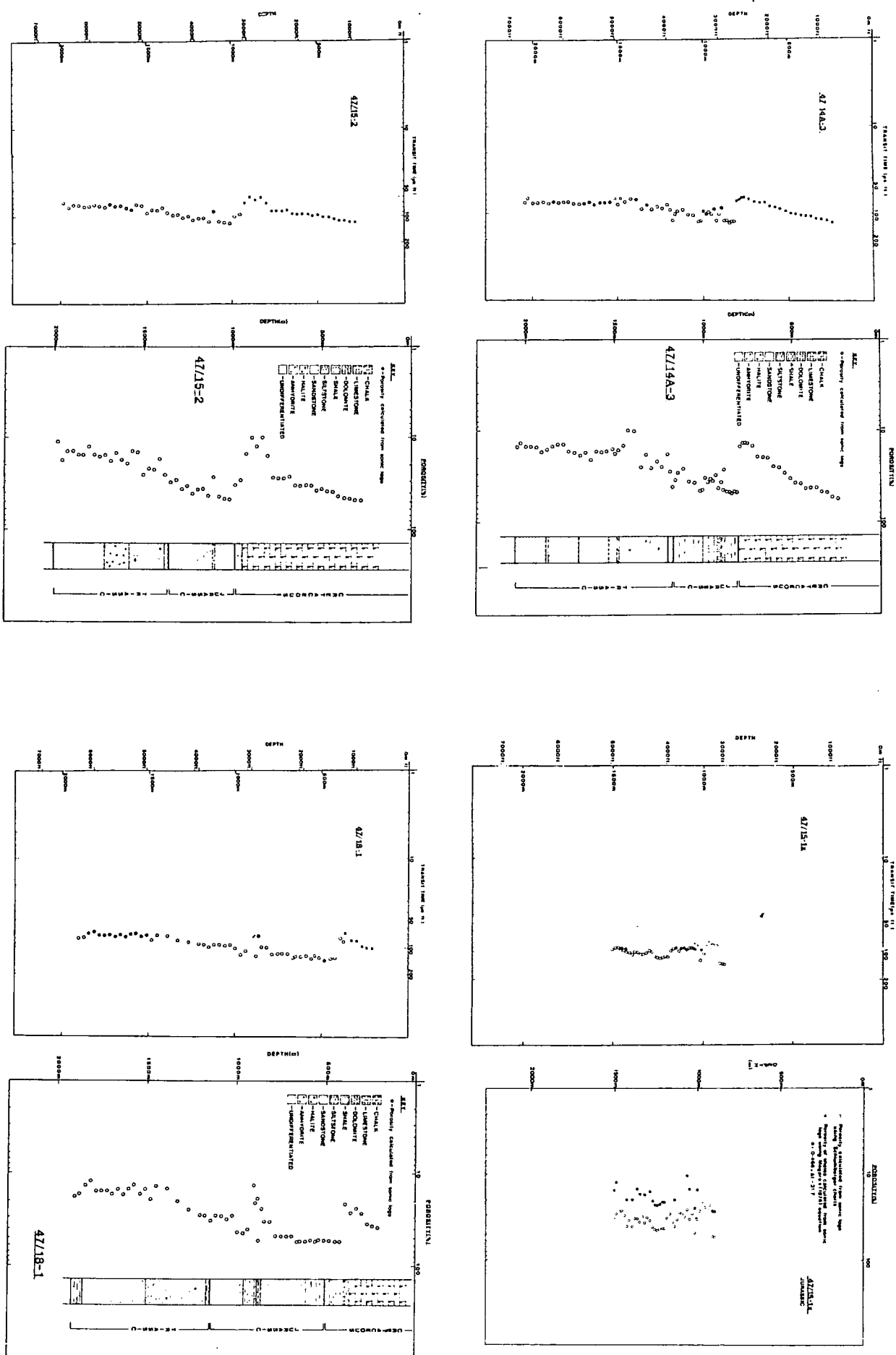


Figure 3.9.12

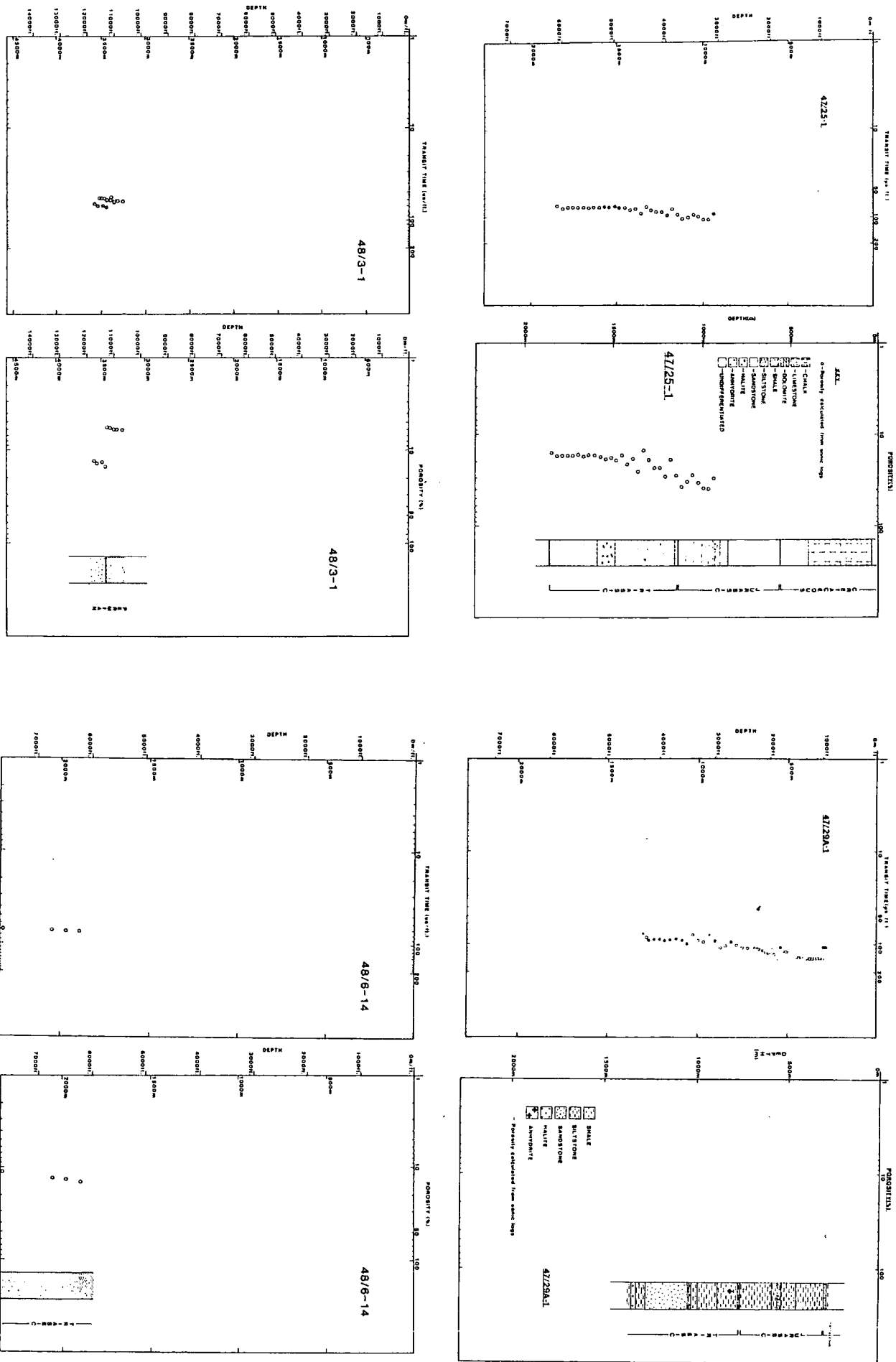


Figure 3.9.13

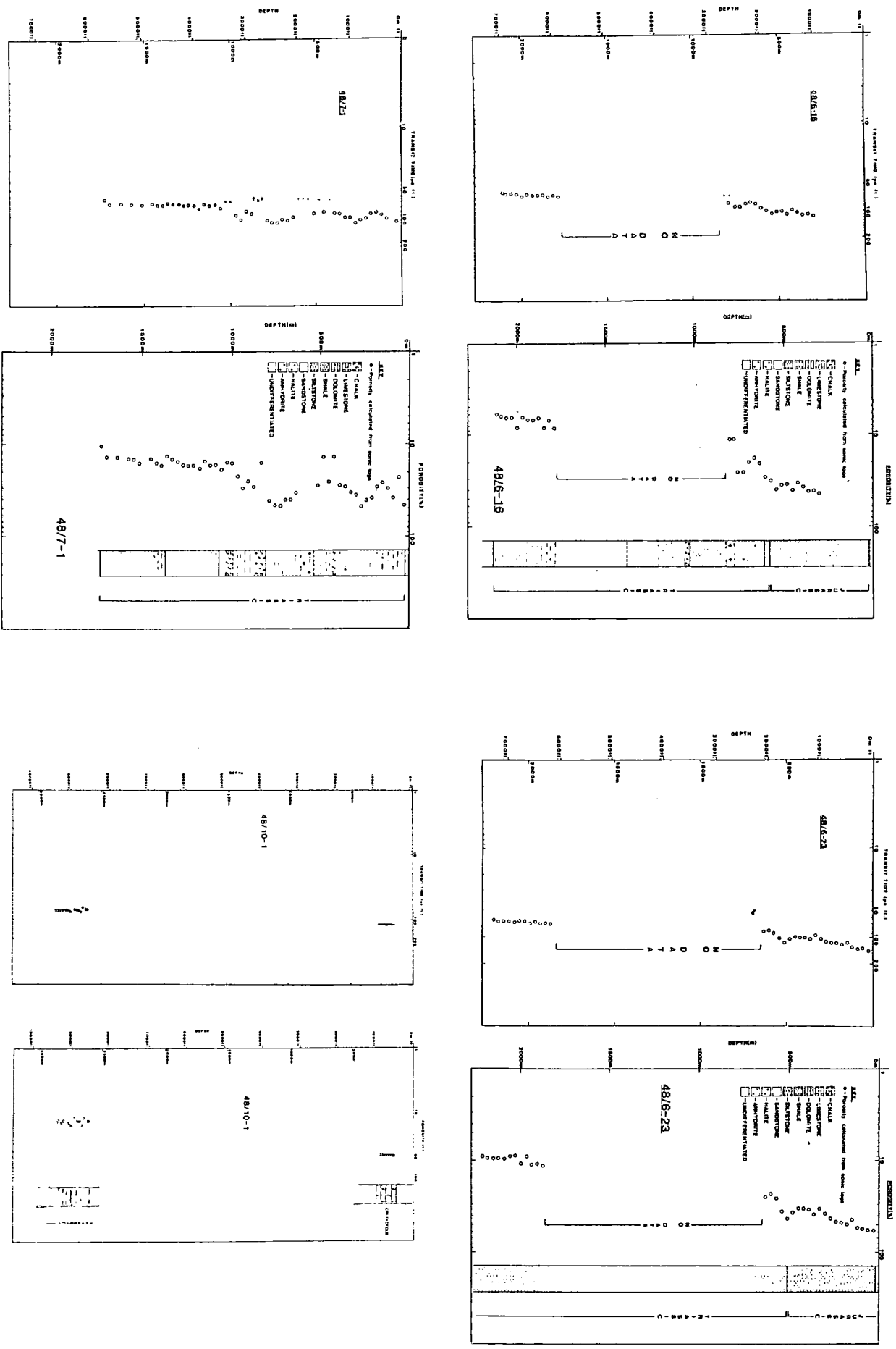


Figure 3.9.14

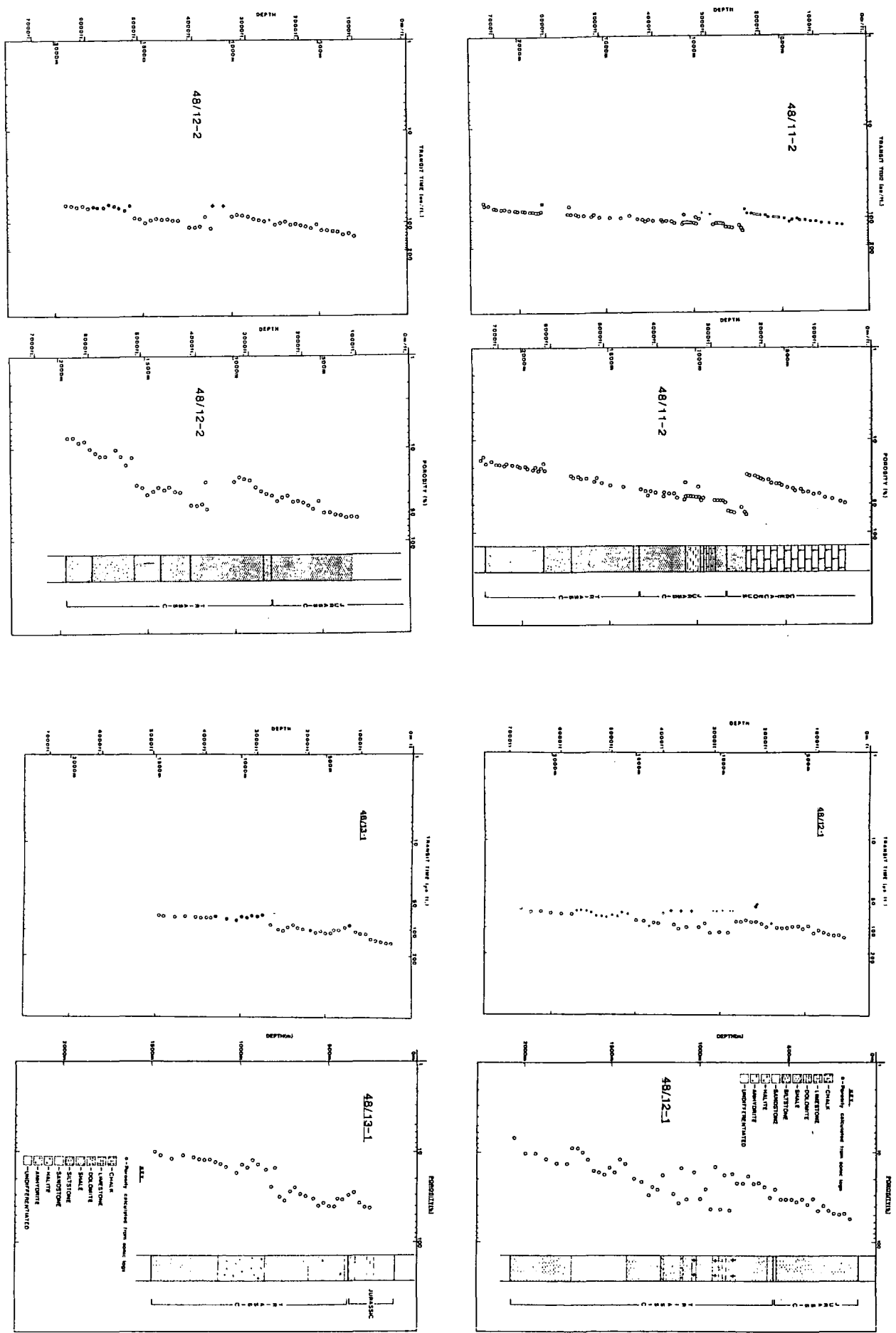


Figure 3.9.15

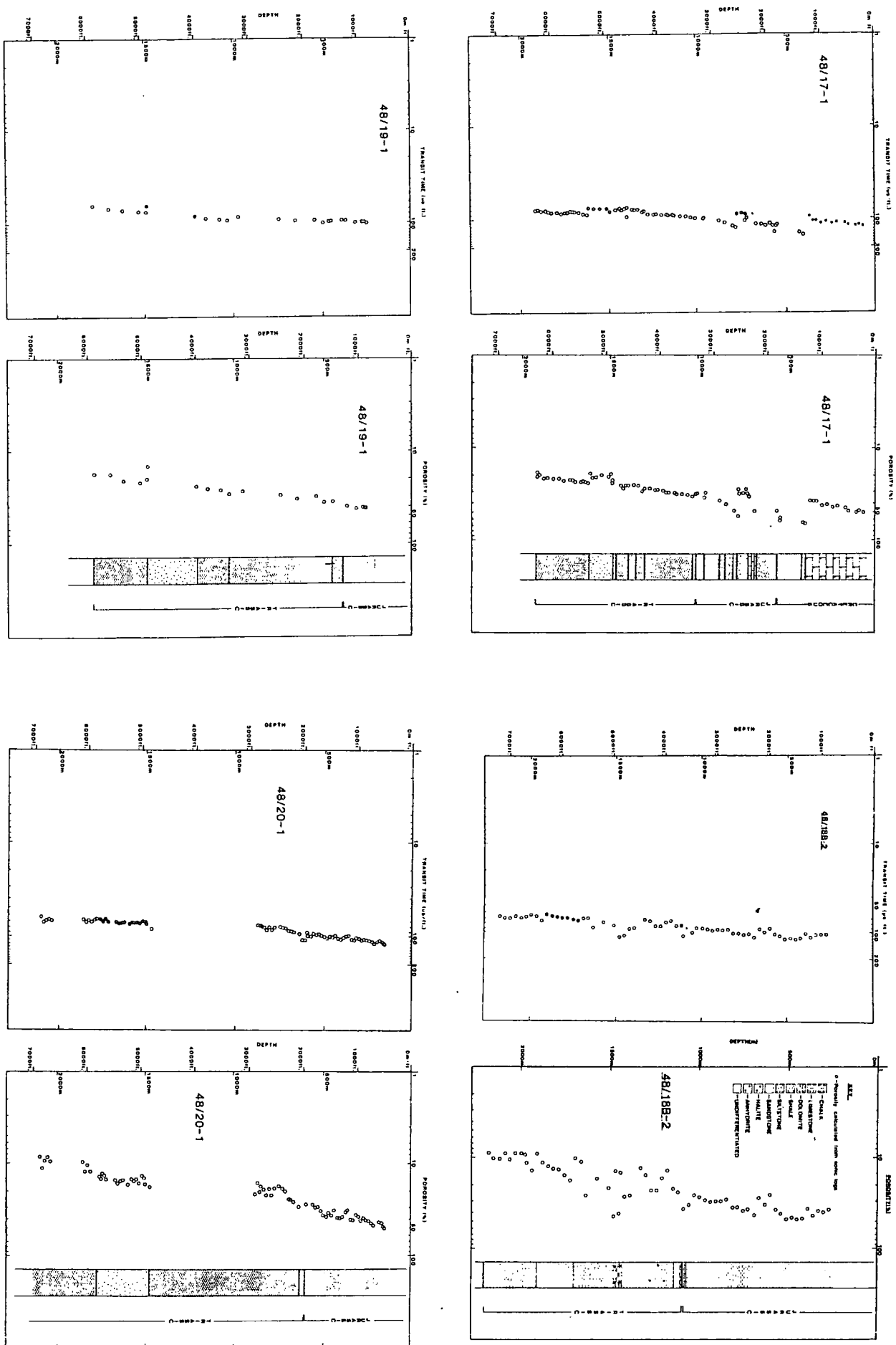


Figure 3.9.16

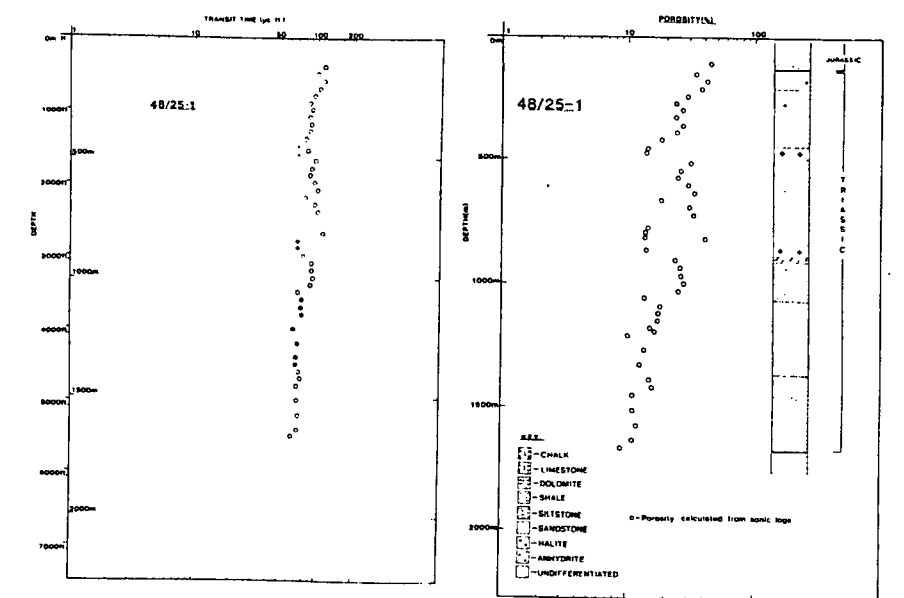
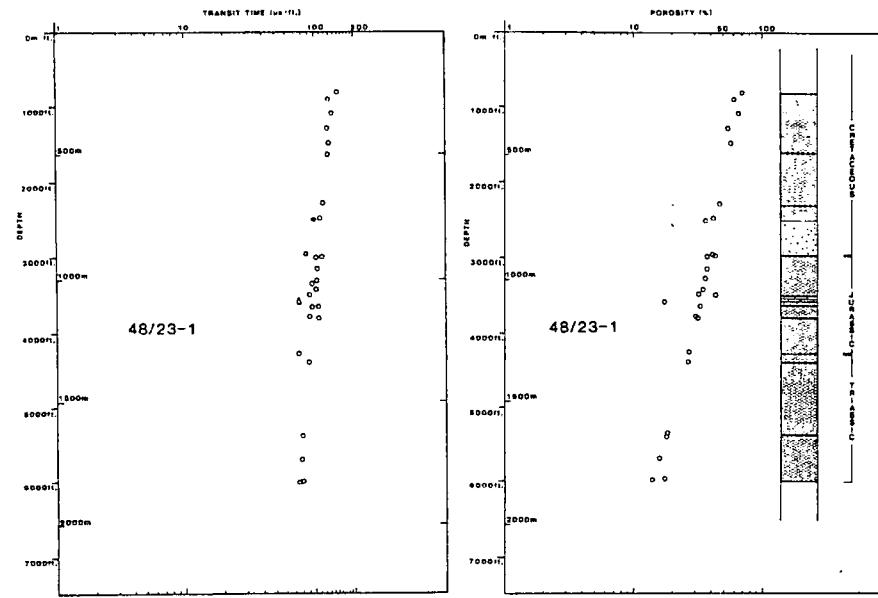
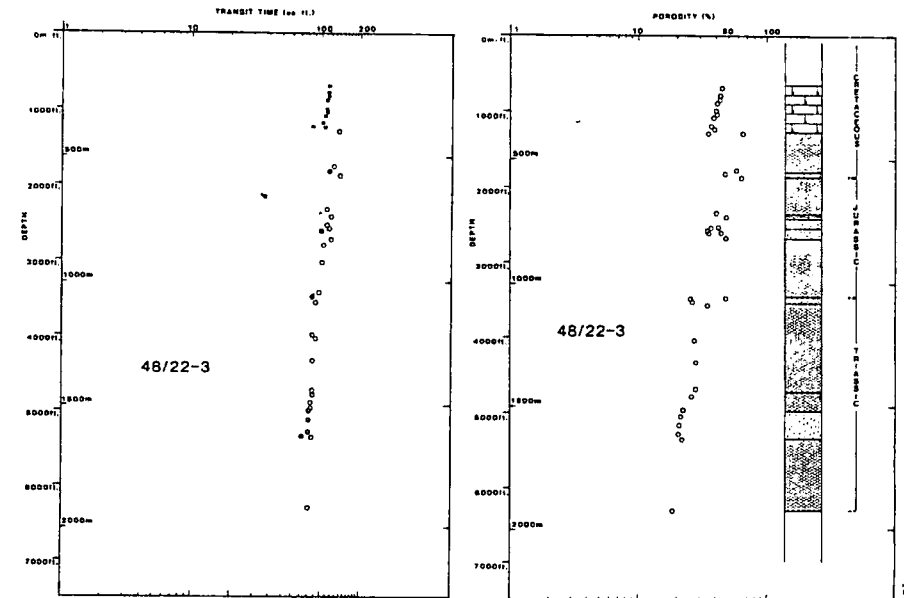
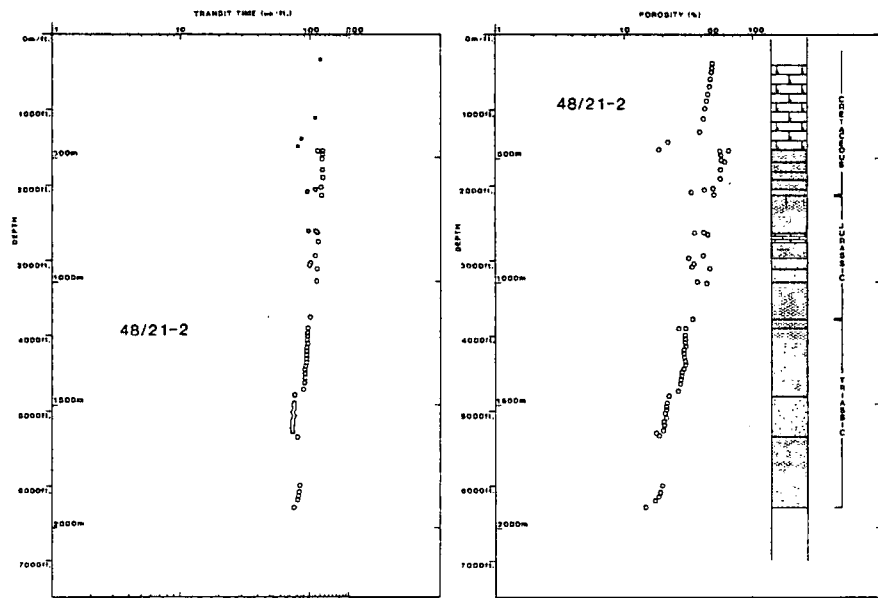


Figure 3.9.17

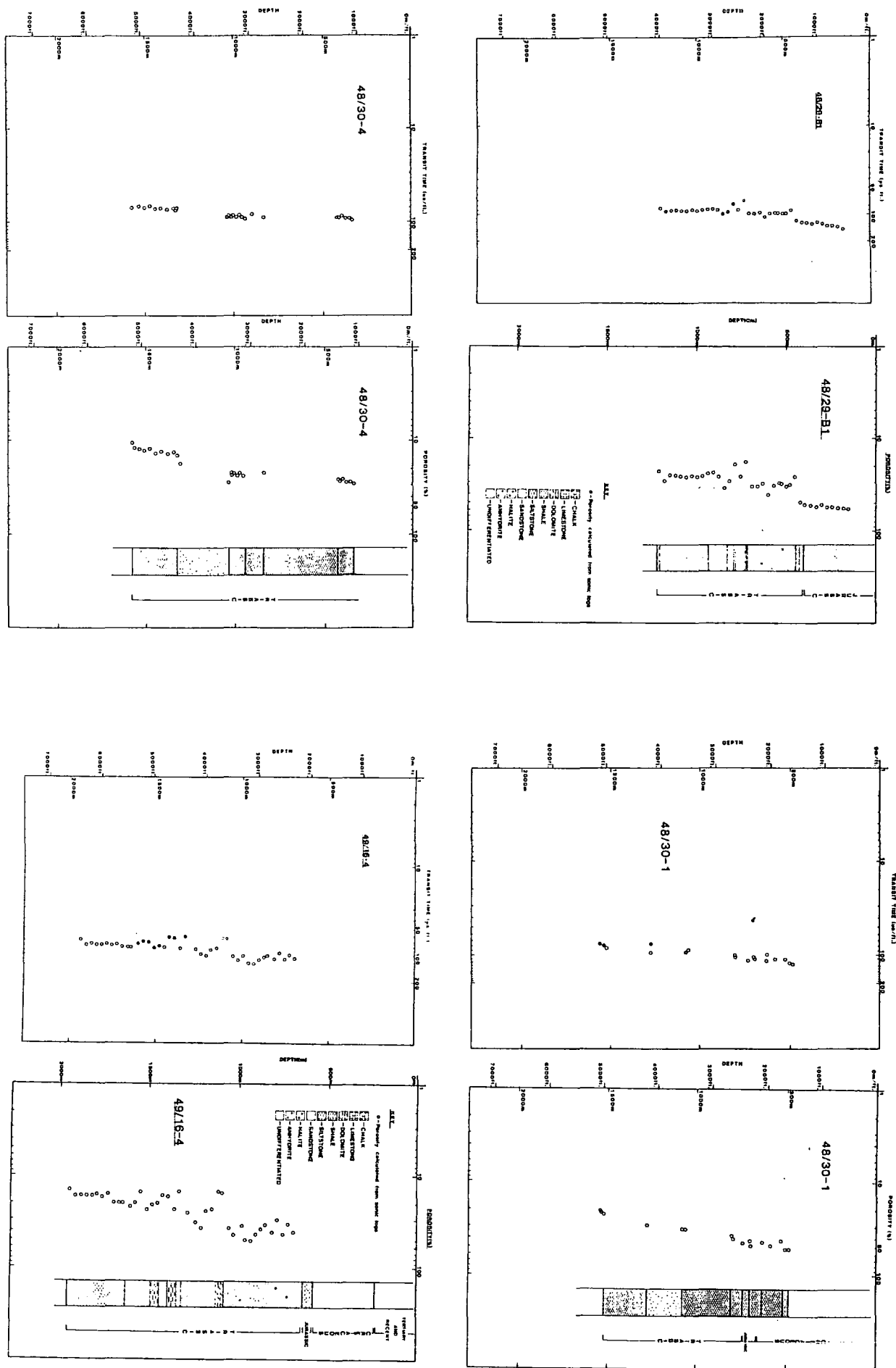


Figure 3.9.18

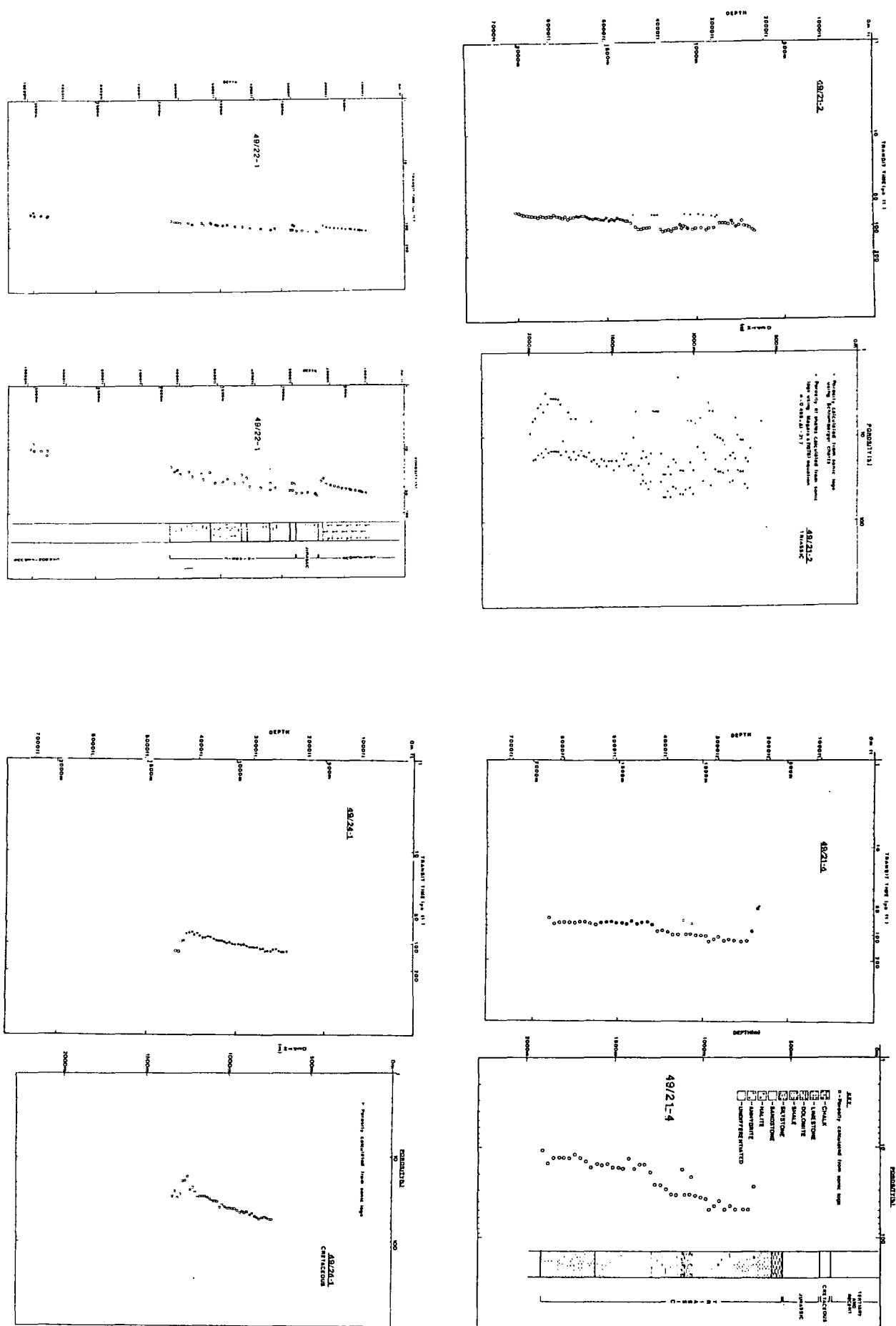


Figure 3.9.19

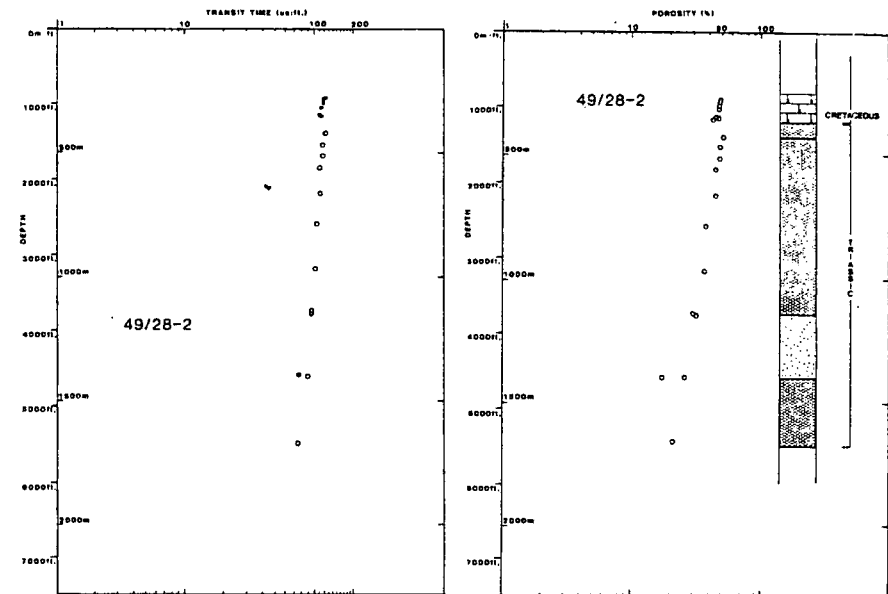
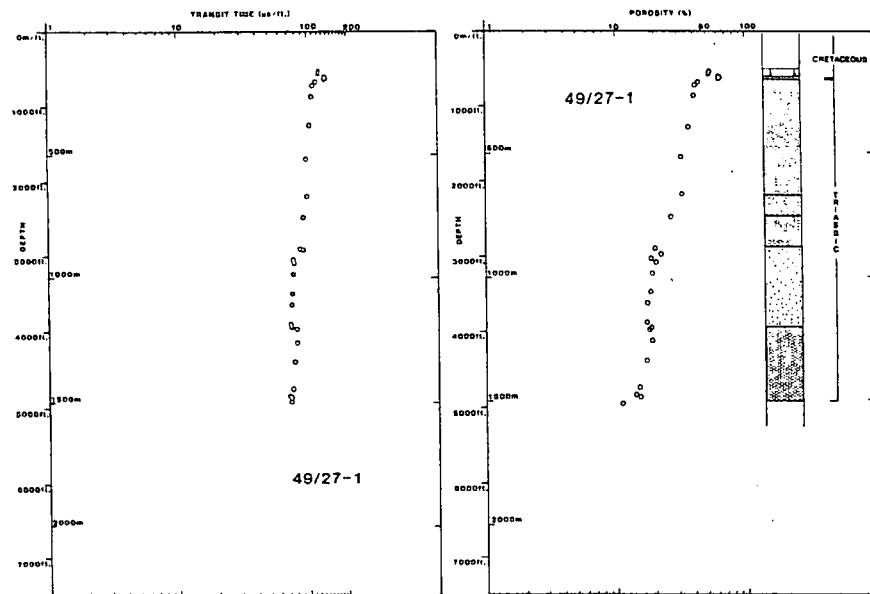


Figure 3.9.20

KEY - INTERVAL TRANSIT TIME

- - SHALE
- - SANDSTONE
- △ - LIMESTONE
- - DOLOMITE
- - CHALK
- △ - ANHYDRITE
- + - HALITE

KEY - POROSITY

- CHALK
- SHALE / MUDSTONE
- LIMESTONE
- DOLOMITE
- SANDSTONE
- HALITE

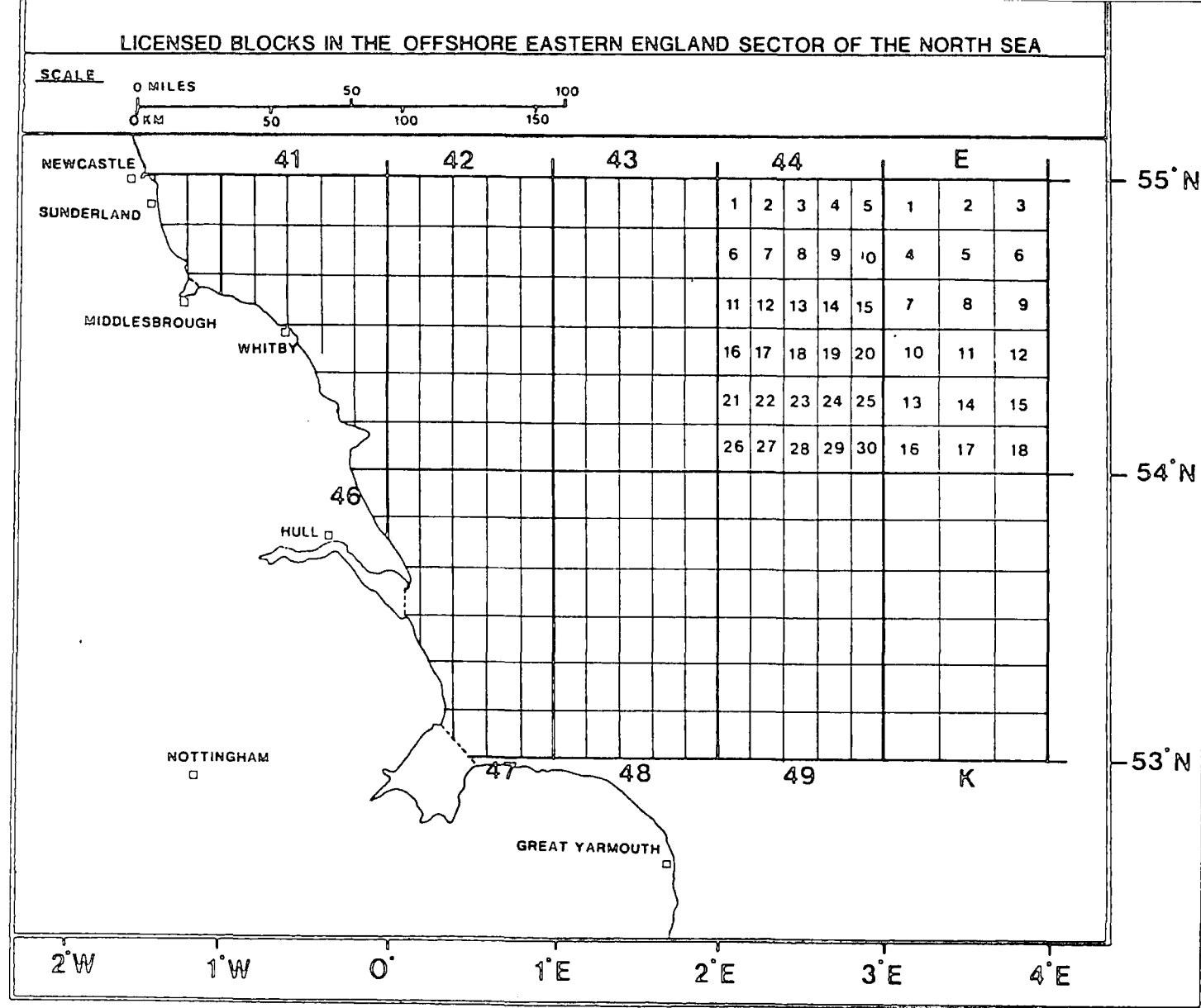


Figure 3.10. Location of offshore licensing blocks in the study area.

normal compaction trend.

Comprehensive coverage of the compaction trends is illustrated in figures 3.9.1 - 3.9.20. These compaction trends have been subsampled to analyse the complexity of their variation with depth, age and lithology:-

1. Compaction trends for one lithology through the whole borehole, eg. shale, encompassing similar lithologies from different formations. The observed trend can be compared to a normal compaction trend for that particular lithology.
2. Compaction trends for one lithology eg. shale, where the lithology is bound within a particular stratigraphic formation. The observed trend can be compared with either a general trend for that particular lithology or a normal trend for that particular formation. In this study, a number of lithology dependent formations are analysed including, Chalk, Lower Cretaceous shale (Speeton Clay); Upper Jurassic shales (Kimmeridge Clay); Middle Jurassic shales (Oxford Clay [pars] and Aalenian/Bajocian deltaic shales); Middle Jurassic deltaic sandstones; Lower Jurassic (Lias) shales; Triassic shales - Mercia Mudstone (Keuper, Muschelkalk and Upper Bunter Shales); Bunter (Sherwood) Sandstone; Lower Bunter shale; Permian dolomitic limestones (Upper and Lower Magnesian Limestones) and Carboniferous shales and sandstones (Westphalian and Namurian). Figure 3.11 illustrates the relative stratigraphic positioning of Permian to Tertiary formations in the Yorkshire, Sole Pit and East Midland Basins, including those used in this particular study of uplift.

The following section outlines the main lithologies encountered in this study and their specific physical and compaction characteristics.

3.5.1 Shales.

Shales, siltstones, mudstones and clays are the most common lithology in the

		YORKSHIRE BASIN	EAST MIDLAND BASIN	SOUTHERN NORTH SEA BASIN			
TERTIARY		Cleveland Dyke	? ?	? ?	T		
CRETACEOUS	MAASTRICHTIAN			CHALK GROUP	CRETACEOUS		
	CAMPANIAN	CHALK	CHALK				
	SANTONIAN						
	CONIACIAN						
	TURONIAN						
	CENOMANIAN						
	ALBIAN	Red Chalk	Red Chalk	CROMER KNOLL GROUP			
	APTIAN	Spoonon Clay	Coratono Suttonby Marl Shognoo Clay Fullotby Boda				
	BARREMIAN	Speeton Clay	Tootby Boda				
	HAUTERIVIAN		Claxby Ironstone				
	VALANGINIAN		Spiloby Sandstone				
	RYAZANIAN						
JURASSIC	TITHONIAN		Spiloby Sandstone	HUMBER GROUP	JURASSIC		
	KIMMERIDGIAN	Kimmeridge Clay	Kimmeridge Clay				
	OXFORDIAN	Amphill Clay Corallian limestone Oxford Clay	Amphill Clay Oxford Clay				
	CALLOVIAN	Hackness Rock Kellaways Cornbrash	Oxford Clay Kellaways Cornbrash				
	BATHONIAN		Blisworth Clay Groat Oolite/Sandy Boda Upper Estuarine Series	WEST SOLE GROUP			
	BAJOCIAN	Scalby Formation Scarborough Formation Cloughton Formation Eller Beck Formation Saltwick Formation Dogger					
	AALENIAN		Lincolnshire limestone Grantham Formation Dogger				
	TOARCIAN	Blea Wyke Beds striatulus Shale Peak Shale Alum Shale Jet Rock Grey Shale		LIAS GROUP			
	PLIENSBACHIAN	Cleveland Ironstone Stalthea Formation Ironstone Shale Pyrilous Shale Siliceous Shale	mudstone Marlstone Rock mudstone Pecten Ironstone mudstone Frodingham Ironstone mudstone/limestone Hydraulic limestone				
	SINEMURIAN	Calcareous Shale					
	HETTANGIAN						
	TRIASSIC	RHAETIAN	Rhaetic	Rhaetic		Winterton Formation	TRIASSIC
NORIAN		Kouper Shale	Kouper Shale	Keuper			
CARNIAN				Muschelkalk			
LADINIAN		Upper Bunter Shale	Bunter(Sherwood) Sandstone conglomerates	Upper Bunter Shale			
ANISIAN		Bunter Sandstone	Lower Bunter Shale	Bunter Sandstone			
SCYTHIAN		Lower Bunter Shale Sulfurous Marl evaporites Upper Magnesian Limestone evaporites Lower Magnesian Limestone Marl Slate Yellow Sandstone	Lower Bunter Shale evaporites Upper Magnesian Limestone Middle Marl Lower Magnesian Limestone Marl Slate Yellow Sandstone	Lower Bunter Shale Sulfurous Marl evaporites Upper Magnesian Limestone evaporites Lower Magnesian Limestone Marl Slate Rotliegend Sandstone			
PERMIAN					PERMIAN		

Figure 3.11. Stratigraphy of the Yorkshire, Sole Pit and East Midland Basins for reference to formations used in the calculation of uplift (figure 3.9.1-3.9.20, and appendix C3).

majority of boreholes across the study area and hence, provide the most data for the quantification of uplift from porosity studies. Physically, these lithologies are assumed to behave in a similar fashion during burial and compaction. Relatively little chemical change occurs in shales that would alter the function of porosity change with depth, and typically 95% porosity loss in shales is due to compaction. Therefore, the abundance of shale or shale-like sediments provides a large data base for the study of the relationship of porosity change with depth and one which is less subject to non-compaction related factors. This is not typical of other lithologies. Despite this, production of a regionally distinct normal compaction trend for shales still proves very difficult as mentioned earlier. Numerous studies have researched the qualitative and quantitative variations within shales during compaction (Hedberg, 1926 and 1936; Athy, 1930; Magara, 1968 and 1976; Baldwin, 1971; Perrier and Quiblier, 1974; Schlumberger, 1974 and 1979; Sclater and Christie, 1980; Brown, 1986; Meade, 1966; Moore, 1931; Shaw, 1915; Meincer, 1980; and Baldwin and Butler, 1985). The results are characteristically similar, but rarely identical (Table 3.1). Thus, the relationship between porosity/interval transit time varies from basin to basin, and even within basins, depending on specific lithologies and the particular burial history. Indeed, Athy (1930) states that down to approximately two thousand feet burial the responses of shales are similar and dominated by mechanical rearrangement, dewatering and mechanical deformation. After this, mechanical deformation and recrystallisation dominate and different factors characteristic of each locality eg. temperature, tectonics, begin to control the physical response of the sediment during further burial. Thus, this response will never be constant. Since most of the shales in the Yorkshire, Sole Pit and East Midland Basins are, or were buried to 2000 feet or greater, some variations and problems may be encountered in the data.

Nevertheless, Table 3.1. does stress the common observation that shales typically have a surface porosity or porosity at deposition of approximately 80% (range

	SCLATER & CHRISTIE 1980	SCHLUM- BERGER 1979	ATHY 1930	SHAW 1915	MEINZER 1923	HEDBERG 1936
SEDIMENT AGE	TERTIARY	ALL	ALL	RECENT	RECENT	ALL
POROSITY %	63	80	50-90	40-90	80-90	70-90
INTERVAL TRANSIT TIME	?	150-180 us/ft.	?	?	?	?

	HAMILTON 1936	MOORE 1932	MAGARA 1968	MAGARA 1976	THOMAS 1984
SEDIMENT AGE	RECENT	RECENT	TERTIARY	CRETACEOUS	TERTIARY
POROSITY %	70-90	80-85	70	80	60-80
INTERVAL TRANSIT TIME	?	?	160 us/ft.	150-200 us/ft.	?

	PERRIER & QUIBLIER 1974	MEADE 1966	BALDWIN & BUTLER 1985	BALDWIN 1971	BROWN 1986
SEDIMENT AGE	ALL	RECENT	ALL	ALL	TERTIARY
POROSITY %	80	80	80	78	70-80
INTERVAL TRANSIT TIME	?	?	?	?	?

Table 3.1. Estimated initial porosity and interval transit time of shales.

70-90%) corresponding to an interval transit time of 150-200 $\mu s/ft$. Also, a number of authors (Sclater and Christie, 1980; Baldwin and Butler, 1985) have illustrated the change in porosity of shales with depth of burial, the results of which are depicted in figure 3.12a, including the corresponding variation of interval transit time and depth. These two curves are found to enclose most other estimates of normal compaction trends. Thus, values for expected surface porosity and compaction trends are available enabling calculation of uplift in the manner discussed (figure 3.8). Figure 3.13 illustrates a cumulative plot of shale porosity data for the Yorkshire Basin. The data represents shales of Triassic to Lower Cretaceous age and is clearly offset from normal compaction trends and expected surface porosity values. One assumes that this reflects uplift and removal of overburden in the Yorkshire Basin.

The above method and previous studies (Table 3.1) provide the basis for the quantification of uplift from porosity and interval transit time data for shaley lithologies in the Yorkshire, Sole Pit and East Midland Basins.

3.5.2. Sandstones.

Sandstones compact until grain boundaries are in contact, after which grains will undergo ductile deformation in response to increasing overburden or lithostatic pressure. Diagenesis, particularly by cementation will play a big role in porosity development both before and during compaction. Hence, sandstones are more susceptible to porosity destruction and creation by non-burial related factors than for example, shale. Often sandstones can be found to be more porous at depth (eg. 4000 feet) than nearer the surface (figure 3.14).

Figure 3.12b illustrates typical values for porosity and interval transit time with depth in sandstones (Schlumberger, 1974; Sclater and Christie, 1980; Selley, 1978). Sandstones commonly have a surface porosity of between 40-55%, but this

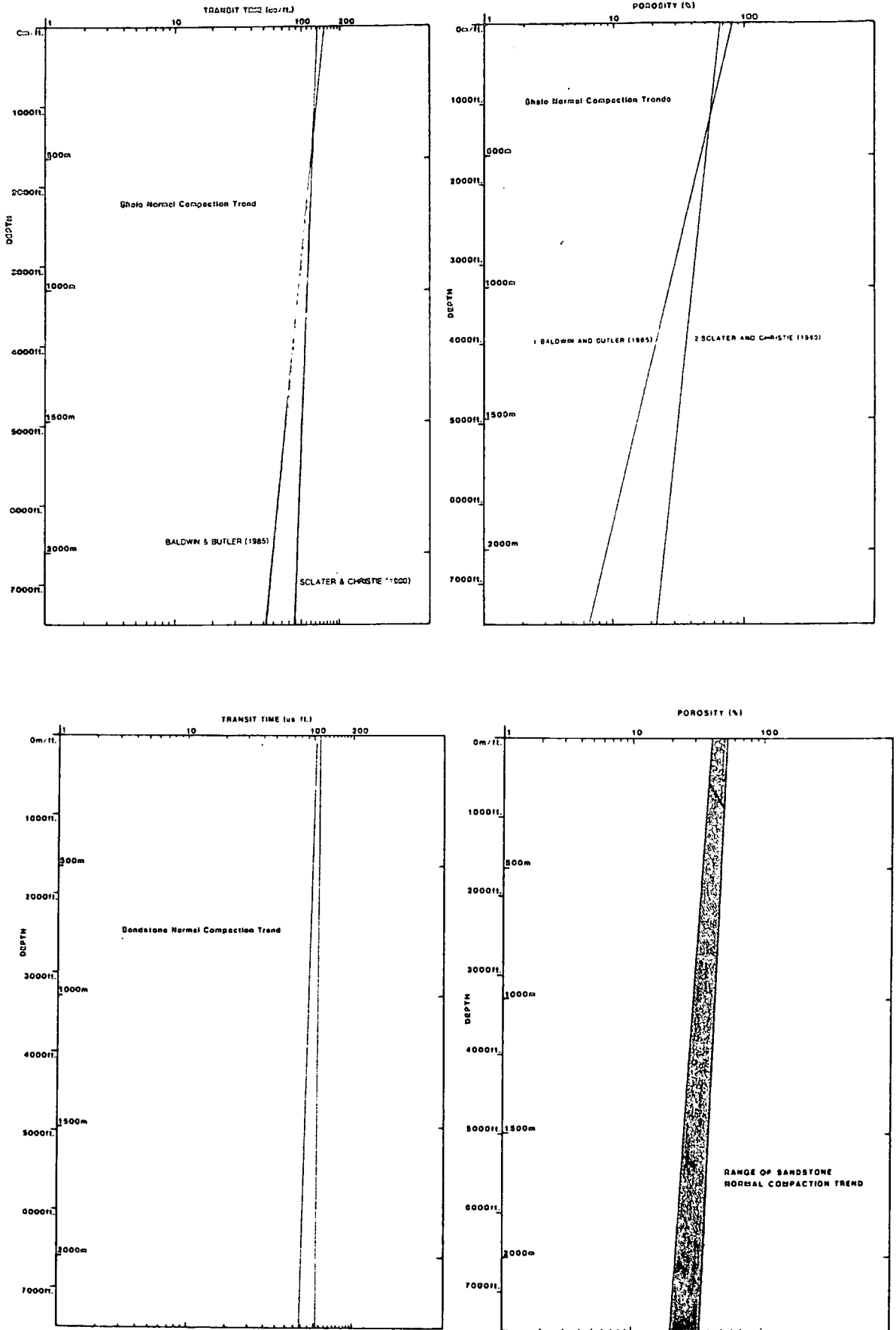


Figure 3.12. Normal compaction trends for shale and sandstone.

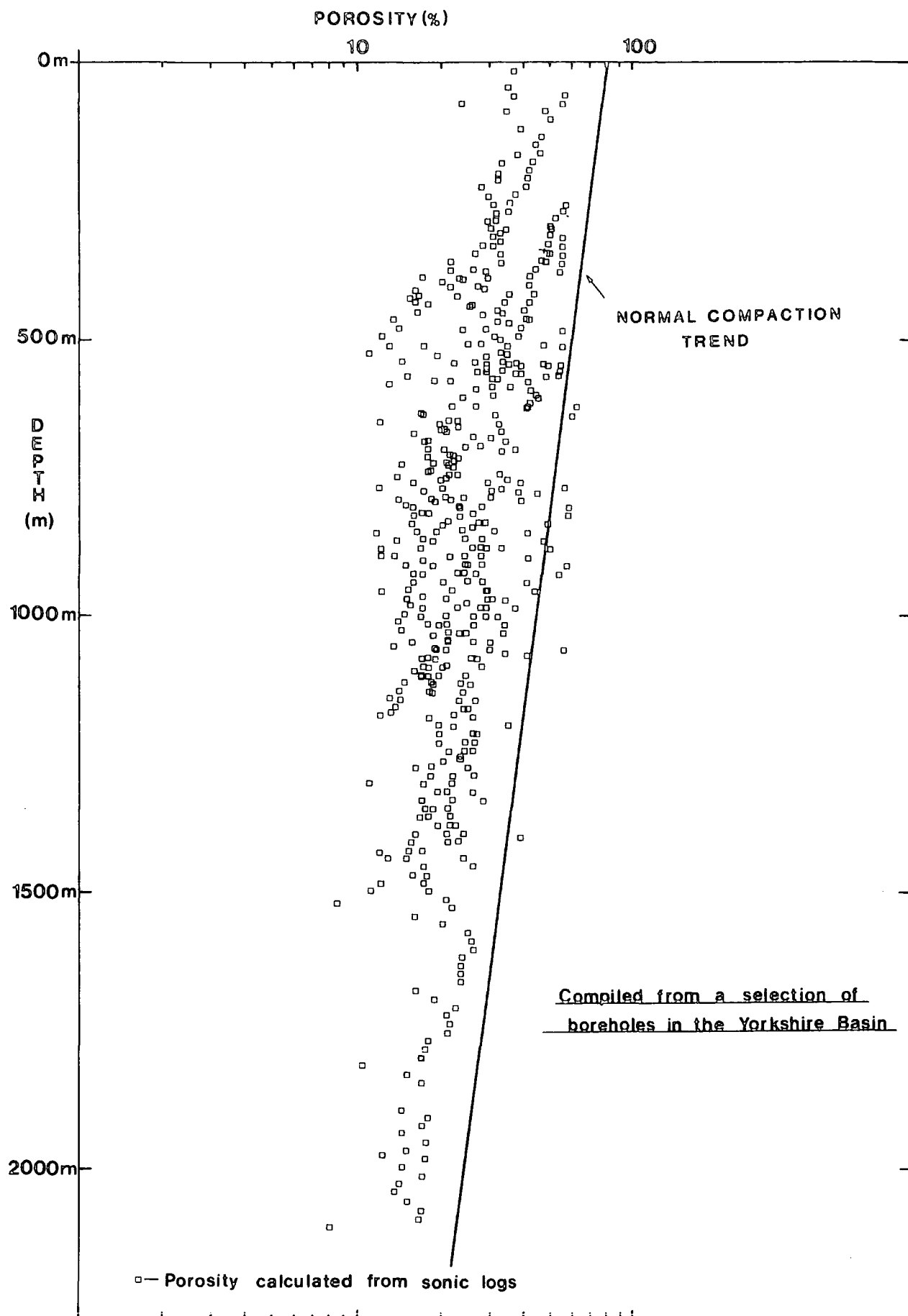


Figure 3.13. Compilation of shale porosity data, from sonic logs for boreholes in the Yorkshire Basin, compared to shale normal compaction trend.

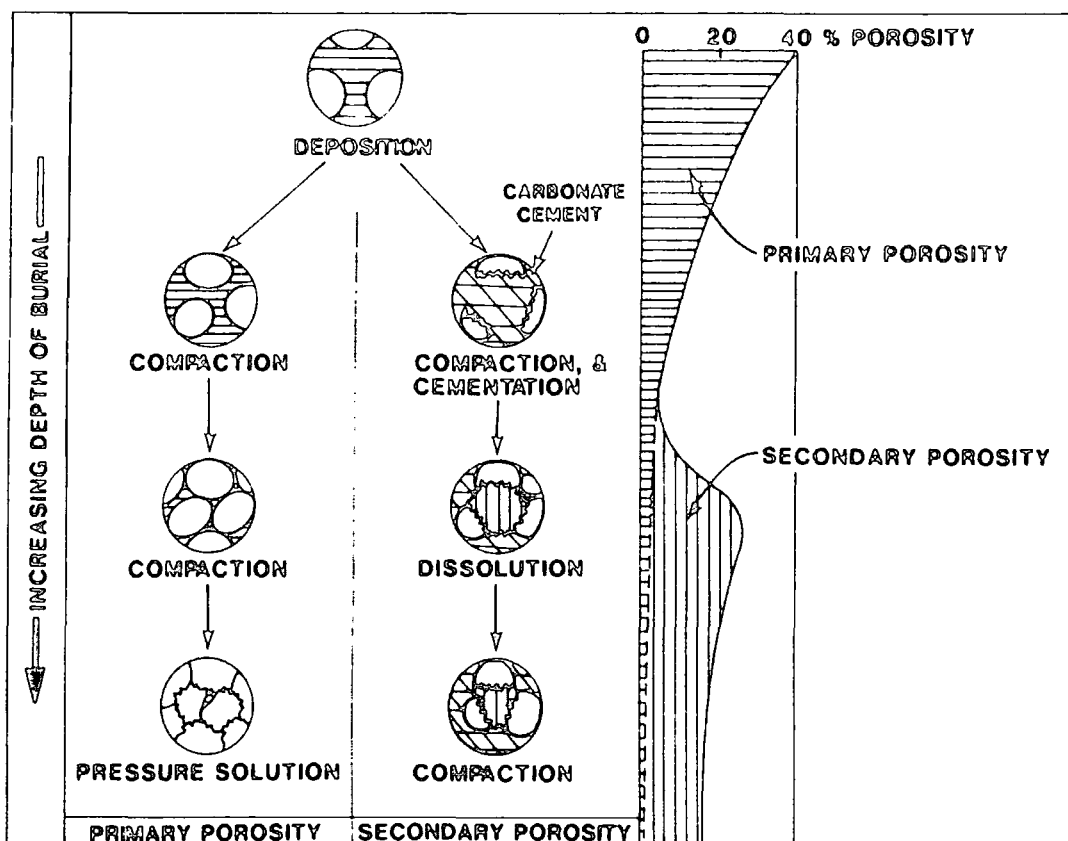


Figure 3.14. Variation of sandstone porosity with depth (Zuffa, 1981)

can vary according to grain size, sorting, packing and clay content. Sclater and Christie (1980) used a value of 47% for surface porosity of Tertiary North Sea sandstones. A similar value is estimated by Selley (1978). Selley's (1978) variable porosity gradients for Tertiary and Mesozoic sandstones confirm the common exponentially decreasing form of the porosity depth:curve or its linear trend in log porosity:depth curves (figure 3.12b). Sandstones do not constitute a major part of the succession in the study area, but major uplift results are computed for correlation with other lithologies.

3.5.3. Chalk.

Chalk is a fine grained carbonate (micrite) composed almost entirely of coccoliths and coccolith fragments. Typically chalk behaves like a shale in the first kilometre or so of burial, with early dewatering and compaction dominating. Chalks do show uniform, measurable physical properties, such as interval transit time and porosity, which can be related to burial depth. Surface porosity is postulated to be approximately 70%, corresponding to an interval transit time of 130-180 μ s/ft (Sclater and Christie, 1980; Hancock and Scholle, 1975; Hancock, 1976 and 1984; Scholle, 1977) as illustrated in figure 3.15a. Cementation occurs in the form of pressure solution and reprecipitation. Stylolites are commonly found in response to both burial (vertical) and tectonic (lateral) stresses.

The curves from Sclater and Christie (1980) in figure 3.15a for chalk in the Central Graben, North Sea are used as the normal compaction trends. Chalk is a unique sediment, having a very uniform lithology in most areas (clay content may vary - Jeans, 1968). In the Central Graben it is buried at present to its maximum depth. Hence, these curves are very likely to represent the normal compaction trend for chalk. Figure 3.15b illustrates the differences in the compaction trends for chalk in a normally compacted sequence from boreholes 43/3-1 and 49/24-1, to the east and north-east of the Sole Pit Basin, and for boreholes in the East

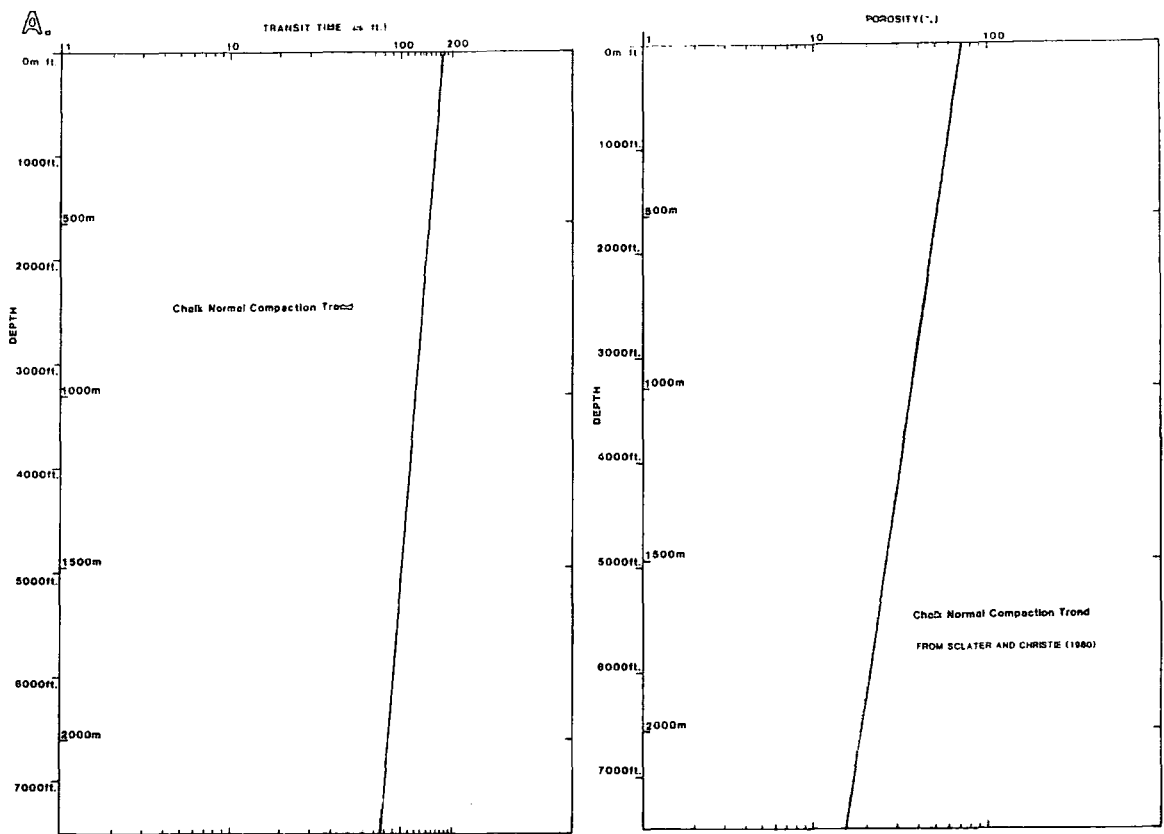
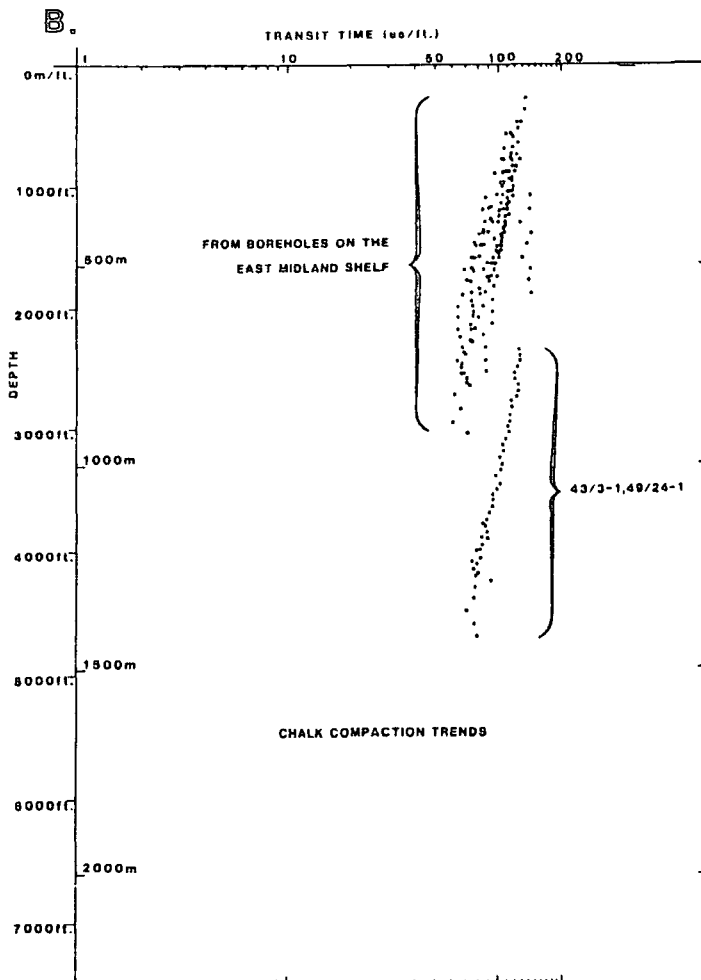


Figure 3.15. A. Chalk normal compaction trends.
 B. Variation in observed chalk compaction trends from the study area.



Midland Basin.

The curves show an offset of approximately 300-500 m, which suggests that part, if not all, of the East Midland Basin has undergone post-Cretaceous uplift.

A feature of the chalk compaction curve in the North Sea area is the marked rapid decrease in porosity at 1-1.2 km burial (Sclater and Christie, 1980 - figure A1b), which is apparently due to the onset of reprecipitation, pressure solution and hence porosity reduction. Similarly, some boreholes in the study area (figure 3.9.1, 5, 7, 8, 10, 11, 12, 17, 19) show a similar reduction in porosity, typically in the Lower Chalk. This could be due to two possibilities:

1. Like the Central Graben area, the chalk in the Yorkshire, Sole Pit and East Midland Basins may have been buried to depths greater than 1km causing reprecipitation and pressure solution as discussed above.
2. In some of the boreholes the sudden drop in porosity values or increase in sonic velocity values is coincident with the incoming of flint and chert in the Lower Chalk formations (figure 3.16). Thus, the sudden decrease in the study area may be due to lithological variations and not directly related to the burial depth the chalk has reached.

3.5.4. Limestones and Dolomites.

These are relatively rare lithologies in the area, dolomites mainly restricted to Permian and Triassic. Occasional limestones are found in the Jurassic (figure 3.11). Both lithologies show few compaction structures, such as packing and sorting. Therefore, it is difficult to use them in the quantification of uplift by the method stated above, as the main cause of porosity loss is not compaction but recrystallisation, cementation and pressure solution. Furthermore, additional non-compaction related volume changes may occur in response to chemical changes

from aragonite-calcite and calcite-dolomite.

Schmoker and Halley (1982) quantified typical values of porosity for depth in limestones and dolomites (figure 3.17) based on analysis of past and present sediments at their maximum burial depths. Figure 3.3 (Schlumberger, 1979) outlines the expected value of porosity for specific interval transit times. An attempt is made to calculate uplift from data for dolomites and limestones, particularly where only Permian and/or Triassic sediments are remaining (section 3.7.4) and to test whether these lithologies give uplift values which correlate with those from other lithologies both in the same borehole and in a regional context.

Figure 3.18 summarizes the normal compaction trends of porosity with depth for the five lithologies mentioned above.

3.6 Quantification of Uplift.

It has been shown that porosity and interval transit time decrease exponentially with burial depth (Athy, 1930; Baldwin and Butler, 1985; Hamilton, 1976; Hedberg, 1936; Potter et al, 1980; Schlumberger, 1974; Schmoker and Halley, 1982; Sclater and Christie, 1980; Selley, 1978). From figure 3.3, it can be shown that the relationship is not constant, but varies according to lithology. Therefore, such variations must be acknowledged and accounted for. This study uses lithologically distinct, observed porosity/interval transit time curves (figure 3.9) and compares them with lithologically distinct normal compaction trends to calculate the amount of sediment lost in the area (figures 3.12, 3.15, 3.17 and 3.18).

One assumes that if a normal compaction trend can be computed for a lithology or formation, then the observed porosity/interval time data, derived from porosity logs for a given sedimentary sequence which has undergone normal and relatively undisturbed subsidence and is at its maximum depth of burial,

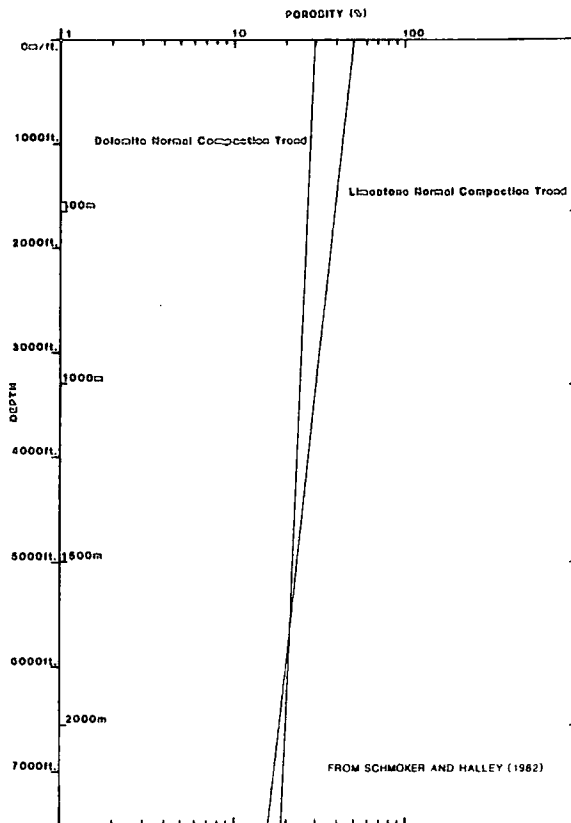


Figure 3.17. Limestone and dolomite normal compaction trends.

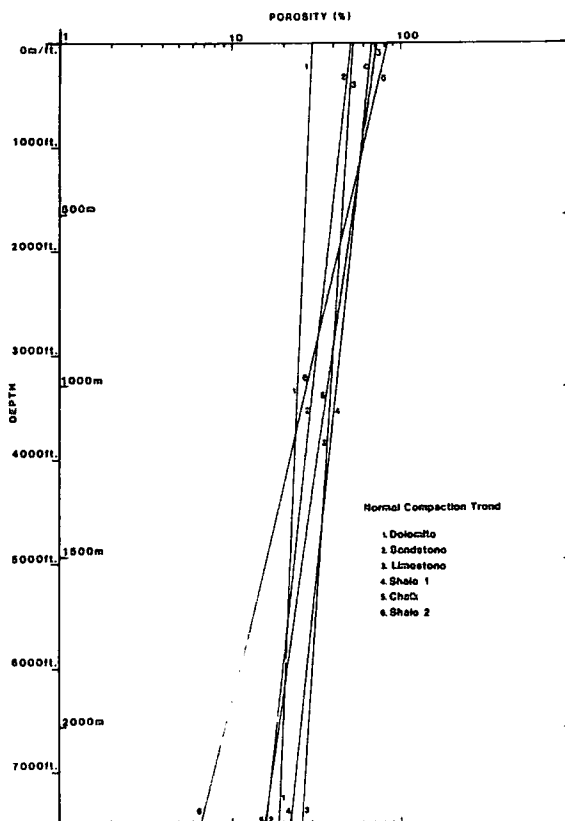


Figure 3.18. Correlation of all lithologically dependent normal compaction trends used in this study.

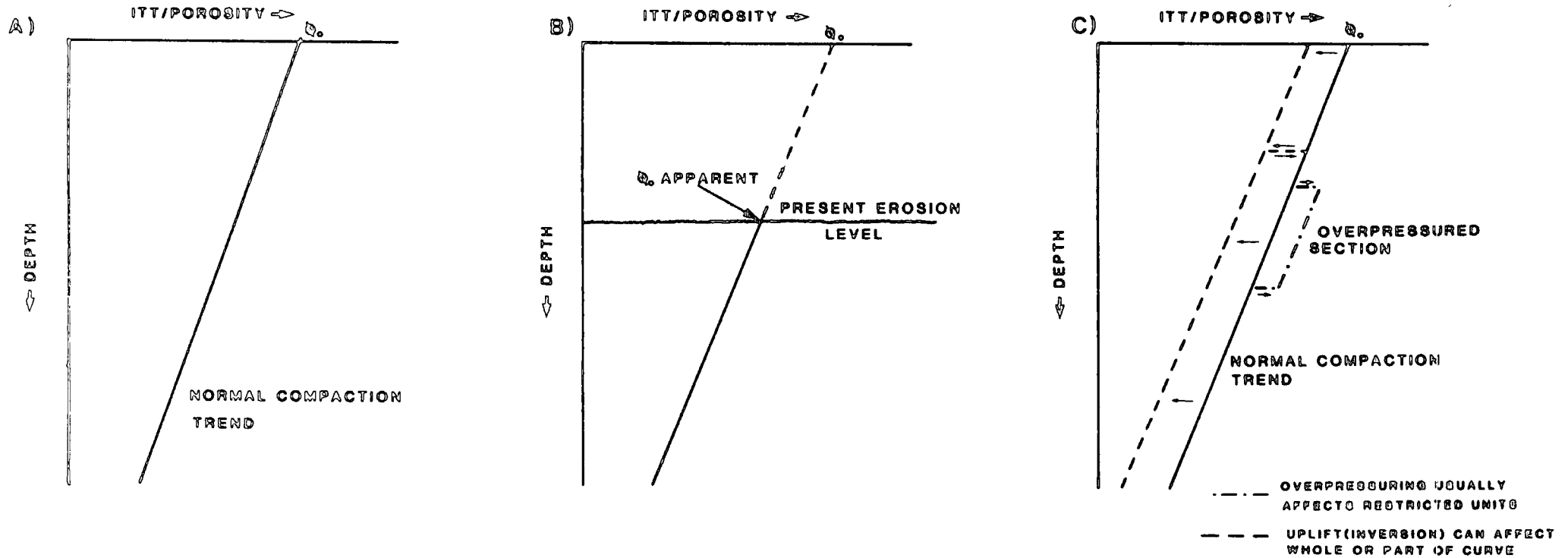
should correspond closely to the normal trend. Conversely, if the sedimentary sequence has undergone uplift for whatever reason- inversion, regional isostatic uplift, diapirism- resulting in the removal of the younger parts of the sedimentary sequence, then the observed porosity/interval transit time data should show an offset from the normal trend. Figure 3.19 simplifies this theory and outlines the general trends of porosity and interval transit time for eventualities such as inversion and overpressuring. Amount of uplift is calculated simply by projection of the observed curve vertically to the value of porosity on deposition, predicted by the normal compaction trend (figure 3.8). Figures 3.20 and 3.21 illustrate the above for examples in the offshore Yorkshire Basin and offshore East Midland Basins respectively. Figure 3.20 shows observed versus normal compaction trends postulating approximately 4000 feet of uplift for all Triassic shales including the Upper and Lower Bunter shales (figure 3.11). Figure 3.21, for chalk, postulates approximately zero uplift or sediment removed.

Although the porosity data is determined directly from the interval transit time (sonic velocity) data (figure 3.3), the amount of uplift is calculated by analysis of both data sets with respect to their normal trends.

A. Interval Transit Time

Interval transit time data is determined from figures 3.9.1 - 3.9.20 and is compared to the normal trends depicted in figures 3.12, 15 and 17. As can be seen from figure 3.9.1 - 3.9.20, the interval transit time data consistently trace an easily discernable trend which shows very little scatter, in contrast to much of the porosity data. Interval transit time values are taken from the top, middle and bottom of each particular formation and lithology. These values and the present burial depth at which they occur are compared to the theoretical values of a normally compacted sequence. This establishes the maximum depth of burial attained by the sediments and thus the amount by which it has been uplifted.

SCHEMATIC REPRESENTATION OF THE POROSITY:DEPTH RELATIONSHIP



1) OVERPRESSURING RESULTS IN HIGHER POROSITY DUE TO RETENTION OF FORMATION FLUIDS.

2) UPLIFT (INVERSION) RESULTS IN LOWER POROSITY DUE TO ELEVATION OF THE SEDIMENTARY SEQUENCE.

Figure 3.19. Schematic representation of compaction trends and the affect of uplift, erosion and overpressuring.

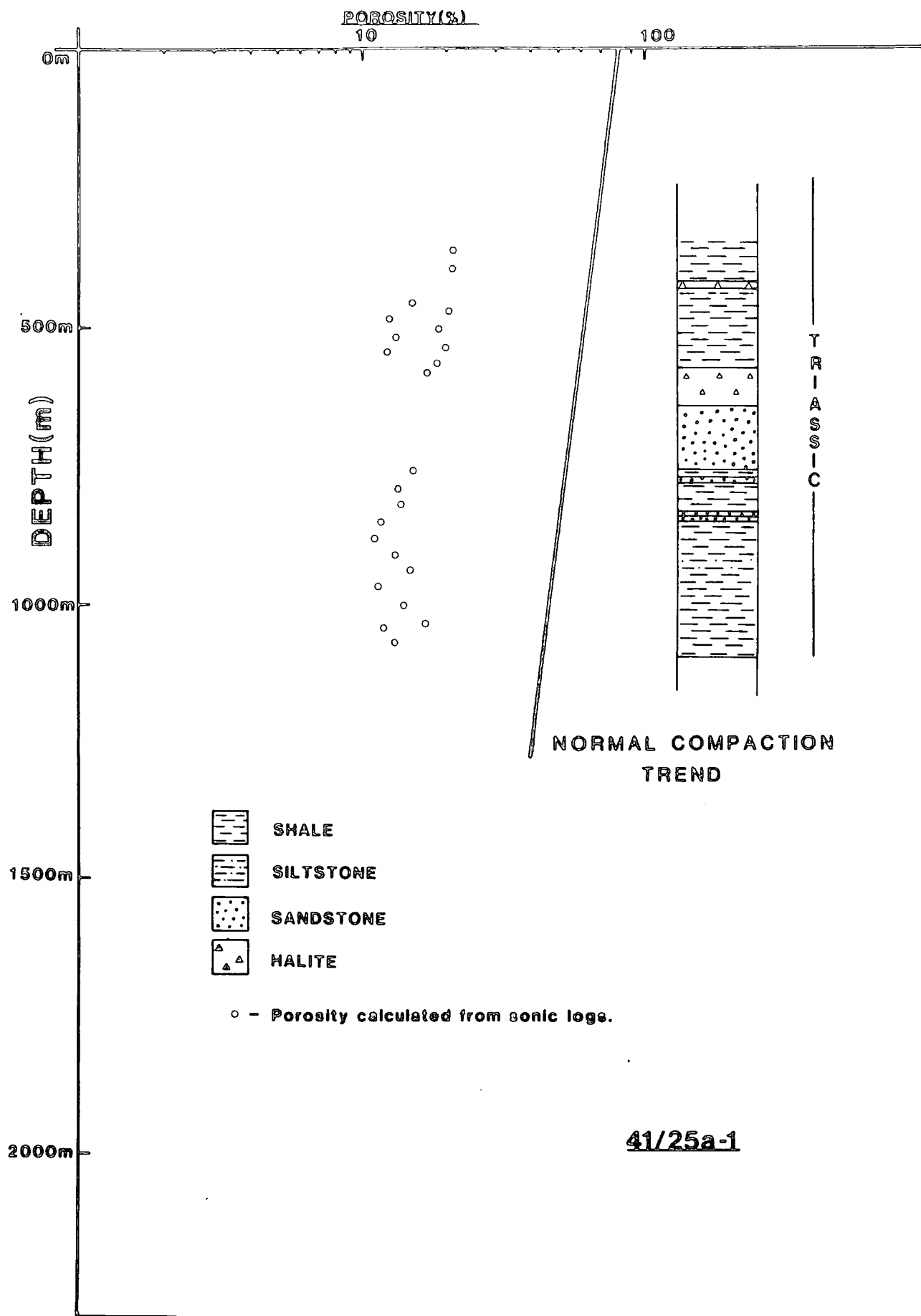


Figure 3.20. Comparison of observed and normal compaction trends for Triassic shales in the Yorkshire Basin.

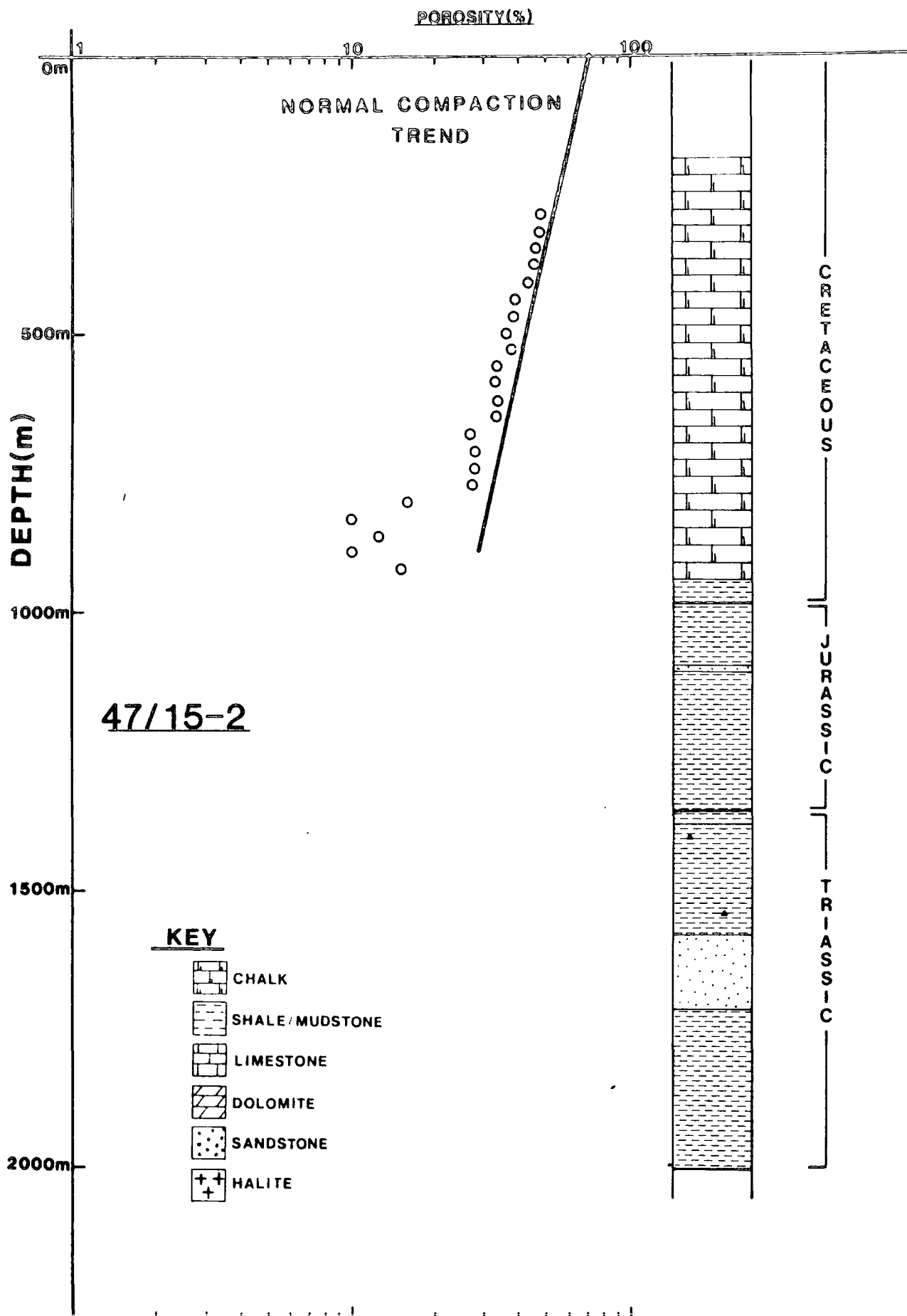


Figure 3.21. Comparison of observed and normal compaction trends for the Upper Cretaceous chalk in the East Midland Basin.

The amount of uplift is assumed to be directly proportional to the amount of overburden removed. The results are illustrated in Appendix C3:Tables.

B. Porosity

The trend of porosity data in figure 3.9.1 - 3.9.20, is analysed mathematically. Because the porosity data commonly displays more scatter than the interval transit time data, it is not easy to visualize the trend. The data points have therefore been statistically analysed (figure 3.22). The value of porosity at the surface (on deposition), is taken as a reference point to which the observed porosity is compared. Then, the trend or regression of the observed data is computed to give a value for the observed surface porosity (figure 3.22). Instead of repositioning the whole observed data curve with respect to a normal curve, as in A above, the uplift is computed directly from the vertical offset of the observed and theoretically expected values for surface porosity (figures 3.8 and 3.19).

A further reason for analysing the porosity data mathematically or statistically is because it is used to produce a representative curve along which the sedimentary columns can be decompacted in the backstripping procedure (Chapter 4). All the porosity points, irrespective of lithology, are used to produce one curve for each borehole. This is discussed below.

In the two methods for calculating uplift, in A and B above, the data is analysed, where possible, with respect to each major lithology eg. shale, chalk, sandstone, and each major formation, also defined by lithology. This ensures that the whole borehole data set (figure 3.9.1 - 3.9.20) is sampled to obtain the best approximation of uplift from the most data sets possible. Results from methods A and B are analysed and an average, or approximate uplift value determined. Variations in the uplift values computed are analysed and assessed in the context of the respective lithology, their stratigraphic age and subsequent burial history.

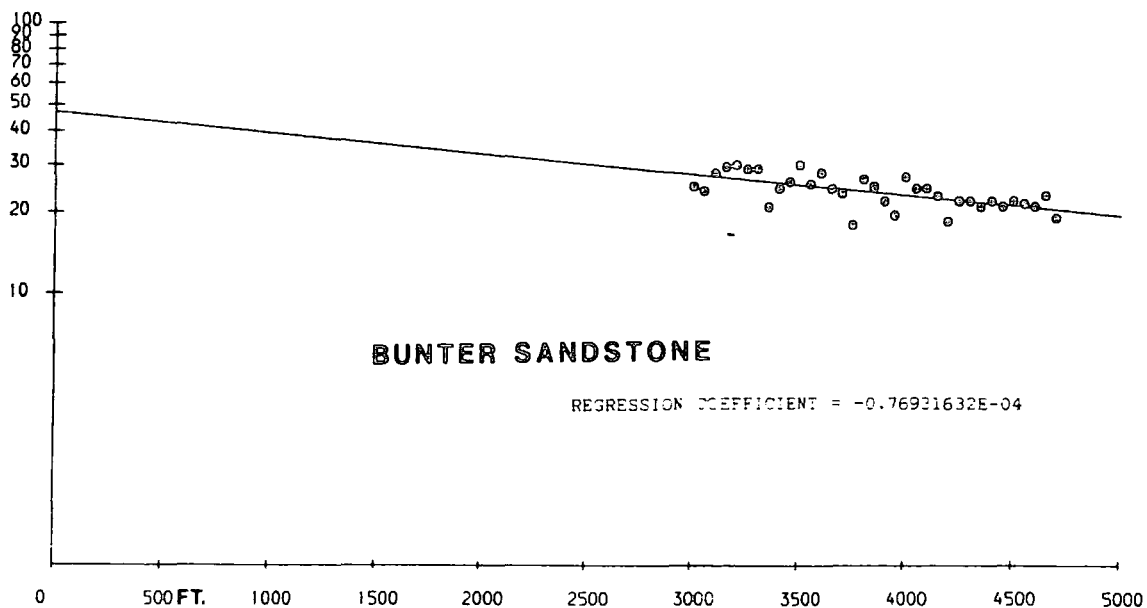
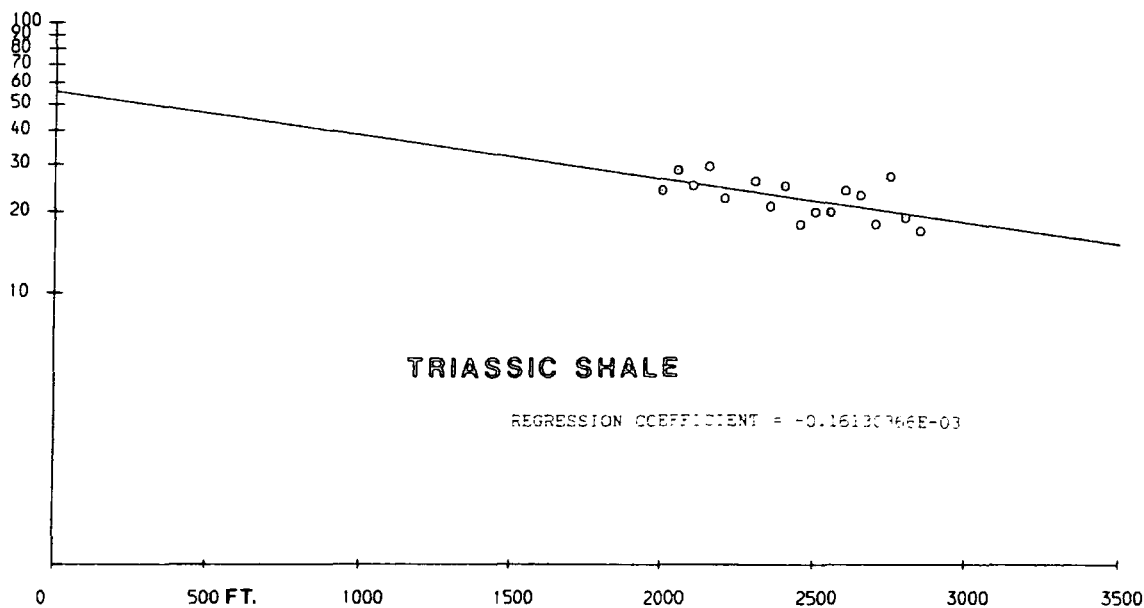
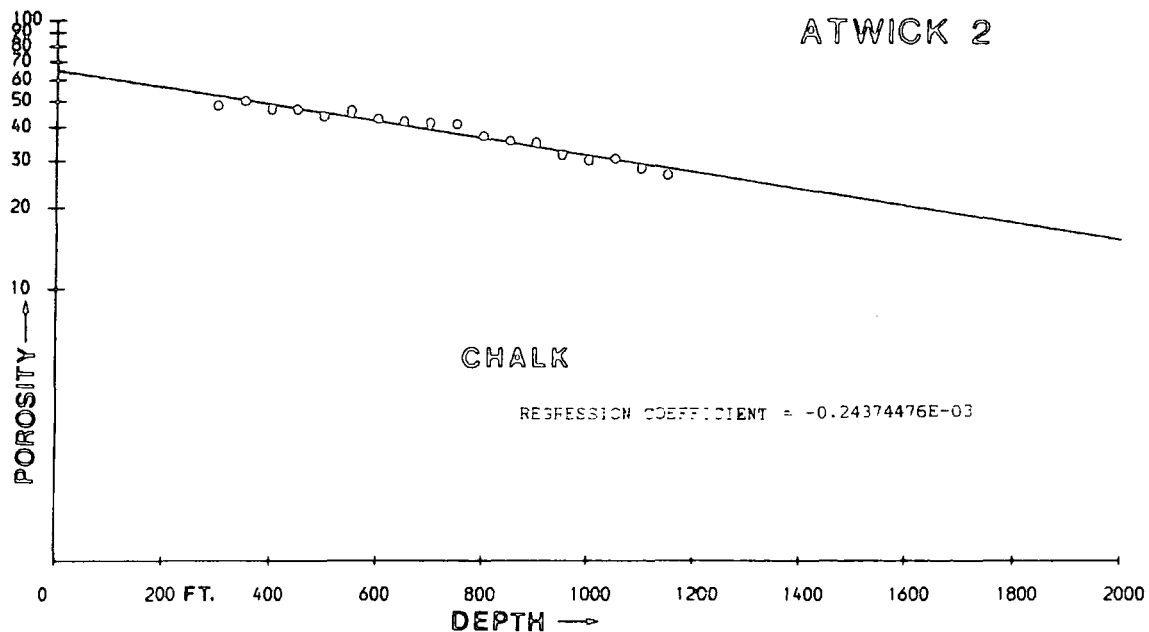


Figure 3.22. Example of regression analysis for porosity data in figure 3.9.1-3.9.20. Example for chalk, shale and sandstone in the Yorkshire Basin.

Results are correlated with local and regional stratigraphic variations from stratigraphically more complete regions found within and adjacent to the study area.

Theoretically, we should expect to obtain the same uplift values for each unit analysed within the same borehole, assuming each unit has undergone a similar uplift and burial history. However, variations in porosity and interval transit time due to mixed lithologies, overpressuring or undercompaction and chemical diagenesis plus the occurrence of unconformities and small uplift/non-deposition events within the sedimentary sequences do occur (see below). This means, that uplift estimates do not necessarily equate between different units in the same borehole as shown in Appendix C3:Tables. Consequently, this causes problems when one wants to use a lithologically dependent porosity:depth curve for backstripping a basin that has been significantly uplifted. As shown in figure 3.23A, which is a hypothetical example, each formation, f1 - f4, has a distinctive porosity curve. From these curves, a distinctive value for uplift is computed. Assuming they are different for each formation, then the situation illustrated in figure 3.23B will arise with an apparently discontinuous sedimentary sequence. If the study area has not undergone any uplift and/or erosion the above will not apply.

Applying this to the study area, it can be seen (figure 3.24 A, B, C and 3.9.1 - 3.9.20) that the scatter of porosity data in most boreholes means that the curves for each lithology tend not to vary by much. This is particularly so for shale and sandstone lithologies, as shown in figure 3.24A and B for boreholes in the Yorkshire and East Midland Basins respectively.

The curves for chalk (particularly its lower or deeper parts - section 3.5.3) and shale and sandstone show some variability and the resultant curve does not correlate as well with all the data points. However, variations are consistently minor and thus errors in the calculation of the load of sediments acting on the basement, will not be significant. The area has suffered uplift which is calculated

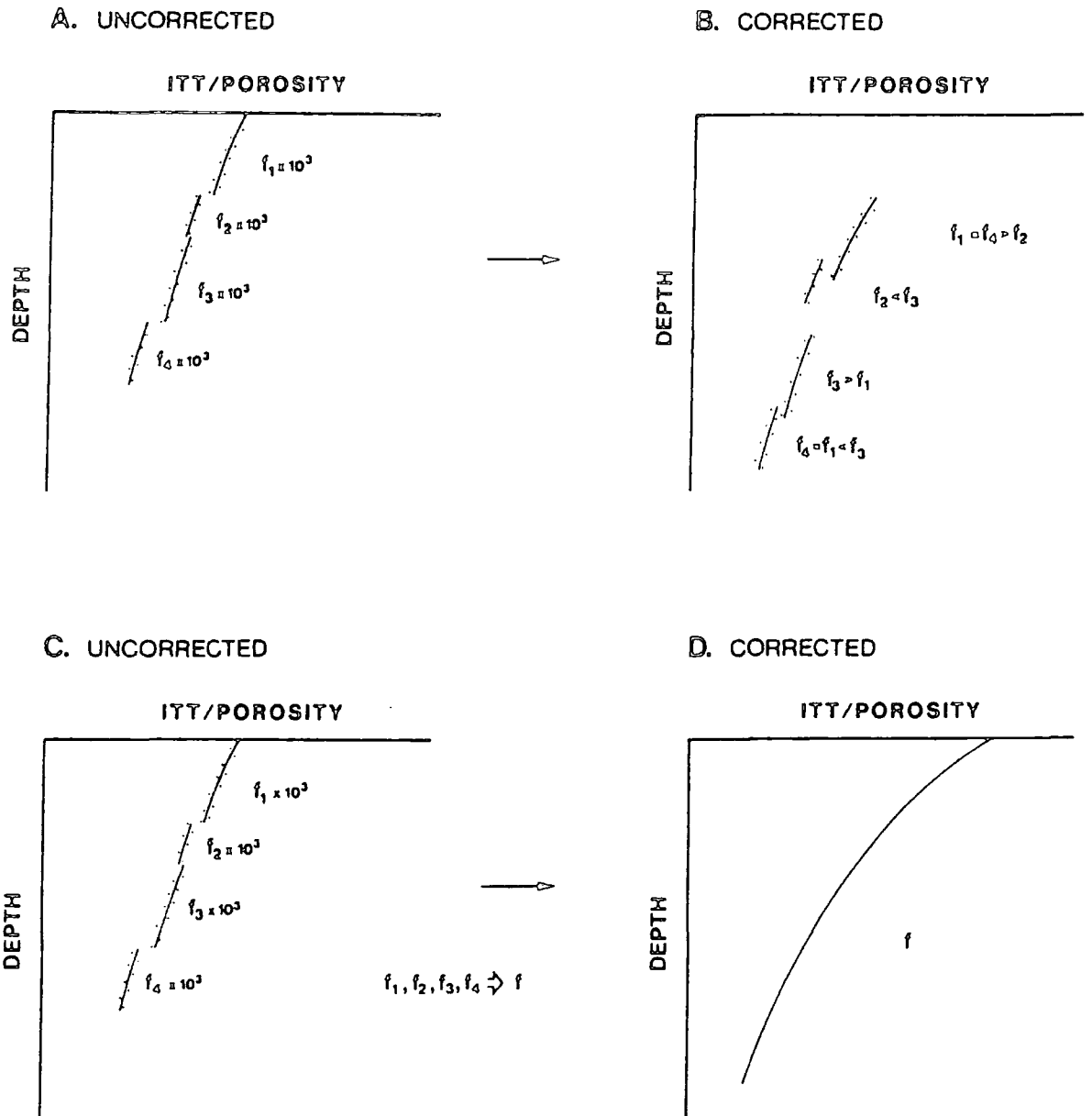


Figure 3.23. Schematic representation of lithologically dependent compaction curves and their correction for removed overburden.

- A: Observed compaction trends for formations/lithologies $f_1 - f_4$.
- B: Amount of uplift computed from each formation is not constant. Resultant compaction trend for whole borehole is anomalous.
- C: As A.
- D: Uplift values $f_1 - f_4$ are analysed to produce one value f . The whole sequence and porosity curve is reset by the same finite value. This produces a uniform compaction trend for backstripping.

on a lithological basis from both porosity and interval transit times. A best fit or average value (f in figure 3.23 C and D) is computed and added to all points on the observed porosity curve. This produces a single, lithologically independent, normal compaction trend for each particular borehole (figure 3.23D) and eliminates the potential problems that are illustrated in figures 3.23A and 23B.

3.7 Erroneous Data.

Not all the data sampled from the sonic logs (figure 3.9.1 - 3.9.20) is found to correlate well with the trends encountered in each borehole. These anomalous data points are usually readily identifiable by careful analysis of the sonic logs and must be accounted for as they can cause errors if one uses this particular method for calculating uplift from visually observed or mathematically derived compaction trends. Typically they are caused by:-

1. Unconsolidation.
2. Overpressuring/Undercompaction.
3. Mixed Lithologies - confusion due to the problems computing the normal compaction trend. They are usually assigned to the most appropriate type lithology.
4. Casing - readily identified, usually by wildly variable response in logs and labelling of composite logs.

3.7.1. Unconsolidation.

Unconsolidation is a problem which is not encountered in the study area but can occur particularly where relatively young, eg. Tertiary - Recent, sediments have been deposited and are not lithified or consolidated. However, all sediments pass through this stage during early burial, where primary porosity decreases

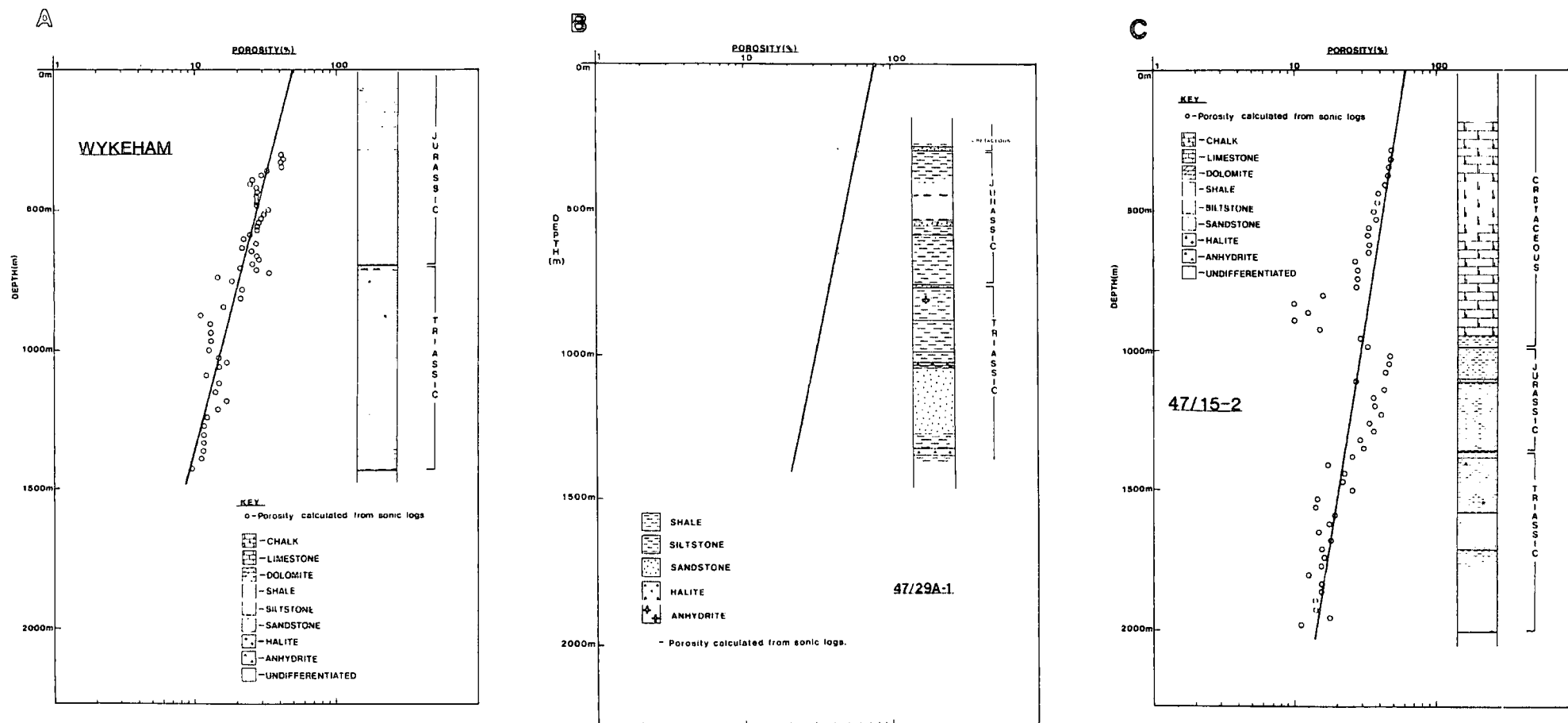


Figure 3.24. The scatter within porosity data for different lithologies in one borehole, usually allows production of one representative but lithologically independent compaction trend.

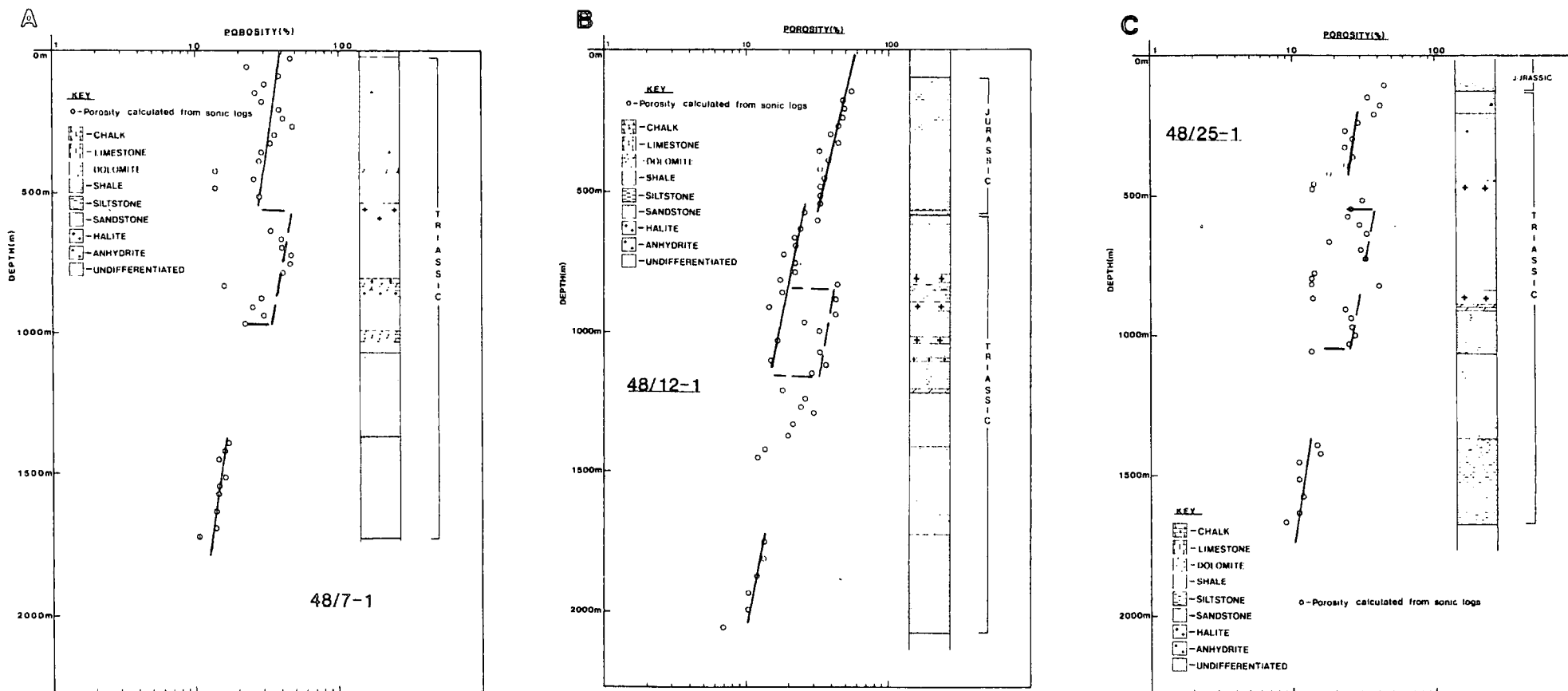
very rapidly with depth, yet the actual behaviour of sediments during this stage is not accurately known. Porosity curves are compensated for uplift using normal compaction trends which approximate porosity in early stages of burial (figures 3.12, 3.15, 3.17). As seen in Table 3.1, the values for the parameters concerned are open to some speculation. All sediments of Permian to Cretaceous age in the study area are fully lithified by compaction during burial prior to inversion, and hence the problem has been ignored.

3.7.2. Overpressuring.

Overpressuring occurs when formation fluids within a sediment are unable to be expelled during burial, resulting in higher porosities and interval transit times (lower sonic velocities) than expected for the actual depth of burial (figure 3.19). This will obviously have consequences if one uses an overpressured section to calculate uplift. However, the overpressured sections are usually restricted formations such as salt bound shales. Figure 3.25A, B, C illustrates three examples from the Sole Pit Basin in Triassic Upper Bunter and Muschelkalk (Mercia Mudstone) shales which show the effect of localised overpressuring on the observed compaction trends (solid and dashed lines). Lower porosities than may be expected are sometimes encountered, particularly in anhydritic Keuper (Upper Triassic) shales (see figure 3.9.1 - 3.9.20).

3.7.3. Unconformities.

An additional complication to the porosity:depth relationship is that in detail, the subsidence of the basins concerned is not continuous. In the Jurassic and Cretaceous in particular, a number of unconformities occur which represent one or more phases of uplift, erosion and non-deposition (figure 3.11). They may be caused by eustatic sea-level changes and/or local tectonic episodes. Depending on the magnitude of the unconformity, if uplift and erosion occur eg. Middle



————— NORMALLY COMPACTED SECTION.

- - - - - OVERPRESSURED SECTION.

Figure 3.25. Representative overpressuring within the Triassic of the Sole Pit Basin.

Jurassic Bajocian-Bathonian uplift (Leeder and Nami, 1979) or Upper Jurassic-Lower Cretaceous uplift (Cimmerian unconformity), it would be beneficial to our understanding of the basin evolution if we could quantify it. We may expect to see such events represented in the porosity/interval transit time curves since as stated above, each uplift and erosion event will offset them from normal compaction trends.

Figure 3.26 explains the situation for one lithology, where normal subsidence occurs along curve P1. Uplift x occurs, elevating points D to the surface at point E, point A to point B, and the compaction curve to P2. If we assume that this event represents the effect that the Cimmerian event had on the sedimentary sequence, then we will only observe this event in a porosity curve if subsequent subsidence does not or did not exceed the previous uplift x . That is, from figure 3.26, if subsidence restarts of magnitude S2, then there will be a residual uplift value in the sub F-G sequence of $x - S2$. This will be represented by the offset of curve P3 from P1, the normal compaction trend. The latter represents the curve along which sediments deposited during S2 will lie. If no further subsidence occurs, then the offset in the two curves, which are for the same lithology above and below the unconformity, will be preserved whether uplift occurs or not.

However, from figure 3.27, it is apparent that curves for all shales above and below the unconformity, but in particular the Speeton Clay (Lower Cretaceous) and Kimmeridge Clay (Upper Jurassic) do not show any marked offset that may be interpreted as due to uplift or removal of sediment. This does not necessarily mean that no uplift or removal of sediment occurred but it is indicative of the magnitude of the subsequent post-Cimmerian subsidence compared to the Cimmerian uplift. Figure 3.28 illustrates the above. Burial to point A along curve P1 to P2 is terminated by uplift x . This is succeeded by subsidence S2, greater in magnitude than uplift x , and causes both pre- and post-uplift sediments to

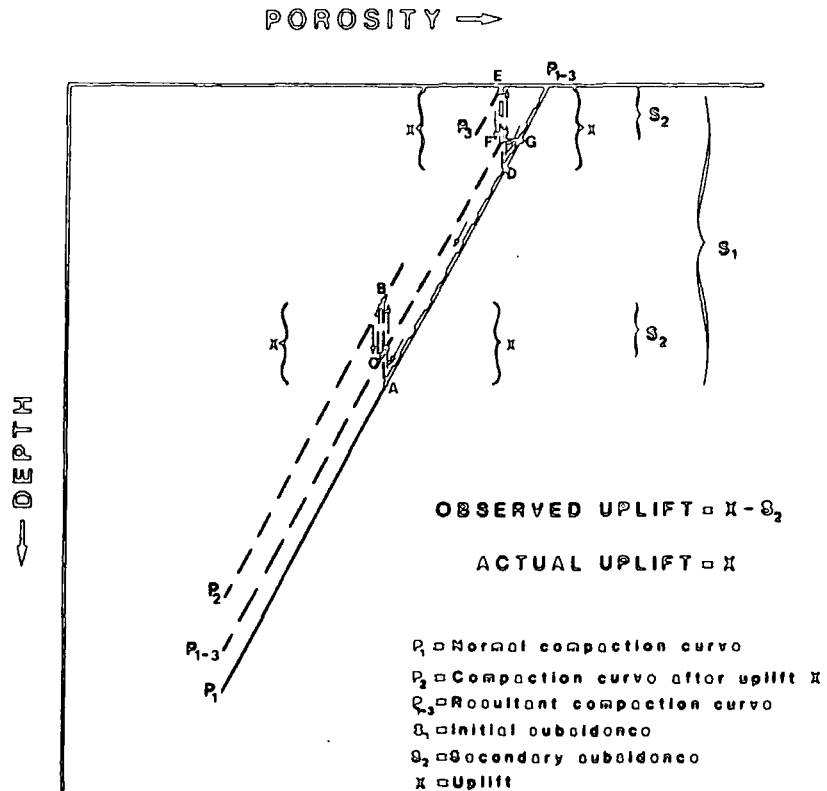


Figure 3.26. Schematic representation of the affect of multiple subsidence and uplift events (unconformities) on the observed compaction trend for one lithology. Unconformity at depth F-G is represented by offset in the compaction trend from P_1 to P_{1-3} .

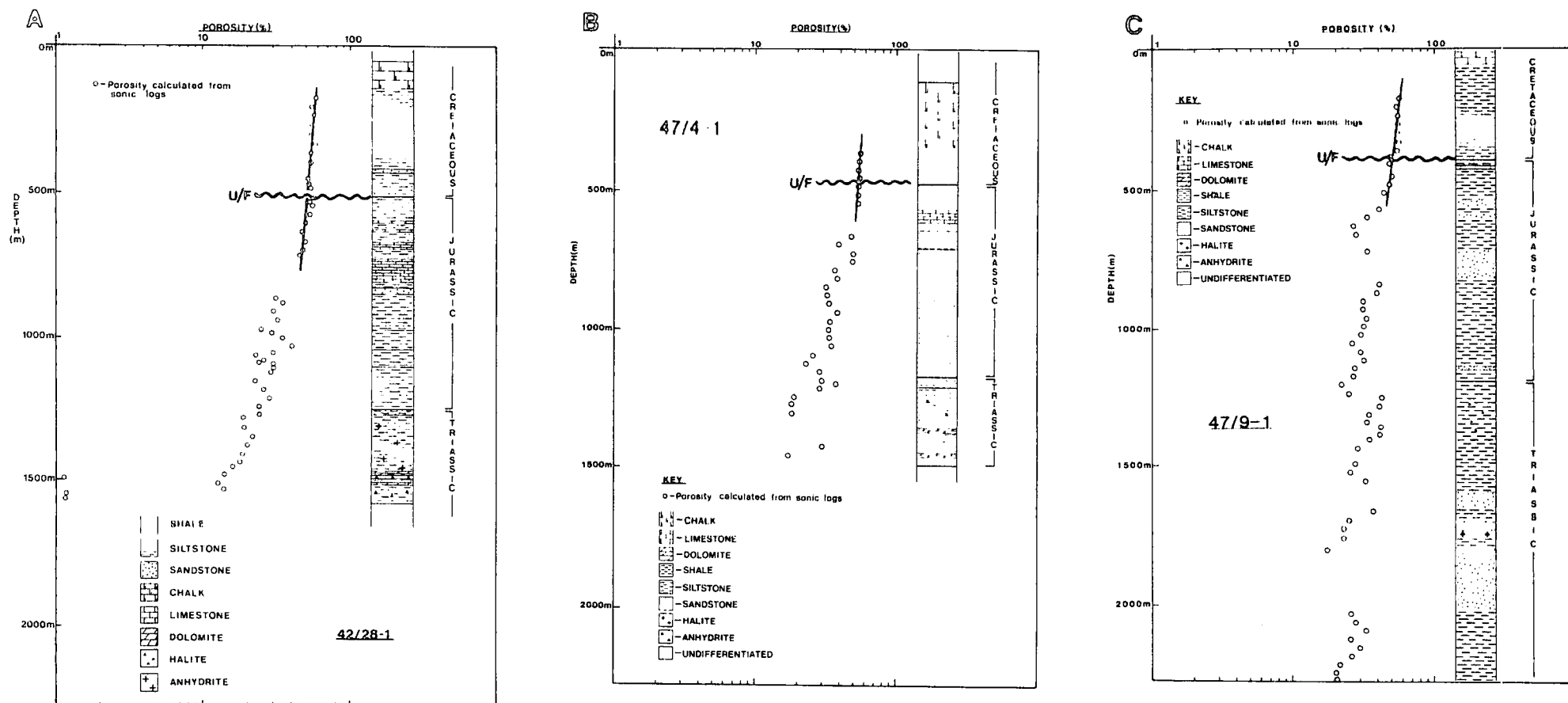


Figure 3.27. Affects of Cimmerian unconformity (U.Jurassic-L.Cretaceous) on the observed compaction trends in the Yorkshire Basin (fig.A), and East Midland Basin (figs B, C). If later Cretaceous subsidence exceeds earlier uplift the compaction trend for one lithology will not reveal the uplift.

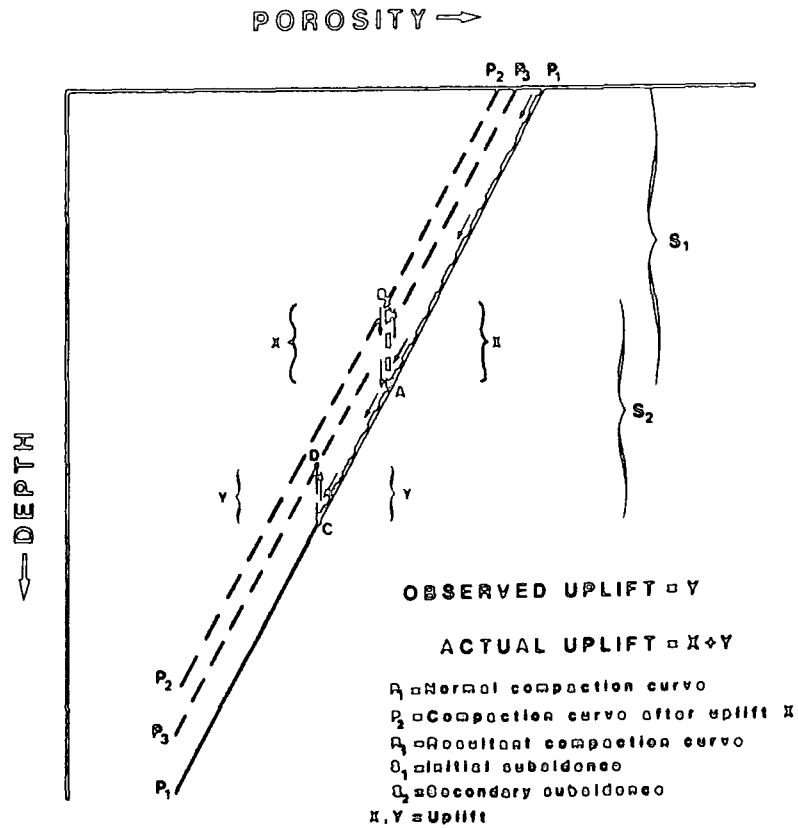


Figure 3.28. Schematic representation of the affect of the Cimmerian unconformity represented in figure 3.27. Post-Cimmerian subsidence S_2 , exceeds Cimmerian uplift x . The unconformity is not necessarily represented in the observed compaction trend. The whole sequence is affected by second uplift event Y (basin inversion?).

compact along the normal compaction trend P1. Thus, although an unconformity exists, both sets of sediments will have the same compaction curve P1. A second uplift event Y occurs, which we assume is the major inversion (Sub-Hercynian to Laramide) in the Yorkshire, Sole Pit and East Midland Basins, and offsets the whole sedimentary sequence to curve P3. If we assume that the initial uplift event of some magnitude x is the Cimmerian event in the study area, one can see that due to later Cretaceous subsidence it is not recognised directly by the porosity curves.

Furthermore, within the Jurassic sequences there are a number of small unconformities. It can be seen from figures 3.9.1 - 3.9.20 and 3.27 that due to the minor uplift associated with such events, the subsequent substantial Jurassic and Cretaceous subsidence, the scatter of data points and the number of data points sampled, they are not easily recognised by compaction curves alone.

3.7.4. Lithological Changes.

Lithological changes may be mistaken for unconformities as they can cause significant offsets in the porosity curve (figure 3.29). For example, on the Market Weighton Axis on the southern margin of the Yorkshire Basin, the Cretaceous chalk lies unconformably on Lower Lias (very thin) and Triassic sediments (figure 3.29A). Data for the Lias show considerable scatter due to casing but it is clear that the unconformity coincides with both the porosity and lithology change. Figure 3.29B illustrates a situation from the offshore Yorkshire Basin where a change in the porosity curve is due to a lithology change from shale to chalk and where the unconformity is unrecognised between curves for similar lithologies as in figure 3.27A, B and C. Figure 3.29C on the contrary illustrates the situation where curves for the same lithologies show a marked offset at the unconformity, postulating substantial Jurassic and Triassic subsidence and sedimentation (>1000m) which was removed prior to Cretaceous- Tertiary subsidence.

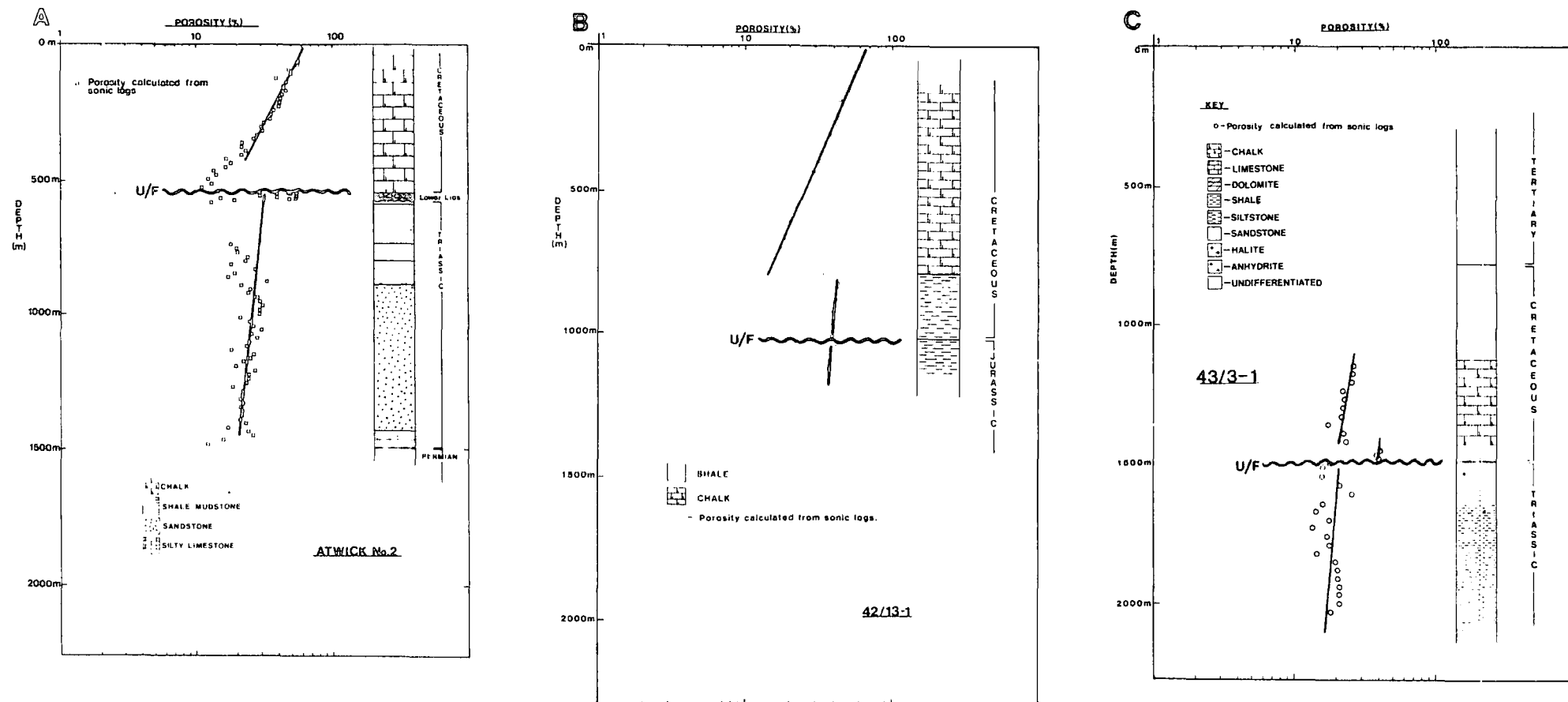


Figure 3.29. Combined affect of lithological changes and unconformities on the observed compaction trend.

Finally, if, as this study does, one assumes porosity loss with increasing burial depth, should one assume porosity increase with decreasing burial depth due to the release of overburden pressure by removal and erosion of sediments? The latter, if applicable, will have an important influence on the final porosity curve if the study area has been subject to a pronounced uplift event, as in the Yorkshire and Sole Pit Basins. The accurate quantification of uplift by the method discussed above will therefore be hindered. Magara (1976) concludes that this effect is minimal, particularly in regions where sediments have had a long history of subsidence and compaction prior to uplift. The sediments in the study area satisfy the above criteria and subsequently cohesive forces are developed within them which are strong enough to withstand the decrease in effective stress associated with uplift (removal of overburden). This study makes three assumptions:-

1. Porosity loss with increasing depth of burial.
2. No porosity gain with decreasing depth of burial.
3. The porosity attained at its maximum depth of burial will be retained by the sediment.

Thus, although normal trends for lithologies are identifiable they can be affected by various phenomena which may alter the expected trend. The porosity and interval transit time of sediments at the time of deposition and through their burial history will be a function of:-

1. Effective stress - overburden.
2. Age.
3. Lithology.
4. Diagenesis.

- (a) Initial Sediment Composition and Mineralogy.
- (b) Initial sediment texture, size, shape and sorting.
- (c) Fluid Chemistry.
- (d) Depositional Environment.
- (e) Pressure and Temperature Gradients.
- (f) Burial History - amount and rate of subsidence.

5. Tectonic Stresses.

- (a) Uplift.
- (b) Compression.
- (c) Diapirism.

All of these parameters are important in the development of a sediment. It is believed or assumed that 1, 3 and 5 are accounted for in the technique used. One measures the effective stress from present and reconstructed sedimentary thicknesses and calculates the observed compaction of the sedimentary column. A wide variety of different age sediments are analysed eg. Carboniferous 286 Ma to Cretaceous 65Ma and the results from each are discussed later. The main lithologies eg, shale, chalk and sandstone, have all been investigated. It is assumed that, although tectonic stresses such as compression and uplift have significantly affected the basin architecture, they have not greatly affected the variation of porosity and interval transit time with depth apart from offsetting it from normal compaction trends in the way discussed. Diagenesis, the fourth parameter, cannot easily be accommodated in the technique used for quantification of uplift but its positive effects are acknowledged in this study.

The above discussion outlines the method employed for the comprehensive quantification of uplift across a large area enclosing the Yorkshire, Sole Pit and East Midland Basins. Many of the problems encountered and other subjects of specific interest have been discussed and illustrated with working examples from the real data. There follows a brief discussion of the results in a more regional context, prior to their utilisation for analysis of subsidence and basin formation, inversion and hydrocarbon potential in Chapters 4, 5 and 6 respectively. The application of the results from this chapter are discussed in more detail in the aforementioned chapters.

3.8 Discussion.

The Yorkshire, Sole Pit and East Midland Basins have undergone uplift since the Upper Cretaceous-Lower Tertiary (Glennie and Boegner, 1981; Kent, 1980a). Consequently, varying amounts of sediments of various ages have been removed from the area. In order that:-

- A. Modelling of subsidence and basin formation, and
- B. Modelling of the uplift mechanism

be possible, this uplift event must be quantified. Modelling of subsidence and basin formation is discussed in Chapter 4. The following discussion focuses attention on modelling the nature of the uplift that is calculated. The mechanisms of this uplift are discussed in Chapter 5.

Figure 3.30 illustrates a selection of simplified stratigraphic sequences from boreholes across the Yorkshire, Sole Pit and East Midland Basins, and their marginal areas. It demonstrates the thickening of, in particular, Jurassic and Triassic sediments into the Yorkshire and Sole Pit Basins indicating that they were differentially subsiding with respect to neighbouring areas. The East Mid-

land Basin displays a more gentle subsidence, the form of which is preserved in sediments of Permian to Cretaceous age. The initiation of the Market Weighton area is also illustrated by Cretaceous sediments overlapping/ overstepping a thin Lower Jurassic sequence. A similar situation appears to occur on the eastern margin of the Sole Pit Basin where thick Cretaceous and Tertiary sediments overlie Lower Jurassic and, in places, Triassic sediments. However, these two apparently similar areas displaying pre-Cretaceous uplift or non-deposition are probably not caused by the same events. Uplift on the eastern flanks of the Sole Pit Basin has been postulated to represent extreme Cimmerian uplift and erosion (Glennie and Boegner, 1981). Subsequent subsidence has been continuous since the Lower Cretaceous.

The Market Weighton area, appears to have been a localised area of relative uplift during the Jurassic and Lower Cretaceous, on the southern flank of the Yorkshire Basin and northern flank of the East Midland Basin. The majority of Jurassic and Lower Cretaceous sediments thin towards it and occasionally the area defines a lateral facies change eg. Lower Cretaceous (Kent, 1974). Some sediment may have been removed from the area during the Cimmerian uplift event, but in contrast to the eastern flank of the Sole Pit Basin, it has been suggested that the apparent uplift of the Market Weighton area is due to a relatively buoyant granite at depth (Bott et al, 1978). The area was probably not one of substantial relief, and was only a temporary feature from Jurassic to the Lower Cretaceous. Permian, Triassic and Upper Cretaceous sedimentary facies and thicknesses are relatively stable across the area (figure 3.30). The porosity and interval transit time data do not infer an additional sedimentary thickness over the area in the Jurassic although any offset originally imparted on the curves may have been overprinted by substantial Cretaceous subsidence (figure 3.22 Atwick). This period of relative uplift and possible erosion does not correspond to the last major period of uplift to affect the area. Compaction trends infer that the Market Weighton

Area subsequently (since the Lower Cretaceous) suffered some further uplift and removal of overburden (figure 3.31 and Appendix C3:Tables).

This final period of uplift to affect the Yorkshire, Sole Pit and East Midland Basins coincides with a period of regional, basin inversion and uplift within north-west Europe during the Upper Cretaceous to Tertiary (Zeigler, 1978, 1987). Previous research by Marie (1975) from analysis of Lower Bunter Shale interval transit times estimate that a maximum of 5000 feet (1500 m) has been removed from the Sole Pit and Yorkshire Basins. Kent (1980a) predicted from local stratigraphic correlations that 500 - 1000 m of sediment has been removed from the Yorkshire Basin, whilst chemical diagenetic research by Hemingway and Riddler (1982) in the same basin infer up to 2500 m of sediment removed, including 1000 m of Tertiary sediments of which there are no records. The present structural and sedimentological configuration (figure 3.30) reflects the relative amounts of uplift and erosion between the Yorkshire, Sole Pit and East Midland Basins. The aim of this study is to accurately reconstruct the original, pre-inversion sedimentary thicknesses within and between these basins. Figure 3.30 illustrates that both subsidence and uplift were not uniform in the study area. Previous research represents the maximum values corresponding to the most inverted or uplift parts within each basin. They do not attempt to quantify the local, lateral variations. Furthermore, there is considerable disagreement for the amounts of sediment removed which does not instill confidence in the applicability of the data and/or the methods used.

The objectives of this research are to:-

1. Eliminate the problems associated with studies that measure temperature changes (not necessarily burial related) in sediments (Hemingway and Riddler, 1982).

2. Eliminate the bias inflicted by the measurement and utilisation of physical changes within one formation (Marie, 1975) for calculating uplift, by analysing the physical response of all lithologies and most individual formations to depth of burial.
3. Produce an objective and comprehensive appraisal of the local and regional uplift in, and sediment removed from, the Yorkshire, Sole Pit and East Mid-land Basins.

Figure 3.9.1 - 3.9.20 illustrates all the data used in this study. Uplift or removed overburden was quantified from this data in the manner described above. The results are summarised in Appendix C3, Appendix C3:Tables and figure 3.31. Appendix C3 graphically illustrates the regression analysis of porosity data for major lithologies and lithologically defined formations. Uplift is computed using theoretical values for surface porosity. These are then compared with the projected values from the observed borehole porosity data. Uplift results from each porosity plot and from the visual determination of observed interval transit time data with calculated normal trends (figures 3.12, 3.15 and 3.17) are held in Appendix C3:Tables. From this large data base a best fit or average value of uplift is calculated. Those boreholes lacking a sonic velocity log, approximately 50% of the total in the study, are assigned an uplift value after careful consideration of the respective stratigraphy in the borehole and the uplift values from porosity and interval transit time data for neighbouring boreholes with sonic logs. This method will not introduce any major error into a determination of uplift since:-

1. Lateral facies thickness variations are not demonstrably abrupt within individual basins.
2. The distribution of the boreholes with sonic logs is excellent.

Thus, local and regional thickness variation and lateral changes in computed

uplift values are accounted for. The average or best fit uplift values are illustrated in a contoured uplift map of the Yorkshire, Sole Pit and East Midland Basins (figure 3.31).

Figure 3.31 shows that the results identify the Yorkshire and Sole Pit Basins as the two main centres of uplift. Further, it illustrates the compartmentalisation of this major uplift event in the two aforementioned areas. The approximate lines of the Dowsing Fault Zone and Outer Silver Pit Fault bound the main Sole Pit uplift and the Vale of Pickering Fault Zone bounds the main Yorkshire Basin uplift. To the north of the Yorkshire Basin, uplift values parallel the major Butterknowle and Hartlepool Faults but a lack of data for the Permian and Triassic sediments does not permit a detailed or accurate study in this particular area.

The two axes of uplift follow the general trends of the two former basinal areas and parallel the main faults in the region. This suggests some tectonic control during uplift along pre-existing basinal structures. Similarly, the basinal structures seem to be controlled by major basement structures (Glennie and Boegner, 1981; Kent, 1980a; Van Hoorn, 1987). Thus, the whole Permian to Mesozoic evolution of the area is controlled by major structures inherent to the basement which are re-activated in normal and reverse senses by changing lithospheric stresses occurring in time.

3.8.1. Yorkshire Basin.

Data from the onshore Yorkshire Basin suggests a maximum uplift of 3000 - 3500 feet decreasing southwards to the Market Weighton area. Values are consistent within the Yorkshire Basin and may locally increase northwards although this is speculative. To the south of the Yorkshire Basin, in the offshore area, uplift values locally exceed 5000 - 6000 feet. Boreholes in this area indicate Triassic (Keuper) sediments at outcrop. A component of the uplift in the region may

be due to diapirism or lateral migration in Permian Zechstein evaporite deposits. Whatever the mechanism causing the uplift, the amount of sediment calculated as being removed is considered representative of the original sedimentary thickness in the area concerned. The method used simply measures the vertical offset of the observed and normal compaction trends. The amount of sediment calculated as being removed is used in analysis of the original form of subsidence prior to uplift. Data is sparse from boreholes to the west of the Yorkshire Basin, towards the present Pennine area, but in general they do not show a significant increase even although older (Permo-Triassic) sediments are at outcrop. This may suggest, as previous workers have implied (Wills, 1951; Anderton et al, 1979; Warrington, 1970; Leeder, 1983) that the northern Pennine area did constitute the western and northern margins to the Yorkshire Basin periodically for most of the Permian to Cretaceous. To the north, the Pennines linked to the Mid-North-Sea High (Glennie, 1984a,b; Ziegler, 1982). Both areas may have been breached in the Upper Cretaceous during a marked eustatic sea-level rise (Vail et al, 1977; Pitman, 1978). Evidence from within the Yorkshire Basin concerning its margins to the north and west, is given by sedimentological analysis of the Lower and Middle Jurassic sediments which coarsen and thicken (marginally) to the north and display a northern to north-western provenance (Bate, 1965, 1966; Tate and Blake, 1876; Alexander, 1986). The above factors occur in sediments south of the Hartlepool and Butterknowle Faults in the Middlesbrough area. To the north and north-east of these faults Jurassic sediments thin towards the Mid-North-Sea-High (Kent 1980b), a further indication that one is approaching the Jurassic basin margins. Additionally, the Permian basin is not postulated to extend much beyond the present outcrop (Anderton et al, 1979; Ziegler, 1982) and Triassic sediments thin and prograde into coarser more sandy facies to the west and north. Immediately north of the Butterknowle and Hartlepool Faults, the Lower Triassic sediments may prograde into Upper Permian sediments (Smith and Francis 1967).

All the above evidence implies the presence and importance of major land masses to the north and west of the Yorkshire Basin, both bounding its extremities and providing an area from which sediments could be sourced. The presence of the major Butterknowle and Hartlepool Faults, played an important role in basin development and destruction during the Carboniferous (Stainmore Trough). Jurassic sediments are discontinuous to the north of these faults and Permian to Jurassic sediments thicken to the south into the Yorkshire Basin, suggesting they may have had an important role to play in accommodating both subsidence and uplift in the area (see also Chapter 5).

Southwards in the Yorkshire Basin, values of uplift do not decrease until the northern margin of the Vale of Pickering Fault Zone is reached. Progressive southward younging of sediments at outcrop (figure 3.32) reflect the general pattern of uplift (figure 3.31). Values of uplift do not increase in the vicinity of this major faulted area suggesting that the uplift was not preferentially accommodated by compressive reactivation (Gilchrist et al, 1987; Whittaker, 1985) of these pre-existing basinal faults (figure 3.32). Both the Vale of Pickering Fault System and the Butterknowle and Hartlepool Fault System are so orientated (east-west) that one might expect their reactivation by a north-south compressive regime (Dewey, 1982; Livermore and Smith, 1986). Between the two fault systems, major uplift of the central and northern Yorkshire Basin has occurred. Figure 3.32 illustrates both the younger sediments (less uplifted) within the still highly extended Vale of Pickering faults in contrast to the presence of older (Triassic and Lower Jurassic) sediments on the footwall and hangingwall of the less extended northern most fault of the Hartlepool-Butterknowle Fault System. This infers that although both sets of faults may have been important in accommodating basin formation, subsidence and extension in the Yorkshire Basin, its subsequent partial destruction by uplift is postulated to have been mainly accommodated along by the northern set of faults, one of which, the Butterknowle Fault, forms a direct link to the

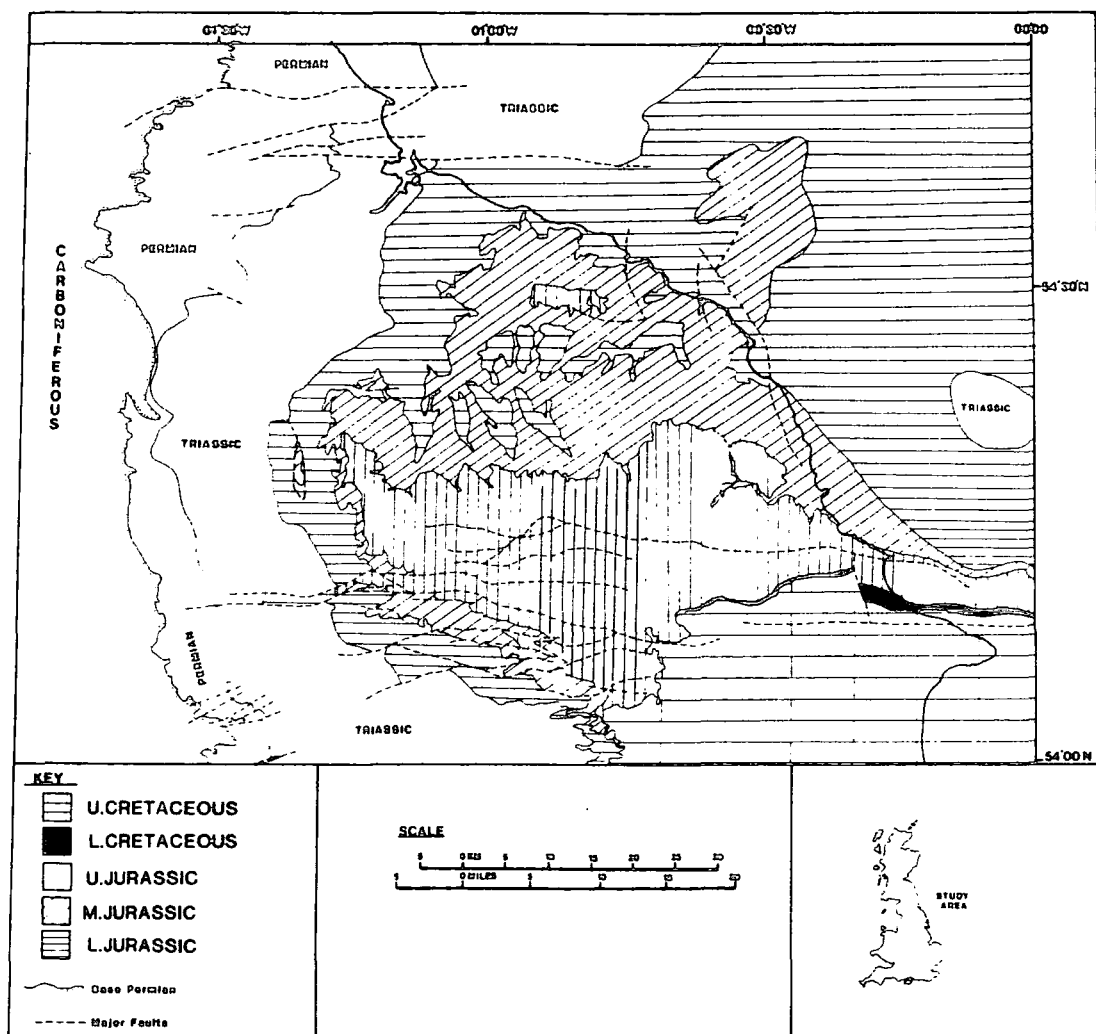


Figure 3.32. Geological map of the Yorkshire Basin. Younging of sediments southwards reflects the computed trends of uplift in figure 3.31

Pre-Permian basement.

3.8.2. Market Weighton Area.

The Market Weighton area is on the footwall of the north downthrowing Vale of Pickering Fault Zone and formed the southern margin of the Yorkshire Basin in the Jurassic and Lower Cretaceous. Uplift values show a rapid decrease from the Yorkshire Basin to the north, and range from 500 to 1000 feet, increasing to 1500 feet around its margins. Permian, Triassic and Cretaceous sediments do not thin across the area, in contrast to those of the Jurassic (figure 3.32 and 3.33). Porosity regression analysis for Triassic and Cretaceous sediments (figures 3.9.1 - 3.9.20, Appendices C3 and C3:Tables) suggest they are not substantially elevated above their maximum burial depth. To the west of the area, analysis of Permian dolomite and Carboniferous sandstones and shales (figures 3.9.1 - 3.9.20 and Appendix C3) yields relatively low uplift values, 1500 feet, considering their low stratigraphic position. This may represent an extension of the Market Weighton structure in the Jurassic to the west which from present stratigraphic thicknesses would leave approximately 600 - 700m of Triassic, Jurassic and Cretaceous sediments that have been removed by uplift. This value of approximately 2000 feet is not vastly different to the uplift from porosity and interval transit time data. We may also expect some thinning of all ages of sediments towards this area due to thinning onto the footwall of the Vale of Pickering Fault Zone and towards the postulated Pennine margin. However, the data is regarded as insufficient to substantiate fully the above hypothesis.

3.8.3 East Midland Basin.

Results over the on- and offshore East Midland Basin indicate that relatively little uplift has taken place (figure 3.31) This accords with the preservation of thick Cretaceous sediments in contrast to the Yorkshire and Sole Pit Basins (figure

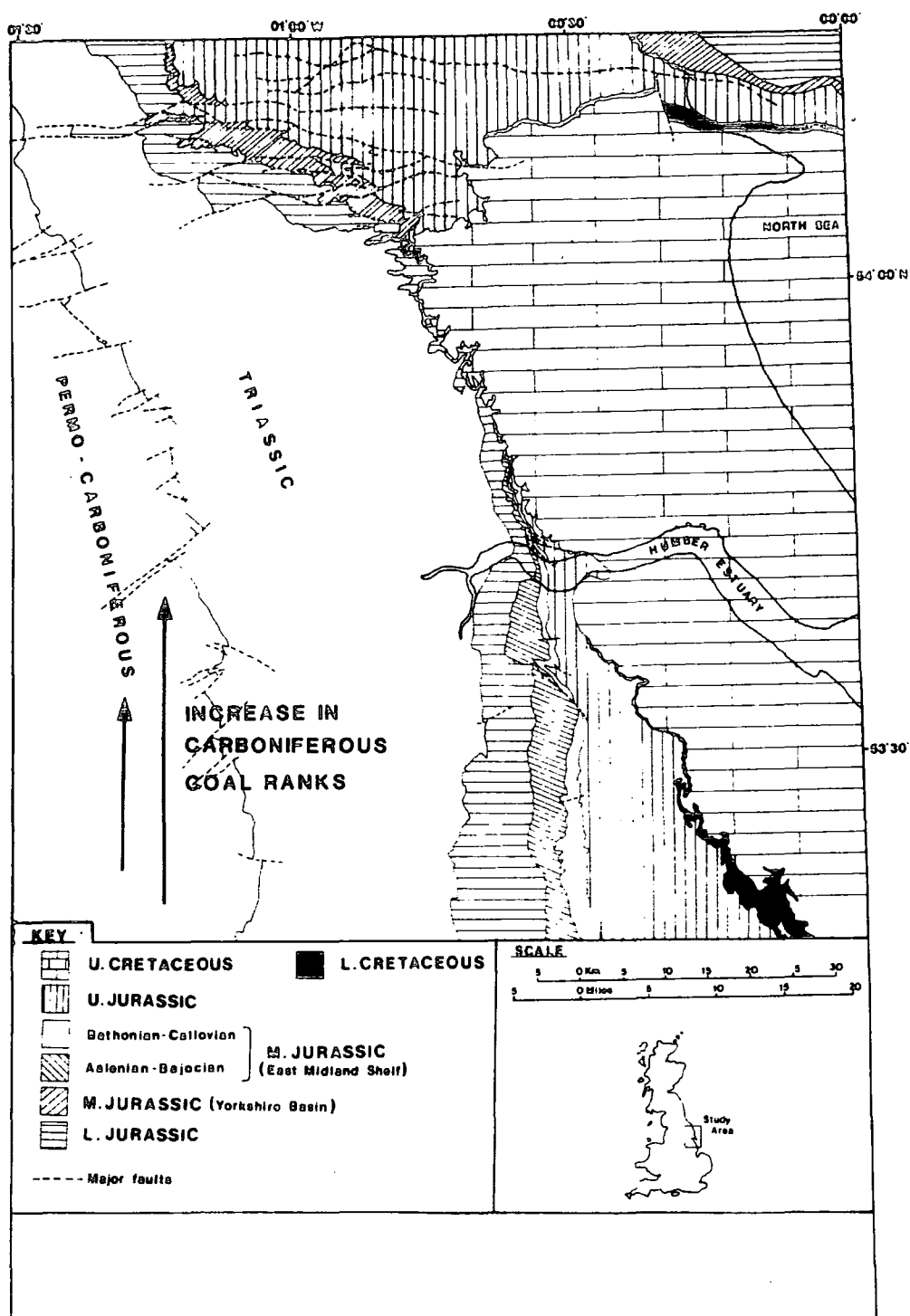


Figure 3.33. Geological map of the East Midland Basin including trends of increased coal rank in Carboniferous coalfields to the west of the present limit of the basin.

3.33). Values show a minimum in the eastern onshore and western offshore areas, towards the London Brabant Platform to the south, and in the Market Weighton area in the north. Westwards towards the Pennines, more extreme uplift and erosion is identified by both the uplift data and the present outcrop of Permian to Cretaceous sediments (figures 3.31 and 3.33). Similarly, eastwards towards the Dowsing Fault Zone and Sole Pit Basin, the uplift values from the porosity and interval transit time data show a rapid increase.

However, uplift values to the west of the area eg. Axholme 1 (Appendices C3 and C3:Tables) are not large considering outcrop is in the Keuper shales (Triassic). Available data suggests that gentle subsidence occurred towards the west and north-west of the East Midland Basin in Nottinghamshire and South Yorkshire. The presence of such a situation is also supported by reduced sedimentary isopach thicknesses seen on available isopach maps (Whittaker, 1985).

Suggate (1976), in a study of coal ranks from the Yorkshire and Nottinghamshire coalfields discovered an increase in rank towards Wakefield in the north from Nottingham in the south (figure 3.33). This area lies immediately west of the study area. The coalfield extends beneath the present outcrop of Permo-Triassic sediments (figure 3.33). Suggate concluded that the observed coal rank increase could be due to three situations:

1. Increased burial by Permian to Mesozoic sediments, now removed.
2. Increased burial by Carboniferous sediments, now removed.
3. Increased palaeogeothermal gradient prior to the Permian.

For the observed rank increase Suggate postulated an extra 1500 - 2000 feet of Permian-Mesozoic sediments, a figure which correlates well with this study and also that of Wills (1951 and 1956). However, it is also very likely that a high

or higher than normal geothermal gradient existed during the Carboniferous as evidenced from volcanic and magmatic activity in the Derbyshire, Leicestershire and northern Pennine district (Anderton et al, 1979; Dunham and Wilson, 1985). Coal ranks from Suggate's study imply that maximum temperatures in the East Midlands area were not extreme, ie. high volatile bituminous coals ($50 - 60^{\circ}\text{C}$). To the north in the Askrigg and Alston Block area (west of the Yorkshire Basin) extreme geothermal gradients of $60 - 70^{\circ}\text{C/km}$ are postulated to have occurred, during the Carboniferous associated with major granitic bodies beneath the two blocks. Temperatures of between $150 - 200^{\circ}\text{C}$ have been calculated from vitrinite reflectance data and fluid inclusion studies in ore deposits (Dunham and Wilson, 1985; Brown et al, 1987; Creaney, 1982). Coals of medium volatile bituminous to semi-anthracite are found. Clearly, the cause of high rank coals and high temperatures in the north Pennines is due to this Carboniferous thermally anomolous situation and need not be explained by later burial under a Permian to Mesozoic cover. Indeed, any subsequent burial under a Permian to Mesozoic cover, after this thermal event, would not be represented in or by an increase in coal rank due to the high relict temperatures. Furthermore, a cover of greater than 5km of Permian to Mesozoic sediments buried under a relatively normal eg 30°C/km geothermal gradient would be required. Such an amount of sediment is not witnessed in the thickest succession of the local Permian to Mesozoic Basins.

Nevertheless, relating the high temperatures of this area to the Yorkshire and Nottinghamshire coalfields to the south infers that possibly some of this heat may have been conducted at least to parts of the northernmost area of the Yorkshire coalfield. This, together with volcanic and magmatic events in neighbouring areas (Derbyshire and Charnwood, Leicestershire), may have caused some of the higher coal ranks than are expected from present burial depths.

All the data cited above provide feasible mechanisms for the observations of

Suggate (1976). It is quite possible therefore, that a combination of increased Carboniferous geothermal gradients, additional Carboniferous sediment and additional Permian to Mesozoic sediment produced the thermally anomalous situation stated above. Hence, data from this study are supported by the findings of previous workers.

3.8.4. Sole Pit Basin.

Data for the Sole Pit Basin (figure 3.31) comply with the hypothesis that this area was one of differential uplift as well as differential subsidence. Uplift values through the majority of the area show fairly consistent results ranging from 2500-4000 feet which correlates well with data from the studies of the Lower Bunter Shale (Marie, 1975; Glennie and Boegner, 1981). They also correspond well with values for the Yorkshire Basin. The two areas appear to have responded to similar tectonic episodes in quite similar proportions. Like the Yorkshire Basin, the main uplift is compartmentalised by the major basin bounding faults eg. Dowsing Fault Zone. Similarly, the uplift values do not reach a maximum in the immediate vicinity of these faults. The Dowsing Fault Zone is a diffuse region of complex faulting (Glennie and Boegner, 1981; Van Hoorn, 1987) and the lack of a sudden increase in uplift may reflect this. However, it may also reflect a lack of boreholes identifying the precise positioning of the uplift. Nevertheless, published geological sections do imply a gradual rather than sudden encounter with the main uplifted region such that the uplifted area forms a dome-like structure (figure 3.34).

In the north of the uplifted Sole Pit Basin, the main uplift is bounded by the Outer Silver Pit Fault (figure 3.31). Values in this region are seen to be 4000 - 6000 feet eg. 48/13-1 and 47/5-1 (Appendices C3 and C3:Tables). However, this area coincides with a large diapiric salt wall which may have occurred in response to the fault or vice versa. Thus, the large uplift values may have two components, namely a diapiric component which is overprinting and adding to the background

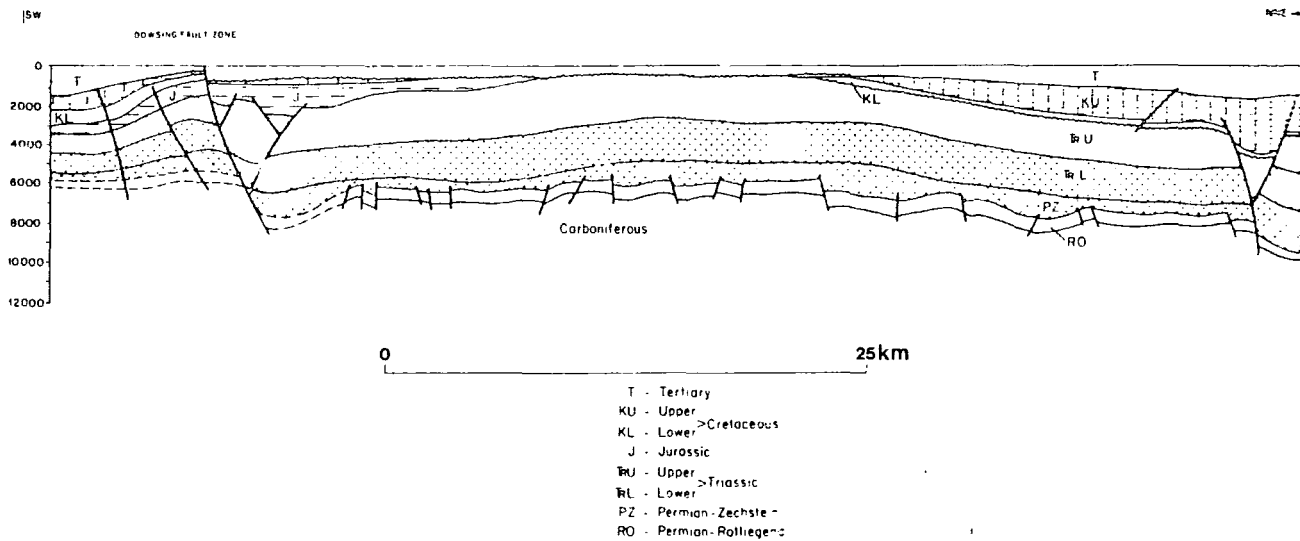


Figure 3.34. Cross-section of the Sole Pit Basin (Glennie, 1984b) displaying relationship of the main uplift to the basin bounding faults.

regional uplift that is localised in the Sole Pit Basin. Some of the uplift values to the east and north-east of the Sole Pit Basin represent relict uplift values from the Cimmerian event. Substantial Jurassic sediment was removed prior to Cretaceous and Tertiary subsidence to the east of the Sole Pit Basin. This is still evident in the compaction data despite subsequent burial eg. figure 3.9.1 - 3.9.20 and Appendices C3 and C3:Tables- 49/28-2, 49/27-1, 49/22-1, 49/16-4. A similar stratigraphic situation occurs in boreholes to the north of the area eg. 43/3-1 Appendix C3:Tables and figures 3.9.1 - 3.9.20 and 3.29.C.

The values for uplift in the Sole Pit Basin also correlate well with postulated thicknesses of sediment from surrounding less uplifted areas, particularly to the north of the area. For example, borehole 48/7-1 in the central area of the uplift has a calculated uplift of 3500 feet. The top unit in the borehole is in the Lower Jurassic with 1000 feet of Lower Jurassic sediments preserved. Isopach data (Glenie and Boegner, 1981) to the north of the Outer Silver Pit Fault, which forms the northern limit of the main Sole Pit Basin uplift, suggests that this area was a continuation of the Sole Pit Basin during subsidence. Boreholes in this area, eg. 42/30-1, 42/29-1, which are less uplifted (figure 3.31; Appendix C3:Tables) may therefore reveal the appropriate amounts of sediments that are now missing from the Sole Pit Basin. They contain 1500 - 2000 feet of Jurassic sediments above the Lower Jurassic. Typical Cretaceous thicknesses, which are preserved, are 1000 - 1500 feet. Uplift data for these boreholes suggests approximately an additional 1000 feet of Cretaceous (and Tertiary) sediments removed. Thus, stratigraphic thicknesses imply 3500-4500 feet of sediment that may have been deposited in the vicinity of borehole 48/7-1 in the north of the area. This correlates well with the calculated removed overburden.

One possible error in this is that locally, the Upper Cretaceous chalk is observed to exceed 800 m or 2500 feet in thickness (Hancock, 1984). As a differen-

tially subsiding area one might expect thicker deposits of Cretaceous sediments in the Sole Pit Basin as occurred in the Permian to Jurassic. If so, and values are of the same magnitude or greater than those stated above, this would cause a quite major discrepancy in the two predicted estimates (calculated and inferred) of the original total sediment. This could be explained by non-representative or erroneous interval transit time and porosity data. However, recent studies (Walker and Cooper, in press) postulate that the Sole Pit area was already being uplifted (relatively) during much of the Upper Cretaceous, ie. after 95Ma. This correlates well with data from Livermore and Smith (1986) who suggest that a major change in the relative motion of the African continent towards the European continent commenced at approximately 95Ma, causing a change to a compressive lithospheric stress field.

These events caused westward onlap onto the uplifting Sole Pit axis from the eastern margin. Walker and Cooper (op.cit.) argue that the structure was probably breached in the late Upper Cretaceous and hence a thinner than expected Chalk sequence was probably developed.

3.9 Conclusions.

The main aim of this research is to reconstruct the pre-inversion regional basin configuration such that the history of formation and development of the Yorkshire, Sole Pit and East Midland Basins could be investigated. Figures 3.31 and 3.35 represent the regional plan view and cross-sectional summaries of the calculated original depths to the basement in these basins. This represents the maximum load acting on the basement. When the basement is backstripped, and the contribution to subsidence from the sedimentary load removed, the background driving tectonic subsidence which initiates basin formation can be isolated. Reconstruction of the original depth to basement is therefore imperative, specifically in basins that have undergone substantial inversion, such as the Yorkshire and Sole Pit Basins.

1. The results show that good correlation can be achieved between uplift values using:
 - a. Single lithologies throughout one borehole, eg. all shales.
 - b. Different formations of similar or the same lithology, eg. Lower Jurassic shale, Kimmeridge Clay, Lower Bunter Shale.
 - c. Different formations of different lithologies, eg. chalk, sandstone and shale.
2. Interval transit time (ITT) and porosity with depth curves suggest each lithology and formation has its own distinctive trend, but uplift results for each are of the same magnitude.
3. Sonic velocity and interval transit time data give consistent results within a single borehole.
4. Porosity data gives less consistent results within a single borehole than interval transit time data. However, as a rule the two data sets correlate well.
5. Older sediments and formations do not give higher uplift values than the younger sediments and formations above them in the sequence (even in the more uplifted areas). In the Yorkshire and Sole Pit Basins, significant burial and uplift have occurred. Hence the younger sediments which are preserved after the later uplift event, eg. Lower Jurassic, have undergone significant burial beneath even younger sediments which have since been removed. The results imply that no expansion or porosity increase has occurred during uplift, which would cause lower uplift values relative to the underlying sediments.
6. In areas subjected to relatively smaller uplifts, eg. East Midland Basin, we may expect younger sediments to be less cohesive and thus, expand or gain porosity during uplift. This would induce a trend towards lower values for

uplift in the upper formations, which should be represented in the interval transit time and porosity data measured from borehole logs. This does not appear to be the case in the majority of the data analysed and so uplift can be computed from sediments of all ages.

7. Evidence exists within the data which suggests that the more the uplift, the greater the variation in uplift results for an individual borehole. This could be due to diagenetic effects during significant uplift or elevation. Also, the sediments of the two major uplifted areas, the Yorkshire and Sole Pit Basins, were buried significantly deeper than the lesser or non-uplifted areas such as the East Midland Basin. Hence, these sediments have had more opportunity to be affected by increased temperatures.

Additionally, these sediments are within the more tectonically active areas during both subsidence and uplift. Clearly, the basin architecture has been affected by the major tectonic events in the area and hence the physical nature of the sediments within the basin may have some tectonic overprint.

8. The consistency of the results between the formations and lithologies suggests that the method used is a valid one and that the changes in sediments during compaction and burial are measurable and regular and can therefore be used to compute maximum depth of burial. This also implies that the assumptions made in this study do not overlook any major parameters which have greatly affected the results.
9. No single formation displays the most consistent results. However, the Triassic sediments which are preserved in the majority of boreholes in all three basins reveal, on their own, the appropriate magnitudes of uplift. This implies that although some facies variations do occur between the basins the major lithologically defined formations are obeying similar laws of compaction and

responding in a similar manner to the uplift that has occurred.

10. Compaction accounts for most porosity loss in shales and chalks. This holds for shales buried to depths in excess of 10,000 feet or 3 kilometers and chalks buried to a kilometer or so depth (Hancock, 1984; Scholle, 1977), whereafter, recrystallisation and pressure solution may dominate causing rapid or irregular loss of primary porosity. Thus, sediments buried in excess of these depths may be expected to show anomalous values of uplift, particularly the older sediments in the sequence. The consistency of the results for the Yorkshire, Sole Pit and East Midland Basins confirms that both shale and chalk respond physically in a regular fashion to burial. The results also confirm that interval transit times and porosity curves for shales are a reliable indicator of burial (and uplift) down to 3-3.5 km, which is the approximate maximum depth of burial of the base Triassic observed in the study area. Similarly, the results imply that chalk has not been buried to greater than 1 kilometre in most places.
11. In sandstones, porosity loss is less related to burial and compaction and therefore, this lithology may be less reliable in a study of this type. Sandstones in the area, particularly the Bunter or Sherwood Sandstone, do display anomalous results particularly in their porosity curves (figure 3.9.1 - 3.9.20) and the subsequent uplift values. It is often found difficult to compute a reasonable trend objectively from the porosity data as the porosity can be higher in the lower Bunter Sandstone than at the top. Thus, statistical analysis of the porosity data is not employed as frequently as for other lithologies and formations. However, where available, the sonic velocity data and corresponding uplift data correlate fairly well. The greater the burial depth of a sandstone, the more probability that secondary porosity is developed and this may be why the Bunter Sandstone (often buried to 2 or 3 km) displays such variable

data.

From field observations of sandstone compaction in the Middle Jurassic Ravenscar Group, Alexander (1986) has concluded that these sediments were not buried to depths much in excess of 600 m (1900 feet). This is consistent with the results from this study (figure 3.32, and Appendices C3 and C3:Tables) and those of Kent (1980a and 1980b).

12. Where possible, analysis of Carboniferous sediments has been avoided.
 - (a.) They are used where no post-Permian sediments are available.
 - (b.) Carboniferous shales and sandstones have undergone a long and complex history of subsidence and uplift, including two major periods of subsidence (Carboniferous and Permian-Mesozoic) interrupted by two major periods of uplift (Variscan and Alpine or Laramide). These sediments have been buried for a considerably long time ($>286\text{Ma}$), often to depths now exceeding 5 km and have been subjected to significant tectonic stresses. Uplift results from such sediments, using a study of compaction trends which makes a number of assumptions as to the primary response of sediments during burial, including the retention of physical characteristics attained at maximum burial, are felt to be too error prone to be regarded as significant or representative. This is particularly so in the two major basinal areas, the Yorkshire and Sole Pit Basins.
 - (c) The Carboniferous, where present, is treated as basement and is therefore assumed to have zero porosity.
13. Although it is not necessary to use a multi-lithology study, the results imply that most lithologies, in the study area at least, show good correlation.
14. The results from this study clearly indicate the Yorkshire and Sole Pit Basins

as areas which were differentially uplifted.

15. Although diagenetic changes do affect the sediments, the consistency of the uplift results suggest that the secondary effects of diagenesis on porosity are perhaps more noticeable on a smaller scale, ie. one formation in one particular area, due to isolated, anomalous conditions of temperature, pressure, fluid chemistry, faulting etc. They do not affect the method used as a regional indicator of uplift and maximum burial depth.
16. The amounts of sediment postulated to have been removed by uplift show, in general, good correlation with expected amounts from known stratigraphic variations across the area.
17. Values are found to be fairly consistent within the two main uplifted areas, the Yorkshire and Sole Pit Basins, which implies that uplift is accommodated equally across the basins. Localised reverse faulting, thrusting and folding occur, associated with transpression, particularly within the Dowsing Fault Zone. This is postulated to reflect ^{the} oblique orientation of the Dowsing Fault Zone with respect to the tectonic stresses applied at this time and thus, represent the localised reactivation of pre-existing structures (Glennie and Boegner, 1981; Van Hoorn, 1987).

Typically, uplift by inversion utilises pre-existing, often basinal or extensional, faults. The maximum uplift calculated in the study area is compartmentalised, as was the maximum subsidence, to the hangingwall sides of major faults. This suggests that uplift by inversion, although not necessarily the sole cause, has occurred in the Yorkshire and Sole Pit Basins. Inversion is defined as:-

- (a. Positive inversion - conversion of former structural low or basin into a structural high.

- (b. Negative inversion - conversion of a former structural high into a structural low (basin).

Positive inversion is an isostatic response to lithospheric shortening or compression. The vertical motions identified during inversion, ie. uplift, are primarily a response to lateral motions induced by major plate movements and readjustments.

This will be discussed further in Chapter 5.

18. One major reason for identifying and calculating the uplift that has occurred in the Yorkshire, Sole Pit and East Midland Basins is to reconstruct the sedimentary sequences such that the thermo-mechanical evolution of the area during basin formation can be quantitatively and qualitatively assessed. This method will calculate the uplift or removed overburden irrespective of the mechanism causing it:-

1. Flexural uplift.
2. Uplifted along tops of rotated fault blocks.
3. Regional Isostatic Uplift.
4. Compressive Reactivation of earlier faults.
5. Diapirism.

The preceeding discussion outlines the main results from this objective study of the uplift across the Yorkshire, Sole Pit and East Midland Basins and correlates them with the present stratigraphic thicknesses and their possible maximum extent through the Permian to the present. The results are further analysed in the context of the mechanisms and tectonics that may have caused the uplift (above and Chapter 5).

CHAPTER 4

BASIN FORMATION AND SUBSIDENCE

4.1 Introduction.

The objective of this chapter is to examine the thermo-mechanical evolution of the Yorkshire (Cleveland), Sole Pit and East Midland Basins and analyse their development with respect to theoretical models for basin formation. Basin formation occurs in response to a driving tectonic force and the magnitude of subsidence is amplified by the subsequent input of sediments, which impart a load on the lithosphere. In order to isolate this driving tectonic subsidence and reveal the components of basin formation, ie. thermal and mechanical subsidence, the loading effect of sediments must be removed. This can be achieved by backstripping the sedimentary column which involves sequentially removing sedimentary layers, modelling the manner in which the basement rebounds and allowing the remaining sediments to decompact in response to the release in the lithostatic pressure (load). There are two requirements for the accurate assessment of basin formation and hence subsidence:-

1. A complete sedimentary sequence - represents the maximum load that was effective on the basement.
2. Variation of porosity with depth of burial - relationship by which the sediments can be decompact and their load in time removed.

Subsidence within the Southern North Sea Basin was initiated in the Permian and continued, with interruptions, to the present day. During this period a number of differentially subsiding units developed within the Southern North Sea Basin including the Yorkshire, Sole Pit and East Midland Basins. Upper Cretaceous and Tertiary inversion and uplift removed a substantial proportion of the sedimentary

sequence, particularly in the Yorkshire and Sole Pit Basins (see Chapter 3). The present geological configuration in the study area does not satisfy the conditions specified above.

- a. The sedimentary sequences are truncated and do not represent the complete subsidence history of the area or the maximum load that acted on the basement.
- b. The porosity:depth profile will be inaccurate, particularly in the areas that have suffered significant erosion.

These two problems have been overcome using the modelling incorporated in Chapter 3. To summarize that work, analysis of present compaction trends using sonic logs has proved a viable method by which firstly the sediment removed can be quantified and secondly the normal compaction trends can be reconstructed. This has provided representative compaction curves across the study area for use in backstripping. Once these corrections have been made it is assumed that accurate modelling of the subsidence in the area can be achieved.

Figures 4.1 and 4.2 represent the depths to the Pre-Permian basement in the study area at the present day and prior to removal of sediment during Upper Cretaceous to Tertiary inversion, respectively. Significant differences are observed. Thus, when the method by which one models basin formation depends on removing the contribution of the sedimentary load, utilisation of the maximum and not necessarily present day sedimentary thicknesses is vitally important.

The history of research into basin formation mechanisms is discussed in detail. This clarifies the principles involved, possible problems and results expected from theoretical modelling of the thermal and mechanical behaviour of the lithosphere during extension. The nature of the subsidence observed in the Yorkshire, Sole Pit and East Midland Basins is examined with respect to this work.

4.2 Basin Formation Modelling.

4.2.1. Initiation of Basin Formation.

Basin formation mechanisms have been the subject of much study in recent years in an attempt to increase our comprehension of the processes that cause the crust/lithosphere to subside. All models have attempted to explain the influences and consequences of mechanical and thermal changes in the lithosphere. It has been shown that no one model can satisfy the criteria for all basins, rather a combination of a number of processes appear most likely to account for the complex structural and sedimentological characteristics developed during basin formation.

The basin geometry, structures and the type and distribution of sedimentary facies provide us with an insight into the evolution of a basin through time. Our understanding of the mechanisms that may cause basins to form fall into 4 main categories (Dewey, 1982).

1. Thermal Causes.
2. Crustal/Lithospheric Thickness Changes.
3. Loading.
4. Stretching.

These are not necessarily mutually exclusive.

Thermal causes and lithospheric thickness changes are implicitly linked although which process dominates is open to speculation. Cooling the lithosphere or lowering the 1333° C isotherm will cause subsidence (thermal subsidence). This causes thickening of the lithosphere and thinning of the crust which allows a load (sediments) to increase the subsidence. Similarly, heating the lithosphere or raising the 1333° C isotherm, thins the lithosphere and thickens the crust causing

load removal and uplift. Therefore, thinning the crust will also cause subsidence by cooling and . thickening of the lithosphere. It is apparent, however, that there is still a need for a driving mechanism which can either initiate subsidence itself or initiate a change in the thermal state and hence thickness of the lithosphere. Subsidence may then progress in response to the changing thermal state of the lithosphere and loading of the basement by sediments infilling the basin.

Lithospheric stretching in response to major plate tectonic readjustments will induce lithospheric thinning and subsidence (McKenzie, 1978). Thus a mechanism exists by which the vertical deformation observed during the formation of a basin, ie. subsidence, can be explained as a secondary response to the lateral deformation, ie. extension of the lithosphere.

4.2.2. Continuation of Subsidence.

It is recognised that having formed a basin, it does not simply cease subsiding and fill with sediments. In many basins subsidence continues for long periods of time, eg. 200Ma, and may occur beyond the limits of the initially formed basin, ie. the basin margins do not remain static. Researchers recognised the formation of graben systems such as those in the North Sea and speculated about their possible causes and consequences of their continued subsidence outside the faulted graben boundaries. Hypotheses include:-

- A. Upward Moho migration in response to increasing sedimentary load within the grabens (Collette, 1968).

Upward Moho migration would result in increasing subsidence yet the rate of subsidence in most basins decreases with age (Sleep, 1971). That is, the subsidence of intra-continental basins shows a exponential decrease in time analogous to the progressive subsidence of oceanic lithosphere (figure 4.3) as it cools and ages away from the spreading axis (Watts and Ryan, 1976; Steckler and Watts, 1978; Keen,

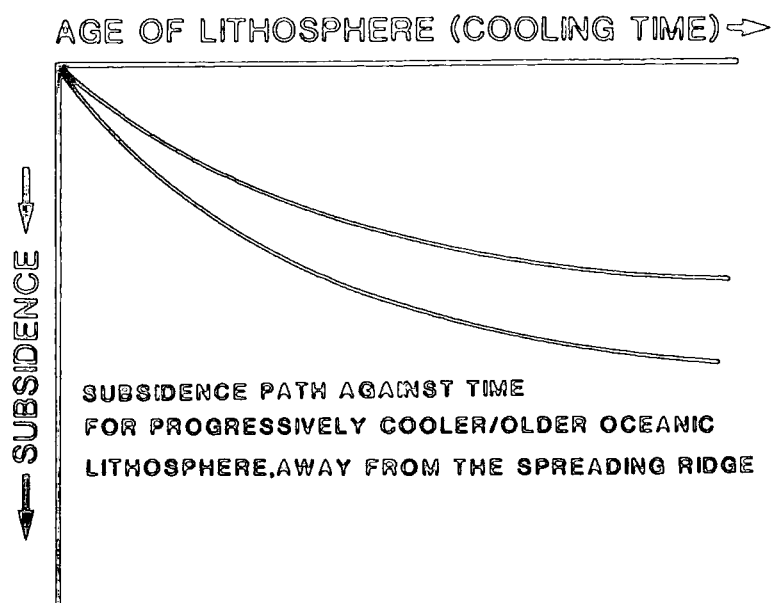


Figure 4.3. Schematic representation of the subsidence of oceanic lithosphere as it cools and ages away from the spreading centre. This is the manifestation of thermal subsidence.

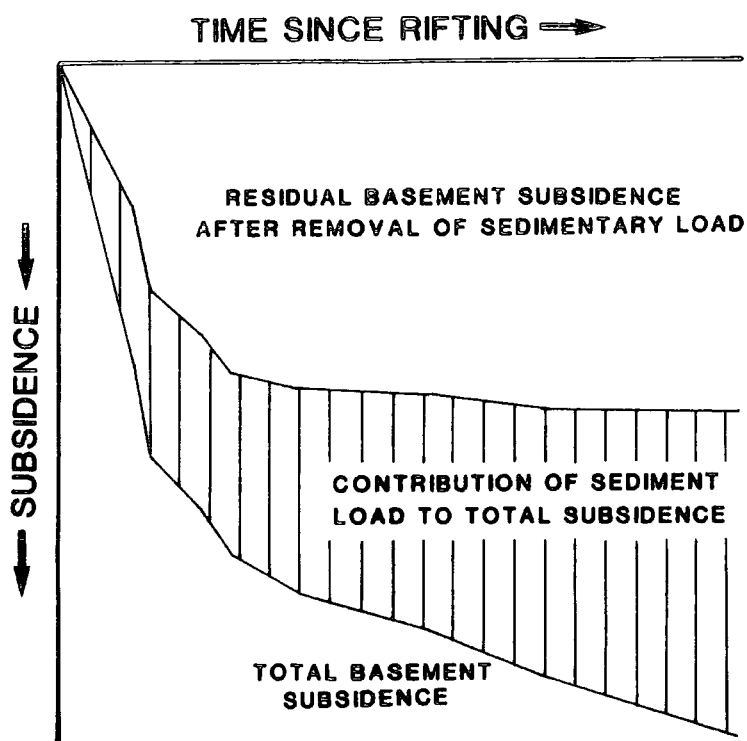


Figure 4.4. Diagrammatic representation of the affect of removing the sedimentary load in a basin. Sedimentary loading is not sufficient to explain all of the observed subsidence of the basement. The additional component defines the driving tectonic subsidence.

1979).

- B. Flexural subsidence due to the response of a cooling lithosphere to sediment loading following graben formation (Beaumont, 1978).

The time constant for the flexural response of the lithosphere is estimated to be less than 100Ma (Sclater and Christie, 1980) yet most sedimentary basins, including the Yorkshire, Sole Pit and East Midland Basins subside or subsided for periods well in excess of this. This implies that flexure such as that caused by the loading of the lithosphere by orogenic massifs, eg. Alps, Variscides (Pre-Permian), cannot alone account for basin formation. It may be that flexure is more important or more pronounced during later stages of basin formation as the stretched and thinned lithosphere re-equilibrates, cools and increases in strength or flexural rigidity (Watts et al, 1982; Chadwick, 1985a). Exponentially decreasing basin subsidence (figure 4.3) thus reflects increasing lithospheric strength (McKenzie, 1978). However, if, as Lake (1985) postulated, basin formation involves a number of discrete rifting or stretching events, one may expect some flexural subsidence following each event as the lithosphere cools and strengthens. The recognition of different subsidence episodes (mechanical, thermal or flexural) can be achieved by analysis of backstripped tectonic subsidence curves, sedimentary facies relationships and basin architecture. The results of such a study of the Yorkshire, Sole Pit and East Midland Basins are discussed in this chapter.

It has been shown (Watts and Steckler, 1978; Dewey, 1982) that if one removes the loading effects of sediments in a basin, they are not sufficient to account for all the basin subsidence. These findings imply that a basin would form irrespective of whether sediments infilled it (figure 4.4). Mechanisms such as Moho migration and flexural subsidence are not the basic cause or driving force that causes this background subsidence but are undoubtedly important components in the evolution of subsidence in a basin.

4.2.3. McKenzie's Model for Uniform Lithospheric Stretching.

McKenzie (1978) assumed that lithospheric attenuation or extension (stretching), readily explained by relative stresses and tensions imparted by plate tectonic motions, is the principle mechanism by which the lithosphere is thinned and subsidence initiated. The amount of stretching is quantified by a factor β , its reciprocal defining the amount of lithospheric thinning. McKenzie's model predicts an initial, instantaneous, mechanical, fault controlled subsidence (graben formation), followed by gentle, regional subsidence as the lithosphere thermally re-equilibrates, cools and thickens.

The model assumes that the whole of the lithosphere, ie. crustal and sub-crustal lithosphere, is stretched by β . Yet, by thinning the lithosphere, we have raised the 1333° C base lithosphere isotherm, inducing thermal uplift prior to lithospheric cooling and subsidence. This apparent contradiction can be accommodated by:-

1. Mechanical, faulted subsidence exceeding thermal uplift and resulting in a net subsidence.
2. McKenzie (1978) argued that the initiation of subsidence or uplift by lithospheric stretching depends on the ratio of the crustal to lithospheric thickness prior to rifting or stretching. Thus subsidence results if:-

$$\frac{C_z}{l_z} \geq 0.1375$$

where C_z is the crustal thickness and l_z is the lithospheric thickness.

If one assumes a lithospheric thickness of 125 km for the North Sea region (Dewey, 1982) then to accommodate uplift by lithospheric attenuation, the crustal thickness must be less than 18 km. Crustal thicknesses in the study area, illustrated in figure 4.5, are of the order of 30 - 35 km (Meissner et al, 1986). Pre-

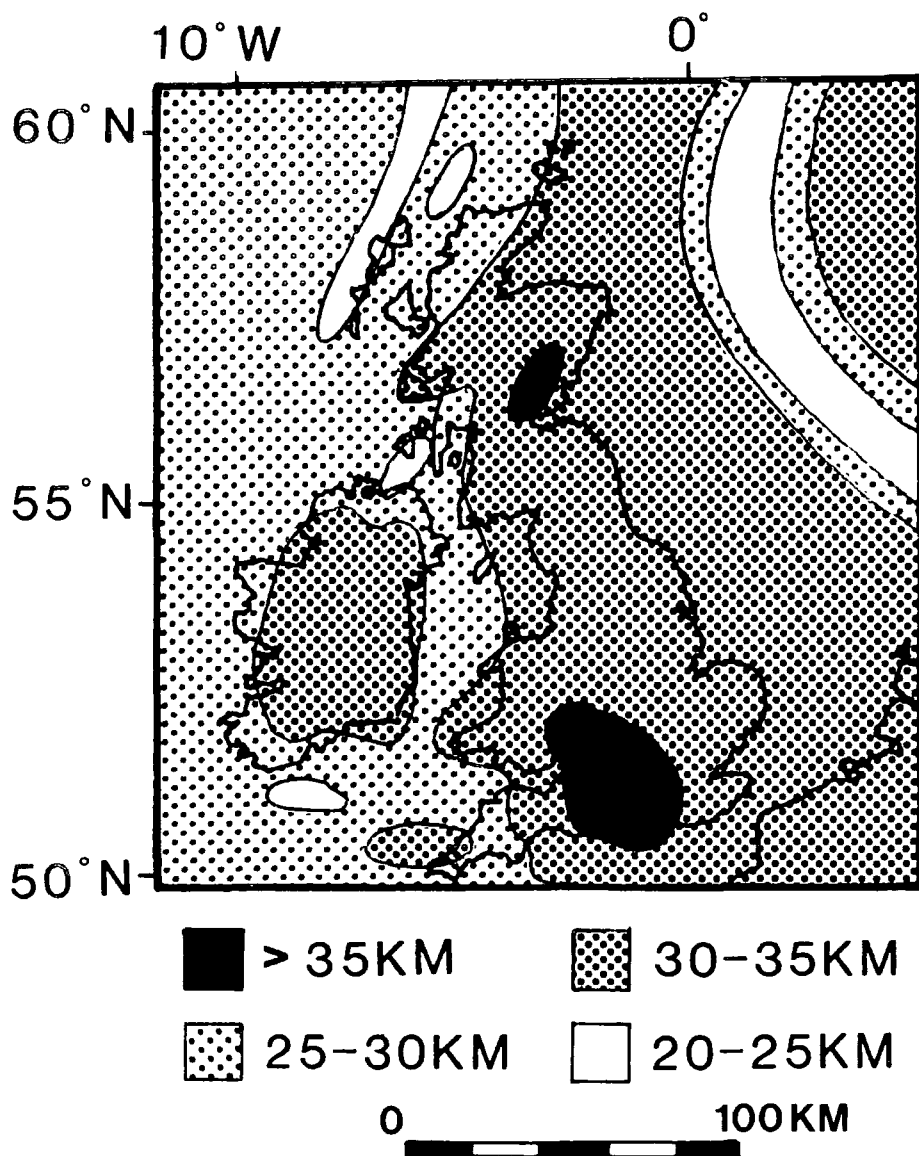


Figure 4.5. Crustal thickness or depth to the Moho around Great Britain and the North Sea (Meissner et al, 1986).

Permian crustal thicknesses in the study area are assumed to have been of the same magnitude due to thermal re-equilibration following Carboniferous basin formation and lithospheric shortening and thickening during inversion in the Vaiscan orogeny. McKenzie's model implicitly assumes that the lithosphere is stretched by β and therefore the ratio of crustal to lithospheric shortening will remain the same. Thus, if $C_z : l_z \geq 0.1375$ at the onset of rifting, then thermal uplift should theoretically not occur.

In the Central North Sea possible thermal uplift and doming occurred in the Middle Jurassic during major extensional tectonics (Ziegler, 1982; Leeder, 1983). This event is synchronous with smaller scale uplift episodes in the study region such as uplift of the Market Weighton area. Uplift of the Central North Sea in an extensional regime can be explained by one of the following mechanisms:-

1. Thermal uplift due to low, ie. less than 0.1375, crustal to lithosphere thickness ratio.
2. Rotation of tilted fault blocks.
3. Progressive, differential, thinning of crust and lithosphere.

McKenzie's model and the postulated lithospheric and crustal configuration prior to stretching do not appear to satisfy criteria for uplift during extension, whilst rotation of tilted fault blocks is not likely to cause regional uplift but more likely localised erosion of the footwall sides of major faults. The latter could explain in part the relative uplift of the Market Weighton area during differential subsidence of the Yorkshire and East Midland Basins.

4.2.4. Progressive, Differential Thinning of the Crust and Lithosphere.

Recent developments in basin modelling have focused attention on observations that extension in the crustal and sub-crustal lithosphere are not necessar-

ily accommodated in a one to one relationship within the basin margins proper (Royden et al, 1980; Hellinger and Sclater, 1983; Lake, 1985; Dewey and Karner, 1986). The crustal lithosphere is stretched by δ and the sub-crustal lithosphere by β . Thus, the relationship of crustal to lithospheric thickness will not always be constant if $\delta \neq \beta$. Excessive crustal with respect to lithospheric thinning may create the conditions for thermal uplift to occur during extension as in the Central North Sea during the Middle Jurassic (Leeder, 1983).

Royden et al (1980), cited a different mechanism for basin formation in order to explain inconsistent observations of δ and β within sedimentary basins. However, their model for the initiation of basin formation by stretching and predicted forms of subsidence are similar to that of McKenzie (1978). The fundamental difference between the two mechanisms is that Royden et al assume the retention of a constant thickness lithosphere by dyke injection. The model of dyke injection is unsatisfactory in intra-cratonic basins unless complete continental rifting is accomplished and a spreading centre developed. This infers β values in excess of 2 and up to 4.43, the value for continental rupture (Dewey, 1982). β values in the Yorkshire, Sole Pit and East Midland Basins are found to be a maximum of 1.5 and significantly less in the majority of the area. Furthermore, recent studies in the North Sea and other regions including deep seismic and gravity profiling (Wernicke and Burchfield, 1982; Barton and Wood, 1984; Beach, 1984; Ussami, Karner and Bott, 1986) have suggested that the sub-crustal lithosphere does undergo stretching and thinning in varying amounts depending on its position with respect to the rift centre and major lithospheric detachments.

McKenzie's model can be used as a basis to study the development of the Yorkshire, Sole Pit and East Midland Basins particularly as it successfully predicts the behaviour of the crustal and sub-crustal lithosphere during stretching and extension. It also provides an excellent theoretical model on which to base

interpretation of mechanical and thermal evolution of a basin from observed geological data. The program on which the study was implemented allows analysis of basin formation using:-

A. Uniform One Layer Stretching Model.

B. Non-Uniform Two Layer Stretching Model.

The following sections discuss these two models and assess their application to the observed subsidence in the Yorkshire, Sole Pit and East Midland Basins.

4.3 Basement Subsidence and Lithospheric Stretching.

Tectonic subsidence of the basement reveals important information as to the mechanism or mechanisms by which a basin forms. The form of the tectonic subsidence within a basin, computed using the backstripping technique (see section 4.4.2) remains constant irrespective of the model used to theoretically explain the observations. Structural and sedimentological analysis within the basin should clarify this. However, if the modelled tectonic subsidence varies from the observed data this does not necessarily mean that the model does not apply to the whole basin but rather that individual locations within a basin may require individual interpretation. Furthermore, the modelled basin mechanism will not necessarily predict the subsidence form of the basin margins where rifting has not occurred. The model lays down a set of ideal conditions from which an ideal subsidence form is computed. Departures from this ideal form can be interpreted using variations on the assumptions of the predicted components of subsidence. Two models, assuming similar responses or behavioural characteristics of the lithosphere, are applied to the data in the study area. The fundamental difference between the two models applies to the specification of intra-crustal or crustal - sub-crustal lithospheric detachments, which delineate the boundary between differential lithospheric involvement ($\delta \neq \beta$). Wholesale lithospheric stretching or

thinning remains the same between the two models but the specification of upper crustal detachments allows more stretching to be accommodated within an upper plate (δ) than a lower plate (β) as in figure 4.6, or vice versa.

4.3.1. Uniform Lithospheric Stretching.

McKenzie (1978) developed this model to depict depth independent stretching and its consequences for basin formation. Stretching, β , is a constant for both the crustal and sub-crustal lithosphere, and creates an increased geothermal gradient in response to thinning of the lithosphere and compression of the lithospheric isotherms (figure 4.7). Two phases of subsidence are modelled and assumed to be the isostatic response to lithospheric extension. Initial, rapid fault controlled subsidence in response to zero flexural strength of the lithosphere (Airy) is followed by gentle, regional subsidence in response to thermal relaxation and increasing flexural strength of the lithosphere (figure 4.8). The model also predicts the geographical relationships between syn-rift (initial, fault controlled subsidence) and post-rift (thermal/flexural subsidence) sediments (figure 4.9). The McKenzie model has been shown to successfully reproduce regional observations of tectonism and sedimentation for both intra-cratonic basins (Sclater and Christie, 1980) and rift/passive margins (Watts et al, 1982).

A number of problems exist with this theoretical approach to basin formation. These include:-

1. Airy Isostasy - McKenzie's model assumes zero flexural strength of the lithosphere at the onset of rifting and hence instantaneous locally compensated subsidence. The lithosphere, particularly at low stretching factors is likely to retain some residual flexural strength. Hence, this will be represented in the tectonic subsidence curves, but it may be masked by the influence of thermal subsidence and hence sub-crustal lithospheric involvement, which will also

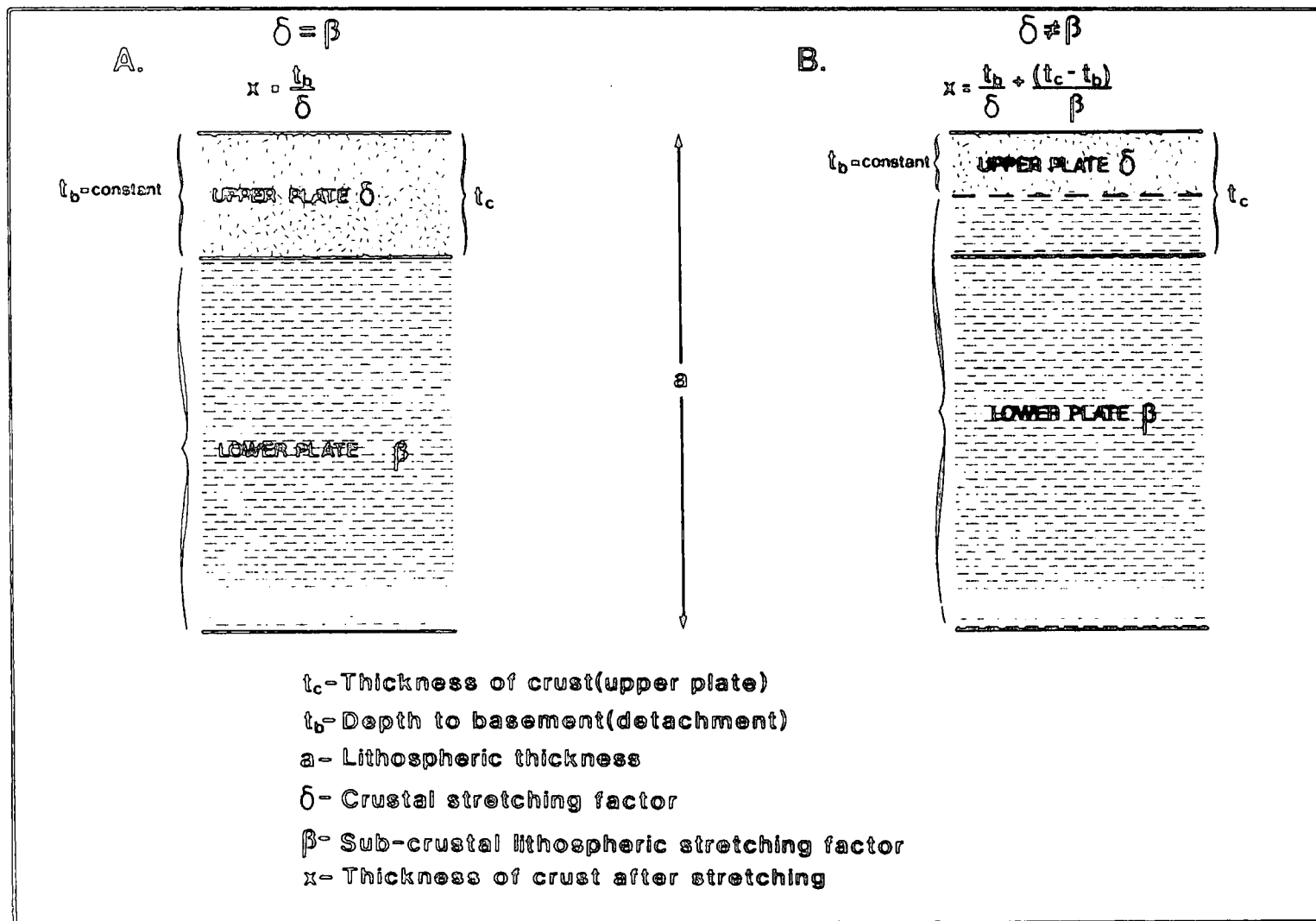
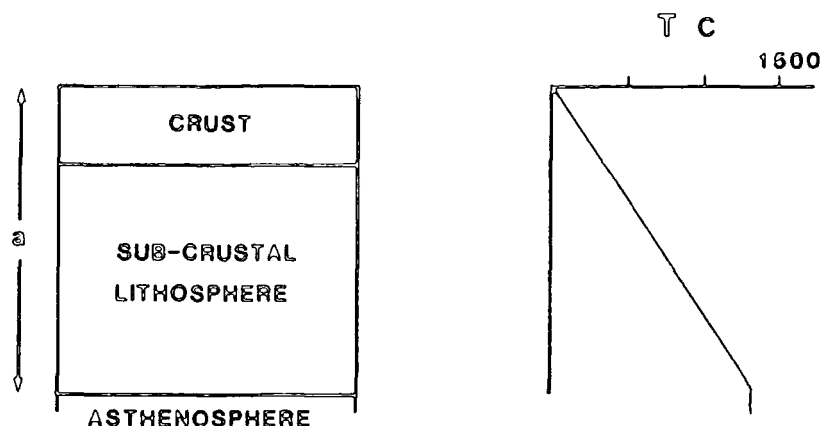
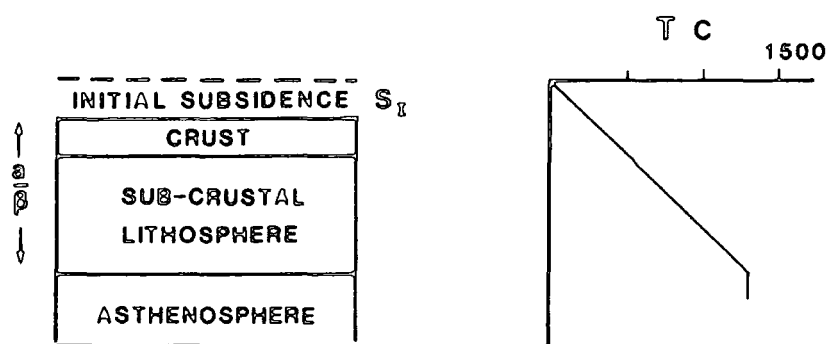


Figure 4.6. Schematic cross-section of the lithosphere. The lithospheric detachment may be at the base of the crust (A) or at some level within the crust (B) eg. brittle-ductile transition at 15KM. McKenzie's (1978) model predicts stretching of the crustal and sub-crustal lithosphere is the same.

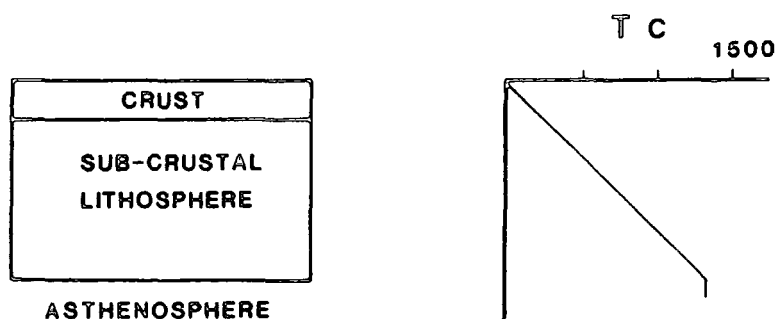
UNIFORM 1 LAYER MODEL



A. PRE-STRETCHING, THERMALLY EQUILIBRATED LITHOSPHERE

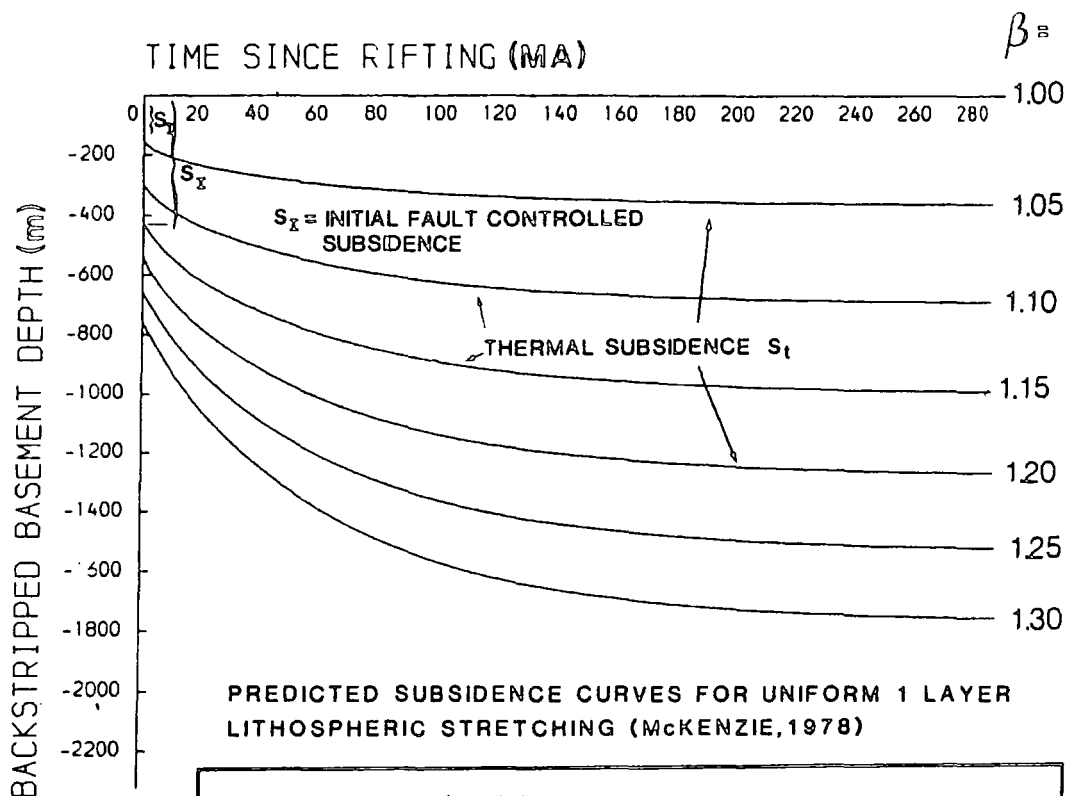


B. WHOLE LITHOSPHERE STRETCHED BY β CAUSING INITIAL SUBSIDENCE S_0 . GEOTHERMAL GRADIENT RAISED.



C. THERMAL SUBSIDENCE, COOLING AND THICKENING OF LITHOSPHERE. RETURN TO INITIAL CONDITIONS.

Figure 4.7. Thermal structure of the lithosphere before, during and after uniform stretching (McKenzie, 1978). Sub-crustal stretching induces an increased lithospheric geothermal gradient which decays slowly causing thermal subsidence.



$$S_x = \frac{a \left(1 - \frac{1}{\beta} \right) \left\{ \frac{t_c}{a} (\rho_m - \rho_c) \left(1 - \frac{\alpha T_L t_c}{2a} \right) - \frac{\alpha \rho_m T_L}{2} \right\}}{\rho_m (1 - \alpha T_L) - \rho_s}$$

$$S_t = \frac{4a\rho_m\alpha T_L}{\pi^2(\rho_m - \rho_s)} \left\{ \frac{\beta}{\pi} \sin \left(\frac{\pi}{\beta} \right) \right\} (1 - e^{-\pi^2 t/\beta^2})$$

LITHOSPHERIC THICKNESS (a) = 125KM

CRUSTAL THICKNESS (t_c) = 31.2KM

MANTLE DENSITY (ρ_m) = 3.33 g cm⁻³

CRUSTAL DENSITY (ρ_c) = 2.8 g cm⁻³

SEDIMENT GRAIN DENSITY (ρ_s) = 2.65 g cm⁻³

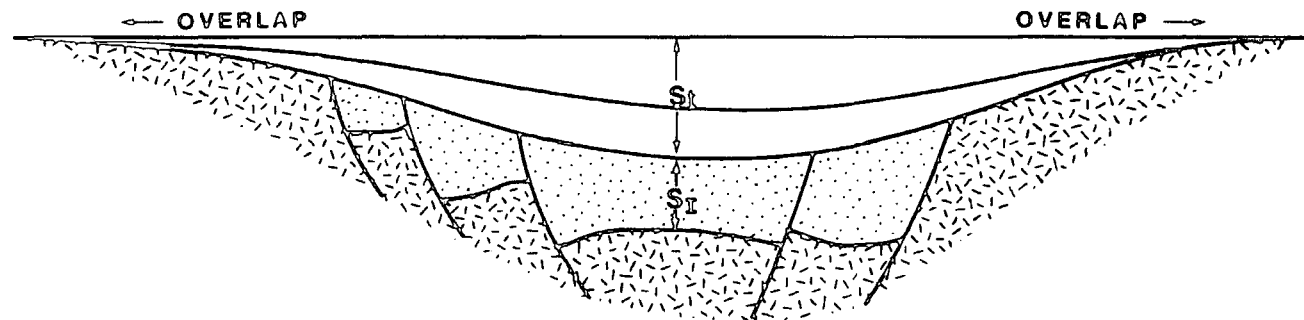
WATER DENSITY (ρ_w) = 1.03 g cm⁻³

BASE LITHOSPHERE TEMPERATURE (T_L) = 1333 °C

COEFFICIENT OF THERMAL EXPANSION (α) = 3.28x10⁻⁵ °C⁻¹

LITHOSPHERIC THERMAL TIME CONSTANT (τ) = 62.8Ma

Figure 4.8. Diagrammatic representation of the components of tectonic subsidence predicted by McKenzie's model. β = lithospheric stretching factor. Model assumes Airy isostasy.



S_i INITIAL FAULT CONTROLLED SUBSIDENCE.

S_t THERMAL SUBSIDENCE.



BASEMENT



SYN-RIFT SEDIMENTS DEPOSITED IN A FAULT BOUND BASIN.



REGIONAL, UNFAULTED SUBSIDENCE IN RESPONSE TO THERMAL RELAXATION AND INCREASING FLEXURAL STRENGTH OF THE LITHOSPHERE. POST-RIFT SEDIMENTS PROGRESSIVELY OVERLAP THE EARLIER SYN-RIFT SEDIMENTS AND THE BASIN MARGINS.

Figure 4.9. Characteristic Steer's Head geometry of subsidence by uniform lithospheric stretching (redrawn from Chadwick, 1985a).

reduce the spontaneity of the initial fault controlled subsidence. However, Whittaker (1985) stated that Mesozoic basins in Southern England appear to be locally isostatically compensated. The form of the subsidence curves will reveal the applicability of Airy isostasy in the Yorkshire, Sole Pit and East Midland Basins.

2. Instantaneous Rifting - this may never occur, but could be spread over a time span of 5 - 30Ma (Jarvis and McKenzie, 1980; Lake, 1985). If rifting is not instantaneous but finite, additional thermal subsidence will occur in response to re-equilibration before rifting has ceased.
3. Repeated Rifting/Subsidence - the mechanical component of tectonic subsidence appears, from both subsidence curves and structural and sedimentological data, to have had more than one initial pulse. This may represent renewed lithospheric extension through time. Each event has associated with it a component of thermal subsidence. Similar observations have been made for the Wessex and Weald Basins (Lake, 1985) and North Sea area (Ziegler, 1982; Wood and Barton, 1983; Leeder, 1983; Thomas, 1984).
4. Flexure - the flexural strength of the lithosphere will affect the subsidence curves and will contribute during both mechanical and thermal subsidence.
5. The model may predict β values which are inconsistent with, or overestimate, observations of extension. However, not all extension is quantifiable in the upper crust from fault geometries. Computed β values represent the maximum lithospheric extension.
6. Lithospheric stretching in some areas appears to be depth dependent. The model may not, therefore, accurately predict the variation of β through the lithosphere.

7. The rheological behaviour of the crust down to the Moho (brittle) and sub-crustal lithosphere (ductile) implies that lithospheric stretching will be accommodated differently. This does not preclude that stretching will be of different magnitude in these two zones.

Many of these anomalous observations, although not accounted for in the model, are readily interpreted or recognised by comparison of the observed tectonic subsidence with the theoretically modelled curves.

4.3.2. Non-Uniform Two Layer Lithospheric Stretching.

In this model, a similar subsidence form to the uniform one layer model is predicted, ie. initial, rapid, fault controlled subsidence followed by gentle, regional thermal subsidence. However, the model allows greater involvement of the upper crust due to more variable strain during mechanical extension and less involvement of the sub-crustal lithosphere and therefore less thermal subsidence (figure 4.10).

Figure 4.11 illustrates the evolution of the geothermal gradient during depth dependent lithospheric stretching and basin formation. Differential crustal and sub-crustal involvement significantly alters the geothermal gradients from the uniform one layer model (figure 4.7) resulting in a depth dependent geothermal gradient. The model maintains strain compatibility such that the whole lithospheric stretching (in a uniform one layer sense) remains constant. The relationship between theoretical crustal (δ) and sub-crustal (β) stretching is proportional to the level of decollement or detachment separating the two lithospheric zones and will influence the contribution of mechanical and thermal subsidence. Structural detachments, associated with upper crustal listric faults and shear zones, and rheological detachments within the lithosphere, do occur. The former possibly sole out into the latter where brittle deformation in the upper crust is translated into ductile deformation in the sub-crustal lithosphere. However, it is debatable as to

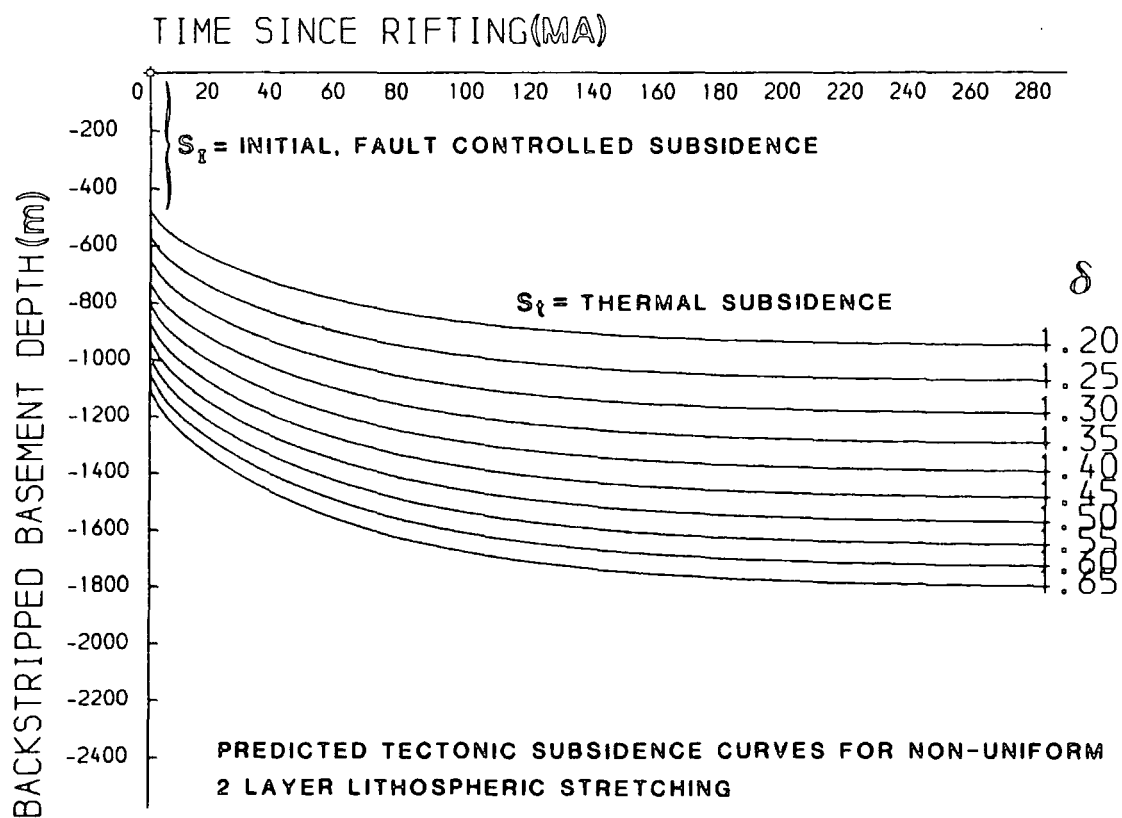
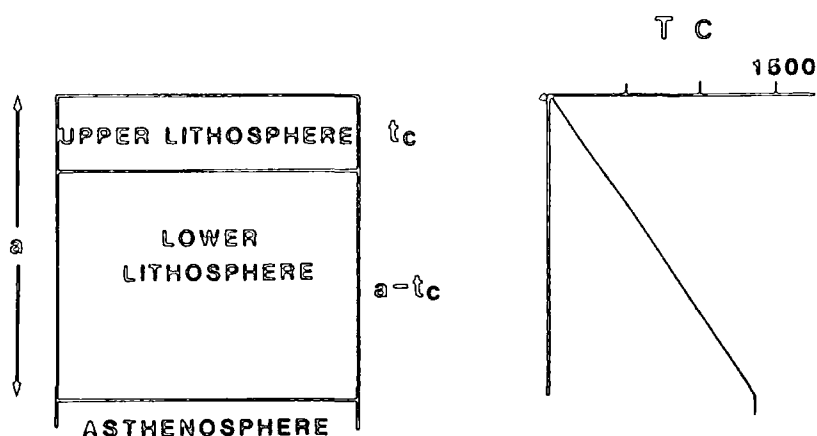
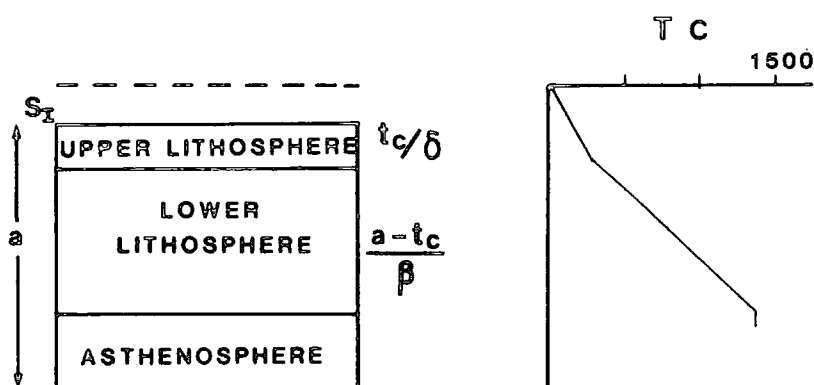


Figure 4.10. Diagrammatic representation of the components of tectonic subsidence predicted by non-uniform, depth dependent lithospheric stretching. Whole lithospheric stretching remains the same as in the uniform stretching model.

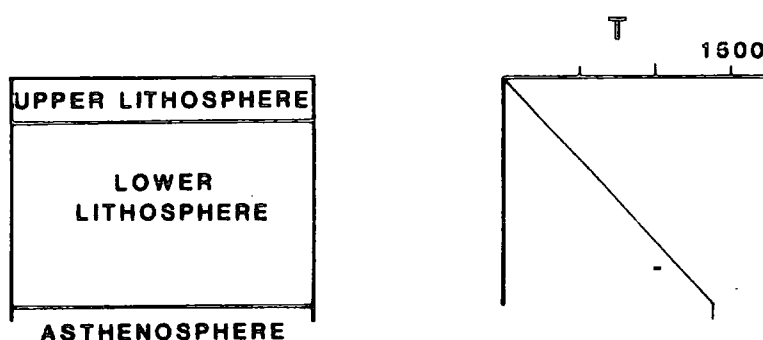
NON-UNIFORM 2 LAYER MODEL



A. PRE-STRETCHING, THERMALLY EQUILIBRATED LITHOSPHERE



**B. NON-UNIFORM LITHOSPHERIC STRETCHING.
UPPER LITHOSPHERE BY δ . LOWER LITHOSPHERE BY β .
KINK IN GEOTHERMAL GRADIENT.**



**C. THERMAL SUBSIDENCE, COOLING AND THICKENING OF LITHOSPHERE.
SUBSIDENCE IS PROPORTIONAL TO THE RATIO OF β TO δ .
RETURN TO INITIAL CONDITIONS.**

Figure 4.11. Thermal structure of the lithosphere before, during and after non-uniform stretching. The degree of sub-crustal lithospheric stretching will influence the amount of heat input into the system. This will be reflected in the component of thermal subsidence. Upper crustal extension may occur with no sub-crustal involvement ie. $\beta=0$.

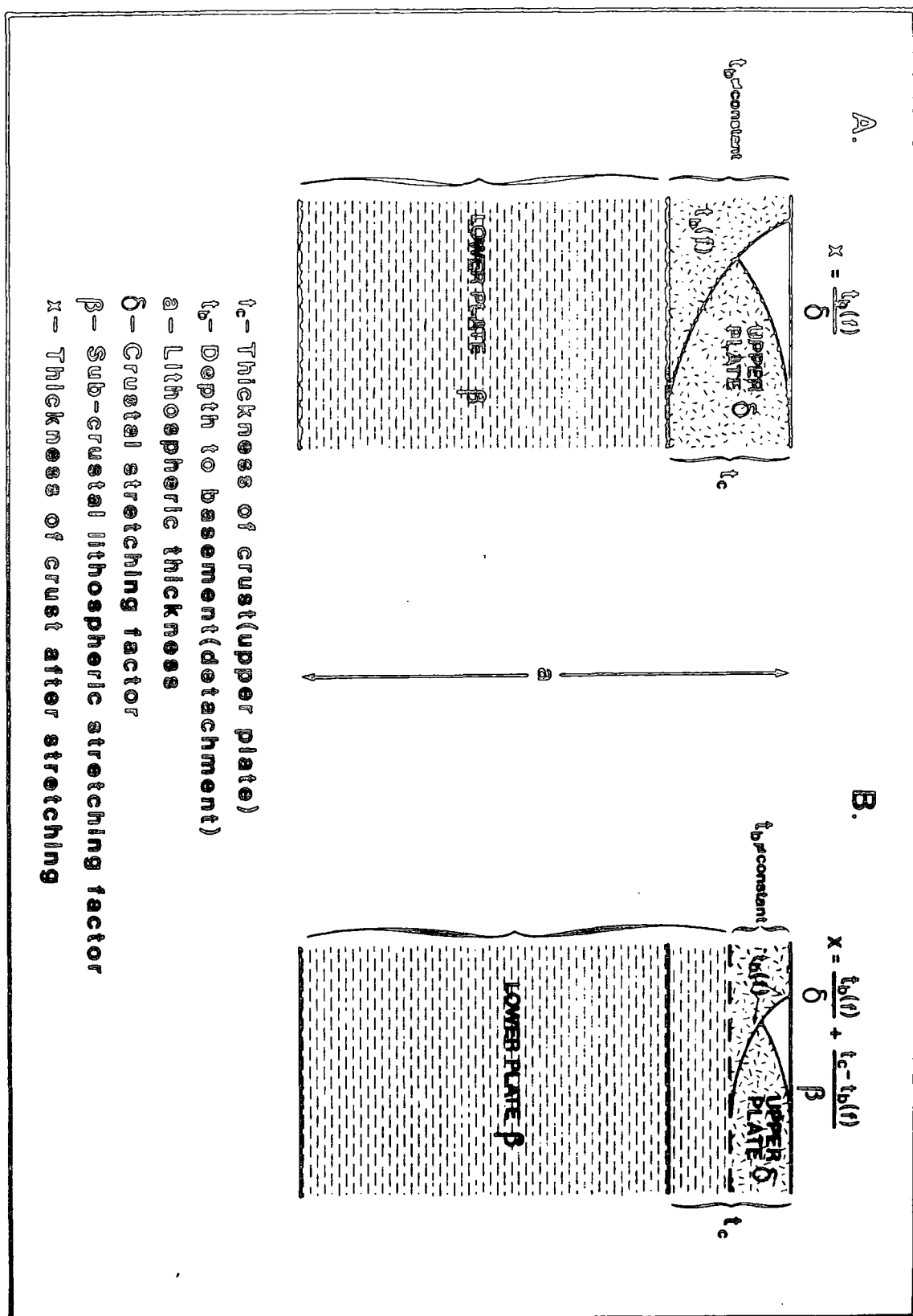


Figure 4.12. Geometry of the lithospheric or crustal detachment may be listric or more simply linear. The depth to the lithospheric detachment will therefore be a function of the relative positioning over the detachment. Horizontal detachments represent the transition between accommodation of brittle and ductile extension in the lithosphere. The depth to the detachment is taken as a constant in this study.

what is an appropriate level of detachment. High level upper crustal detachments do exist along which thin-skinned extensional tectonics is facilitated. Such basins reveal a subordinate component of sub-crustal lithospheric stretching and thermal subsidence.

Within the Yorkshire and Sole Pit Basins, there is evidence that the major basin bounding and controlling faults are listric in geometry and sole out in Triassic and Permian evaporite sequences thus apparently restricting mechanical deformation to very high levels in the crust (Van Hoorn, 1987; and this study figure 4.2). The presence of major crustal detachments in the study area (thrusts or wrench faults) like those imaged in Southern England (Chadwick et al, 1983; Brooks et al, 1984; Whittaker and Chadwick, 1984), is uncertain due to a lack of deep seismic data. However, mechanical or brittle deformation in response to extension and stretching is evident in Pre-Permian structures and it is not expected that brittle deformation ceases at such high crustal levels.

Applying a high level decollement like a Permian evaporite, to this model produces extortionate amounts of upper crustal stretching (δ). Thus the major crustal - sub-crustal lithospheric detachment is kept a constant and is assumed to be represented by either the depth to the brittle-ductile transition, 15km (Sellevoll and Warrick, 1971; Smith and Bott, 1975; Bamford, 1978; Dewey, 1982; Lake, 1985; Whittaker, 1985; Williams and Brooks, 1985; and Lake and Karner, 1987), or the base of the crust (Moho), 30 - 35 km (figure 4.5). Both of these specific lithospheric configurations are applied to the modelling of subsidence for selected boreholes in the Yorkshire, Sole Pit and East Midland Basins.

Figure 4.13 illustrates the theoretical lithospheric configuration of a depth dependent stretching model with subsidence and uplift both accommodated, as they are in real geological situations, during extension and basin formation. The model can thus apply to basins where $\delta = \beta$, $\delta > \beta$ or $\beta > \delta$.

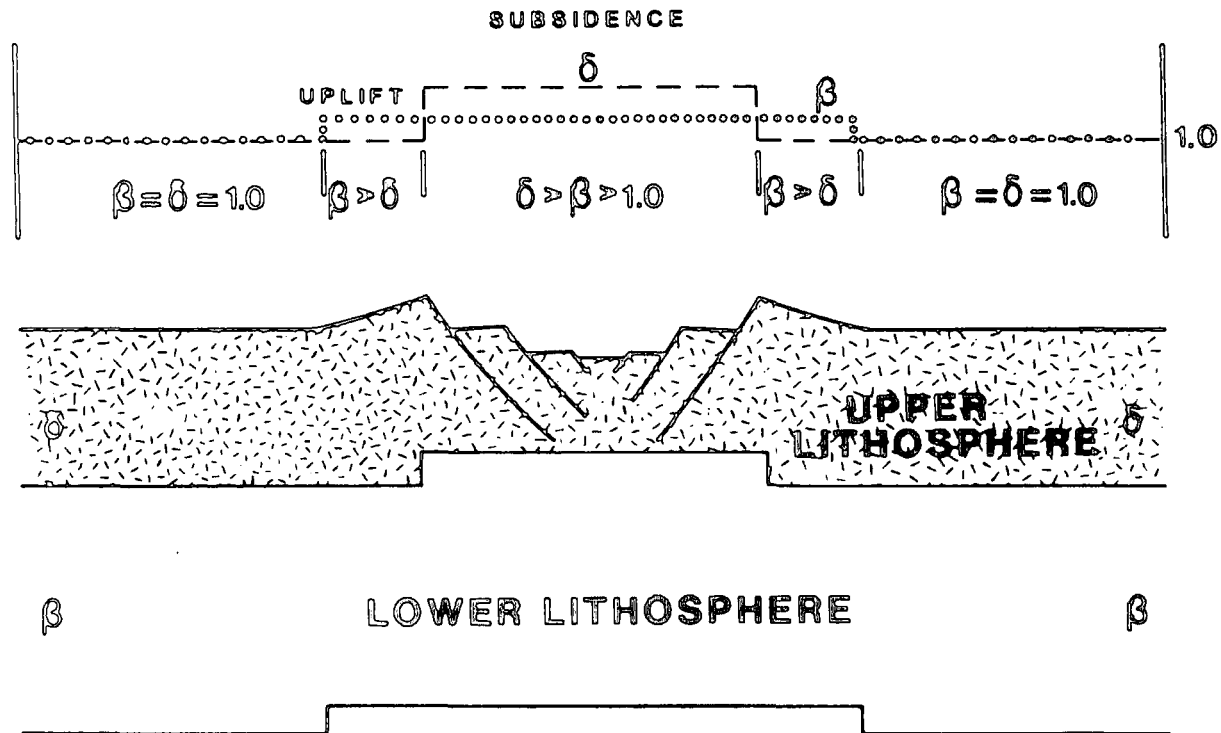


Figure 4.13. Depth dependent lithospheric stretching allows subsidence and uplift depending on the crustal:lithospheric thickness ratio. Uplift during extension is a phenomenon observed in the Central North Sea in the Middle Jurassic (Leeder, 1983).

4.4 Backstripping.

4.4.1. Introduction.

Lithospheric and crustal extension, β and δ , can be estimated from consideration of pre- and post-rifting lithospheric thicknesses and from analysis of the brittle extension along upper crustal faults. Both methods, however, are unsatisfactory as the former purely reveals the cumulative stretching and little of the detailed evolution of a basin, and the latter is subject to error due to lack of resolution of structures particularly with increasing depth. Backstripping not only provides one with quantitative estimation of δ and β through time, but also reveals much information on the thermal and sedimentological evolution of a basin. Backstripping is a tool from which we can analyse:-

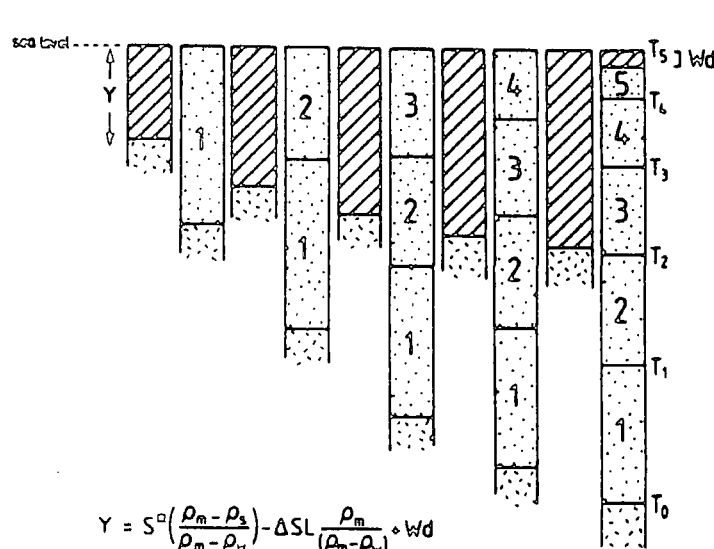
1. Extension in the lithosphere - δ and β .
2. Type and amounts of subsidence - tectonic, mechanical, thermal or flexural.
3. Decompaction of the sedimentary sequence.
4. Thermal evolution of the basin and sediments.

The total subsidence of the basement is comprised of the tectonic driving subsidence plus subsidence caused by other loads, eg. sediments, water, flexural loads - thrust sheets. The sediment and water loads can be removed, isolating the tectonic driving subsidence which itself constitutes the mechanical and thermal components of subsidence. Flexural subsidence, although not accommodated in the model may be recognised from the form of the tectonic subsidence curves.

4.4.2. Backstripping Procedure.

Backstripping involves sequentially decompacting the sedimentary column back in time to the onset of initial subsidence or rifting, and removing the load

SCHEMATIC REPRESENTATION OF THE BACKSTRIPPING PROCEDURE.



Y = Tectonic subsidence

S^0 = Sediment thickness corrected for compaction

ρ_s = Mean sediment density

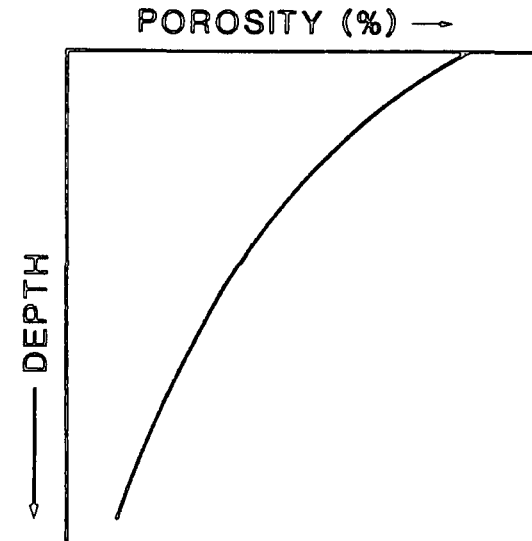
ρ_m = Density of mantle

ρ_w = Density of water

ΔSL = Sea level

Wd = Water depth

SEDIMENTARY UNITS 1 TO 5 ARE BOUND BY AGE AND, WHERE POSSIBLE, LITHOLOGY.



1. SEDIMENTARY UNITS 1 TO 5 SEQUENTIALLY DECOMPACTED USING POROSITY CURVE. CURVE REMAINS CONSTANT AND REPRESENTS A NORMAL COMPACTION TREND.
2. DENSITY AND DECOMPACTED THICKNESS OF SEDIMENTS IS USED TO CALCULATE THE LOAD REPRESENTED BY EACH UNIT.
3. SEDIMENTARY LOADING EFFECT IS REMOVED ALLOWING BASEMENT TO REBOUND ISOSTATICALLY.
4. RESULTANT DEPTH TO BASEMENT REFLECTS THE DRIVING TECTONIC SUBSIDENCE THAT WOULD HAVE OCCURED IRRESPECTIVE OF SEDIMENT INPUT.

Figure 4.14. The backstripping procedure. The porosity curve is determined individually for each borehole from sonic logs.

imparted by each sedimentary unit on the basement (figure 4.14). Airy isostasy is assumed but this may not reflect the physical state of the lithosphere throughout basin formation (Karner and Watts, 1982). However, this assumption does not greatly affect the form of the subsidence curves (Bond and Kominz, 1984).

Data required for backstripping includes:-

1. Downhole stratigraphy. Subdivision of the sedimentary sequence into units of known thickness and whose boundaries are defined by age and/or lithology.
2. Accurate representation of the variation of porosity with depth of the sediments down to basement facilitates decompaction.
3. Palaeobathymetry.
4. Eustatic sea-level variations.

From the above data, tectonic subsidence is computed using the equation given in figure 4.14. Step by step backstripping of a borehole succession in the East Midland Basin is illustrated in figure 4.15. This procedure facilitates the reconstruction of decompacted sedimentary thicknesses in time. This is important when studying subsidence and sedimentation rates as compaction can severely affect interpretation of the older, more compacted sedimentary units.

4.4.3. Uplift, Inversion and the Variation of Porosity with Depth.

Two of the most important requirements for the accurate determination of basin subsidence are:-

1. Presence of complete sedimentary sequence - ie. at the point in time prior to uplift and erosion when there was maximum loading on the basement.
2. Variation of porosity with depth.

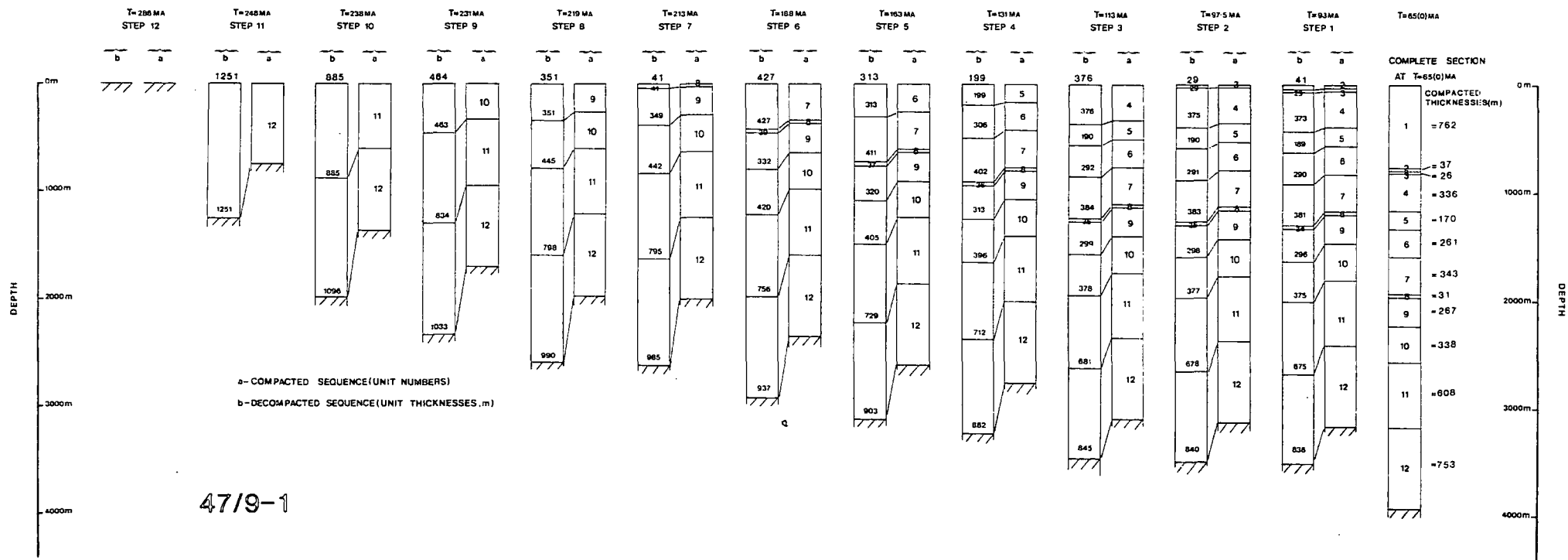


Figure 4.15. Step by step backstripping of borehole 47/9-1, in the East Midland Basin. Decompacted sedimentary thicknesses can be computed. It is important to account for compaction when studying subsidence and sedimentation rates.

The variation of porosity with depth is determined from the analysis of sonic velocity logs (Chapter 3). It is found that uplift, inversion and removal of overburden has caused displacement of porosity and interval transit time curves from their expected trends. Using these data the amount of removed overburden is quantified and added to each borehole to formulate the depth to the basement during maximum loading (figure 4.2). In this way the porosity:depth curve is repositioned and projected upwards to approximate a normal, non-inverted (uplifted) configuration (figure 4.16). This is a very important step, particularly in basins that have undergone substantial uplift such as the Yorkshire and Sole Pit Basins. The consequences of failing to compensate for removal of overburden can be seen in figure 4.17 for a borehole in the Yorkshire Basin. Comparison between the residual, uncompensated tectonic subsidence curve with one compensated for uplift is made. The uncompensated tectonic subsidence is severely truncated and the estimates for β vary greatly between the present day and pre-inversion situations as might be expected. This difference provides useful data for analysis of tectonic uplift and lithospheric shortening and thickening during inversion. This is examined further in Chapter 5.

Compensating for uplift, erosion and removal of overburden in the total subsidence curves (decompacted or compacted) and tectonic subsidence curves has important consequences for analysis of the potential maturity of source rocks in a basin. This is discussed further in Chapter 6 and is a factor which has not always been accounted for in similar studies (eg. Lake, 1985). Uncompensated tectonic subsidence curves tend to reflect, by the severity of their truncation, the amount of uplift. Such tectonic subsidence curves are difficult to interpret in terms of a basin formation mechanism since the whole secondary development is not represented. Thus, only regions in a basin which have been subjected to minor uplift can be analysed with confidence. If an accurate basin wide interpretation is to be made one must assess the uplift history of the whole area. Analysis of subsi-

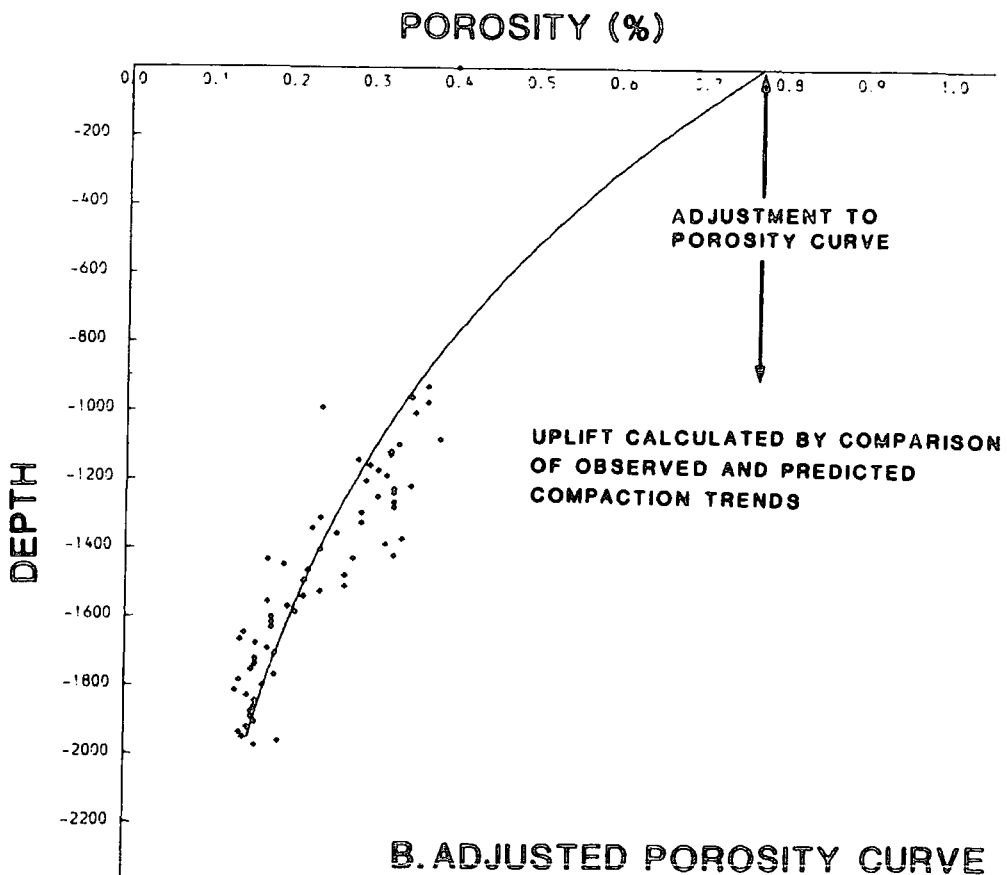
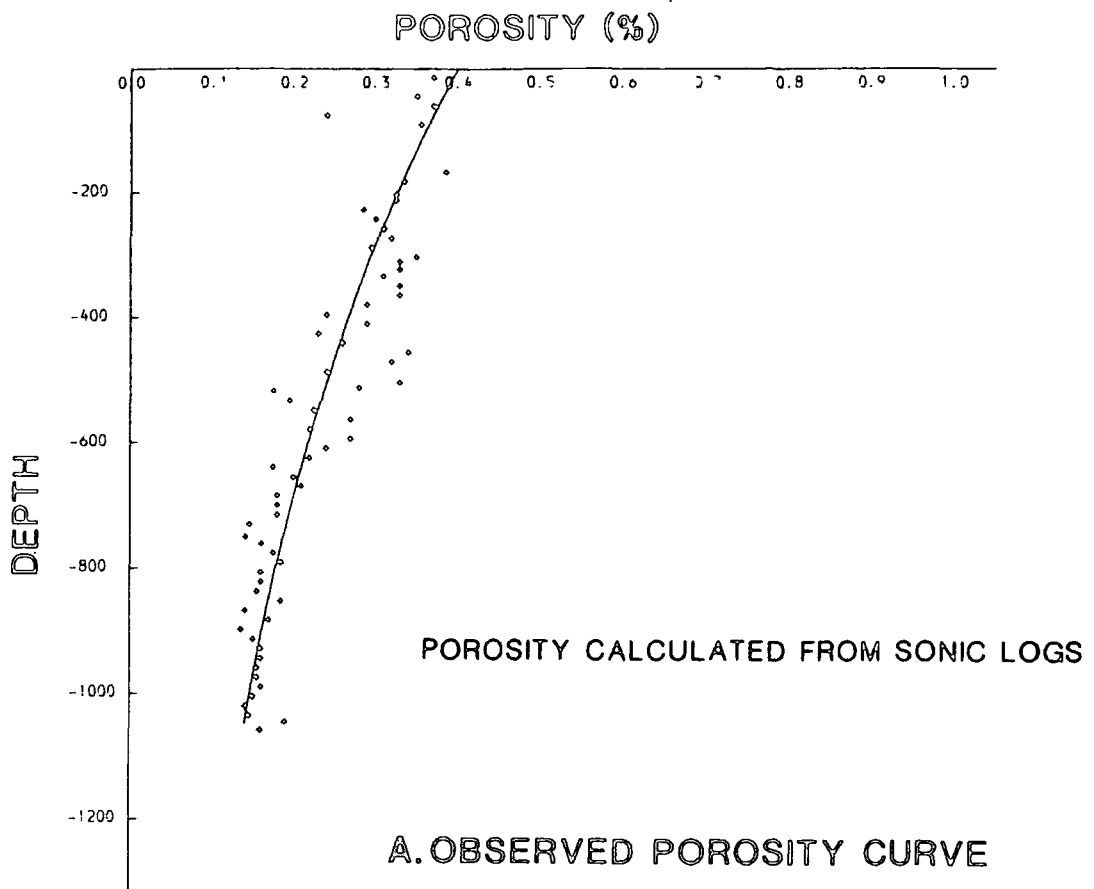


Figure 4.16. Basin inversion and removal of overburden offsets the porosity curve from normal compaction trends (A). This must be compensated for prior to backstripping.

BACKSTRIPPED SUBSIDENCE CURVES AND THEIR DEPENDENCE ON THE POROSITY:DEPTH RELATIONSHIP

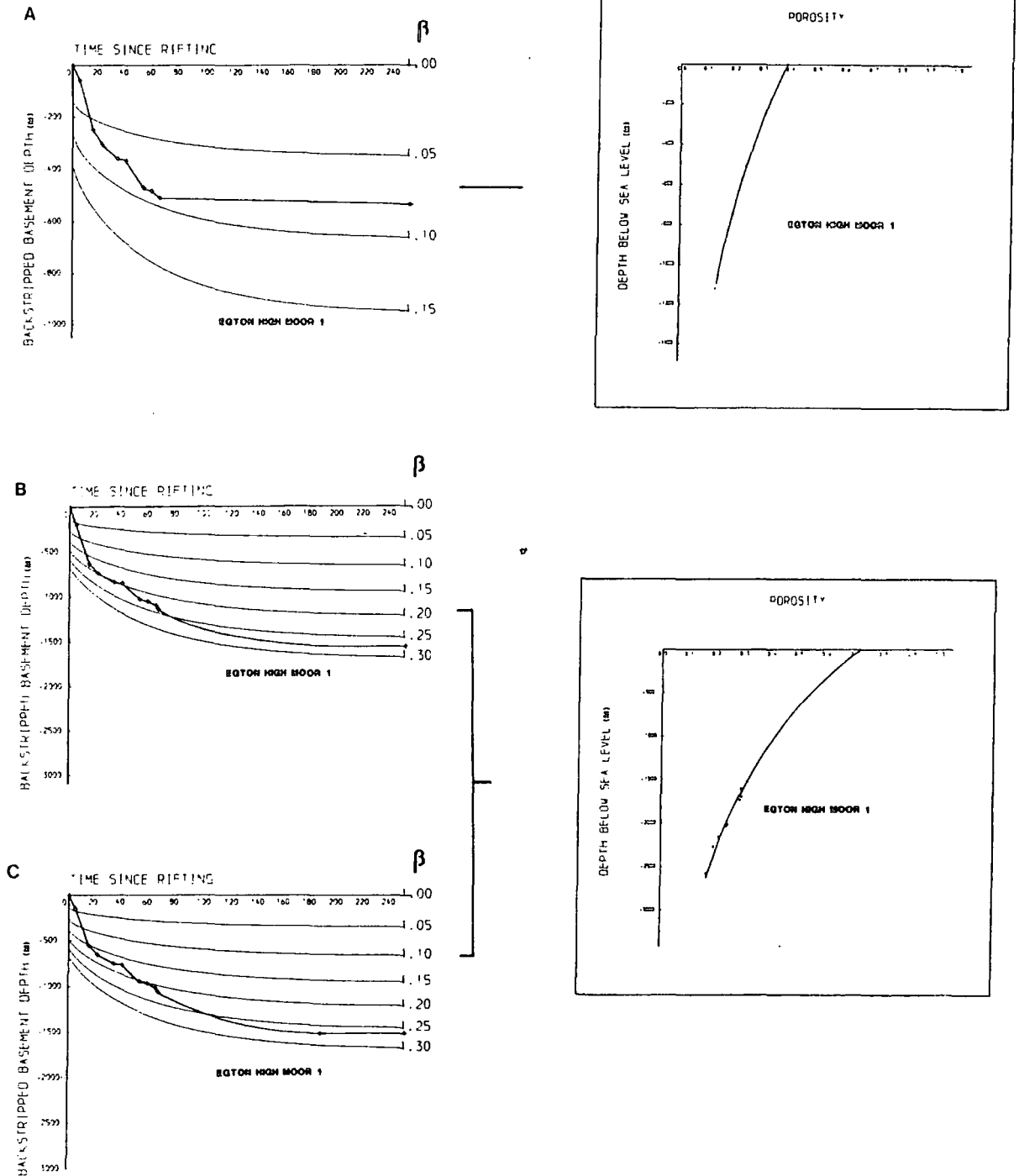


Figure 4.17. Tectonic subsidence curves uncompensated (A), and compensated (B, C) for removal of overburden offset of porosity curve. Example from the Yorkshire Basin.

dence in both basin centres and basin margins can then be accommodated into one geological model.

Although the variation of porosity with depth is lithologically dependent, and has been used in assessing the amount of uplift in the Yorkshire, Sole Pit and East Midland Basins, the relationships are not strictly accounted for in the back-stripping procedure. The approach adopted is similar to that of Steckler and Watts (1978) where one lithologically independent porosity curve is used for the whole sequence, as opposed to a separate curve for each major lithology in the manner of Sclater and Christie (1980). This will impart some error on the tectonic subsidence curve but these are regarded as minimal for the following reasons:-

1. The small scatter of porosity data, initially computed accounting for lithology (figure 3.3, Chapter 3), means that a smoothed porosity curve is feasible (figure 4.16).
2. The smoothed curves closely resemble compaction trends for shales and chalk, which make up the majority of lithologies in the study area.
3. The smoothed curves may underestimate the surface porosity of shales and chalk but similarly, a lower value approximates more closely to expected surface porosities for sandstones, shaley sandstones and silty or sandy shales, which occur throughout the sequence. The smoothed curves correlate well with observed sandstones at depth, eg. Bunter Sandstone.
4. Each borehole that has porosity data from sonic logs has utilised its own smoothed curve, thus creating a relationship specific to that one location, ie. a model for basin subsidence is not determined from a single basinwide curve but rather from the combined analysis of all available curves.
5. Boreholes without their own porosity data utilise a curve from a neighbouring

borehole.

6. Overpressuring is ignored as it is usually confined to small areas in a sequence, and will not greatly affect the computation of tectonic subsidence.
7. Within sequence unconformities have been input as hiati where possible. In the majority of boreholes, small unconformities are not recognised in the stratigraphy or porosity data and are therefore ignored. Particular attention is however, paid to the significant Late Jurassic - Early Cretaceous Cimmerian unconformity.

It is regarded as important that regional and local porosity variation be accounted for in such basin studies, not only for analysis of basin formation, but also for analysis of basin destruction (see Chapter 3).

4.4.4. Palaeobathymetry.

Accurate and detailed palaeobathymetric data is difficult to acquire and have often been ignored in the computation of tectonic subsidence. Much of the Permian-Triassic sequence in the study area was probably at or about sea-level with subsidence keeping pace with sedimentation. Jurassic palaeobathymetric variations are postulated to be extremely variable. It is not possible to include a representative variation of these due to the few points available for backstripping in a borehole. Disregarding palaeobathymetry for the Upper Cretaceous chalk, when water depths may have been significant, may cause errors.

4.4.5. Eustatic Sea-Level Variations.

The variation of eustatic sea-level through time has been the subject of much discussion (Vail et al, 1977; Pitman, 1978; Bally, 1981; Watts, 1982; Thorne and Watts, 1984; Hallam, 1978 and Burton et al, 1987). Figure 4.18 illustrates relative sea-level changes computed for the Jurassic to Recent (Vail et al, 1977).

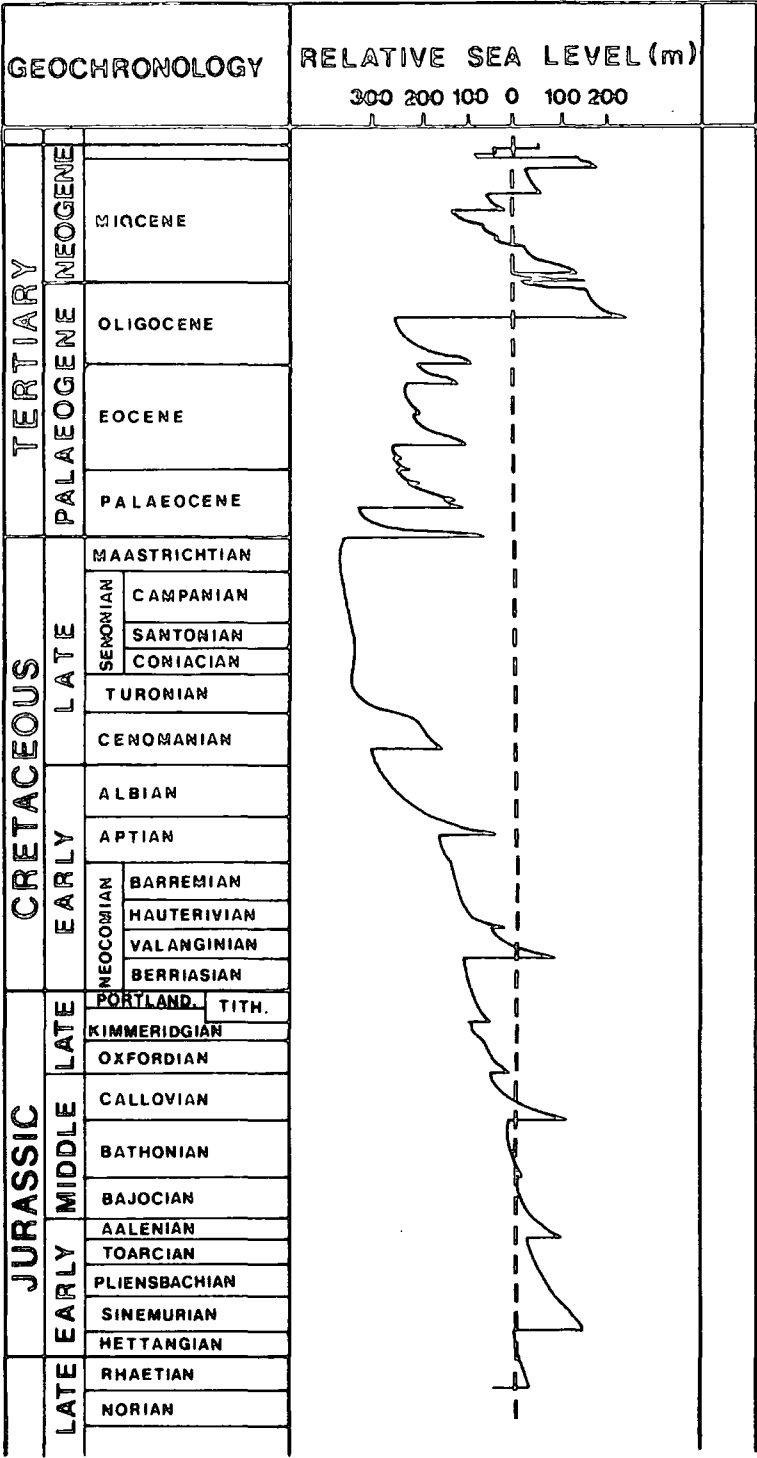


Figure 4.18. Global eustatic sea-level changes (Vail et al, 1977). For discussion on their influence on the tectonic subsidence in the study area, see section 4.6.

Although all authors record the occurrence of such events, their magnitudes are not easy to calculate - authors speak in relative terms. Subsidence within a basin comprises tectonic subsidence, mechanical subsidence, thermal and flexural subsidence, loading by sediment accumulation and eustatic loading. Burton et al (1987) say that eustatic sea-level changes cannot be distinguished from these other parameters. This infers that graphic illustrations of sediment fill and subsidence, such as backstripped tectonic subsidence curves, may enclose a number of solutions for the evolution of a basin. These are to be assessed in the light of structural and sedimentological characteristics peculiar to the basin concerned. For these reasons and the probability that the magnitude of eustatic sea-level changes on subsidence is minimal (Thomas, 1984), their variation has been ignored in the original computation, but not the interpretation.

The tectonic subsidence of the Yorkshire, Sole Pit and East Midland Basins has been analysed by the backstripping method using the following criteria:-

1. Stratigraphic and porosity data are acquired from borehole composite and sonic logs.
2. Formation ages are determined from Anderton et al (1979) and Harland et al (1982), (figure 4.19).
3. Porosity is assumed to decrease exponentially with depth.
4. Inversion, uplift and erosion have been accounted for.
5. Palaeobathymetric and eustatic sea-level variations are ignored.
6. Basement is assumed to be Pre-Permian. All Pre-Permian sediments are therefore assumed to have been consolidated prior to Permian subsidence.
7. Mantle density = 3.33 g/cc, sediment density = 2.65 g/cc and crustal density



Era	Sub-era Period Sub-period	Epoch	Age	Ma age	Age abbrev.	Ma inter- vals
Cenozoic	Tertiary	Quaternary or Pleistogene	Holocene	0-01	Hol	01
			Pleistocene	2-0	Ple	1-99
		Pliocene	Piacenzian	2-0	Pia	3-1
			Zancian	5-1	Zan	6-2
		Miocene	Messinian	5-1	Mes	6-2
			Tortonian	14-4	Tor	3-1
			Serravallian	24-6	Srv	8-2
			Langhian-Late	32-8	Lan2	5-2
			Langhian-Early	38-0	Lan1	4
			Burdigalian	42-0	Bur	8-5
			Aquitania	50-5	Aqt	4-4
		Oligocene	Chattian	54-9	Cht	5-3
			Rupelian	60-2	Rup	4-8
	Paleogene	Eocene	Priabonian	65	Prb	8
			Bartonian	73	Brt	10
		Lutetian	Lutetian	83	Lut	4-5
			Ypresian	87-5	Ypr	1
		Paleocene	Thanetian	88-5	Tha	2-5
			Danian	91	Dan	6-5
		Cretaceous	Maastrichtian	97-5	Maa	15-5
			Campanian	113	Cmp	6
			Santonian	119	San	6
			Coniacian	125	Con	6
			Turonian	131	Tur	7
			Cenomanian	138	Cen	6
			Albian	144	Alb	6
			Aptian	150	Apt	6
Mesozoic	Jurassic	K ₂	Barremian	156	Brm	6
			Hauterivian	163	Hau	6
		K ₁	Valanginian	169	Vlg	7
			Berriasian	175	Ber	6
		Malm	Tithonian	181	Tth	6
			Kimmeridgian	188	Kim	6
		Dogger	Oxfordian	194	Oxf	7
			Callovian	200	Clv	6
		J ₂	Bathonian	206	Bth	6
			Bajocian	213	Baj	6
	Triassic	J ₁	Aalenian	219	Aal	7
			Toarcian	225	Toa	6
		Lias	Pliensbachian	231	Plb	6
			Sinemurian	238	Sin	6
		Tr ₃	Hettangian	243	Het	7
			Rhaetian	248	Rht	6
		Tr ₂	Norian	253	Nor	6
			Carnian	258	Crn	6
		Tr ₁	Ladinian	263	Lad	7
			Anisian	268	Ans	5
Paleozoic	Permian	P ₂	Spathian	273	Spa	1½
			Smithian	278	Smi	1½
		P ₁	Dienerian	283	Die	1½
			Griesbachian	288	Gri	1½
		P ₂	Tatarian	293	Tat	5
			Kazanian	298	Kaz	2-5
		P ₁	Ufimian	303	Ufi	2-5
			Kungurian	308	Kun	5
		P ₁	Artinskian	313	Art	5
			Sakmarian	318	Sak	9

Figure 4.19. Chronostratigraphic column from Harland et al (1982).
Used as a reference for sub-division of the sedimentary
succession.

$$= 2.8 \text{ g/cc.}$$

4.5 Analysis of Results.

The evolution of subsidence in the Yorkshire, Sole Pit and East Midland Basins is recorded in the sedimentary fill within each respective basin. Relative degrees of crustal and sub-crustal lithospheric involvement are implicated by the tectonic subsidence and the quantity and distribution of the sedimentary facies. Thus, the more complete the sedimentary sequence, the more detailed is the record of basin formation. Inversion, uplift and erosion has removed significant amounts of Mesozoic and possibly Cenozoic sediments, particularly from the Yorkshire and Sole Pit Basins, and this will therefore inhibit precise analysis of the subsidence. Removed overburden has been computed (see Chapter 3) and added to the present stratigraphic thicknesses to reconstruct the maximum depth to the basement (figures 4.1 and 4.2).

This study utilises comprehensive, reconstructed borehole sequences and assesses not only the applicability of various theoretical models of basin formation to the observed subsidence in the area but also how successfully this method can be applied to inverted basins. Previous studies (Sclater and Christie, 1980; Wood, 1981; Brunet, 1984; Thomas, 1984 and Lake, 1985) have either ignored the removed overburden or have been undertaken in areas of relatively continuous subsidence and no subsequent inversion.

The borehole data acquired for this work provide excellent coverage over the present extent of the three basins (Enclosure-map 1). The forms of subsidence recorded are assumed to be representative of the typical forms of subsidence that influenced each basin. Observed subsidence is compared to predicted subsidence from the uniform lithospheric stretching model in each individual basin. The results are assessed with respect to their local and regional significance. Subse-

quently, the same observed subsidence (total and tectonic) is compared to predicted subsidence from the non-uniform two layer model. Appendix C4 provides all the observed backstripped tectonic subsidence curves compared to theoretically derived, uniform lithospheric tectonic subsidence curves for boreholes shown in map 1. Suitable individual examples of representative tectonic subsidence types are presented in the text as required.

4.5.1. Stretching Models and Observed Tectonic Subsidence.

The degree of lithospheric stretching, β , whether in a uniform or non-uniform lithospheric stretching model, is proportional to the amount of sub-crustal lithospheric involvement and hence represents the amount of heat input or thermal subsidence (figure 4.20). The degree of sub-crustal lithospheric involvement will also affect the duration of the initial rift time, assuming rifting is not instantaneous and some heat is dissipated during initial rifting. That is, the observed tectonic subsidence may always have a component of both mechanical and thermal subsidence and hence may not exactly represent or correlate with theoretical curves.

Figure 4.20 illustrates the affect of varying degrees of crustal and sub-crustal lithospheric involvement and how they may be manifested in the observed backstripped tectonic subsidence. They are seen to differ from theoretical curves for uniform stretching (figure 4.20). Curve 1 represents pure mechanical subsidence initiated during one rapid or instantaneous stretching event and followed by no subsequent thermal subsidence. This is analogous to the total isolation of extension to the brittle upper crust and thus represents an extreme example of the non-uniform lithospheric stretching mechanism. Curve 2 illustrates a fairly rapid but finite initial subsidence closely parallelling the predicted thermal subsidence of the uniform stretching model. The non-instantaneous, initial subsidence may represent a component of sub-crustal stretching and thermal subsidence during

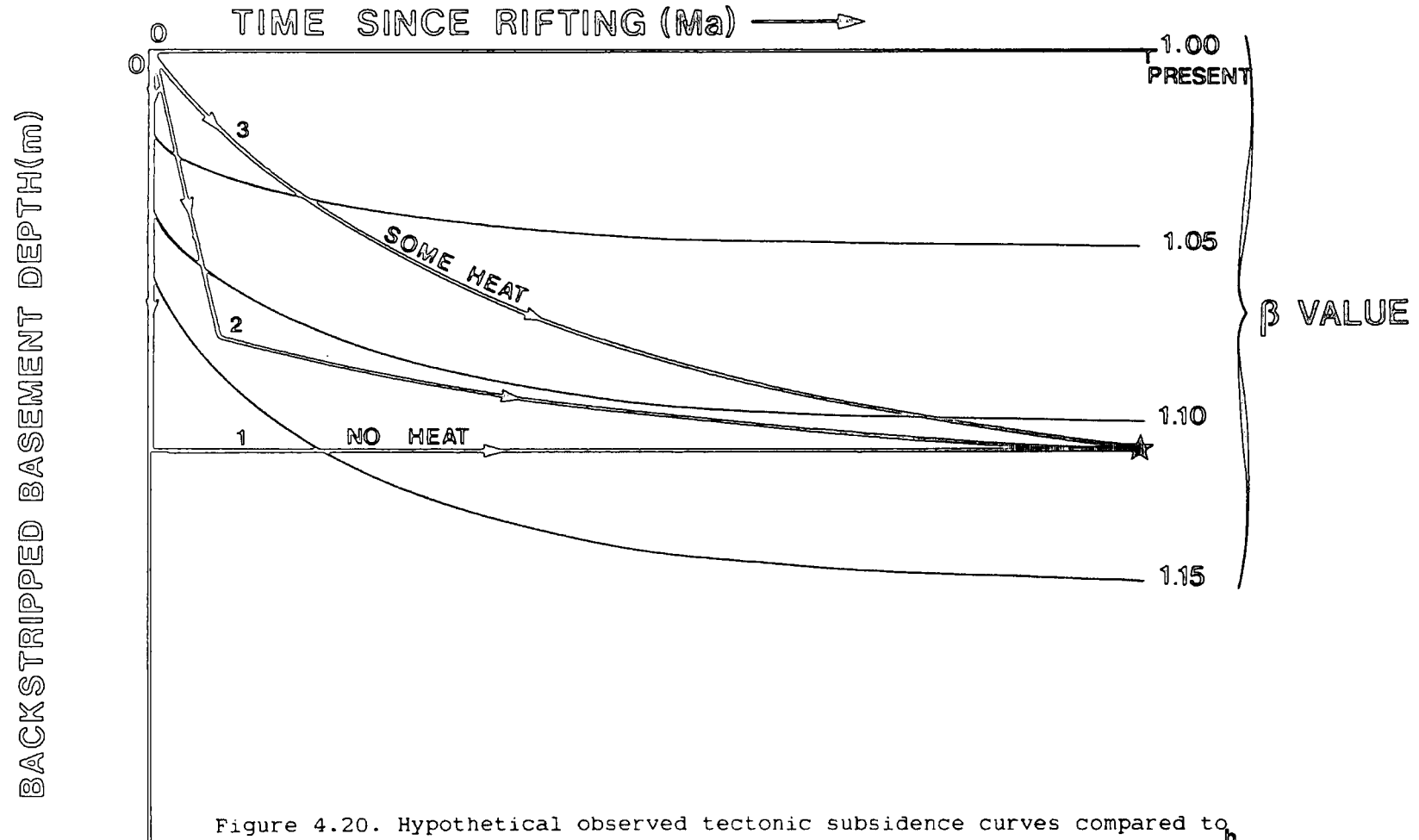


Figure 4.20. Hypothetical observed tectonic subsidence curves compared to theoretically derived curves for uniform lithospheric stretching. The form of the curve is a reflection of the degree of crustal and sub-crustal stretching.

ripping and mechanical subsidence. Thus, the amount of sub-crustal involvement, β will influence and affect the rift time. Curve 3 displays a gradual truncation of the theoretical, negative exponential tectonic subsidence curves. It may represent a combination of gentle, mechanical and thermal subsidence through time, flexural subsidence possibly along basin margins or a dominance of regional, thermal subsidence in basinal areas outside zones of active mechanical, fault controlled subsidence. In this way, the observed forms of tectonic subsidence are analysed and the controlling mechanisms isolated.

Tectonic subsidence is assessed quantitatively (figure 4.21) as well as qualitatively. Figure 4.21 represents the contoured, computed tectonic subsidence of the backstripped pre-Permian basement in the Yorkshire, Sole Pit and East Midland Basins.

Tectonic subsidence trends (figure 4.21) correlate well with the basin distribution and emphasize the influence of faulted and unfaulted margins on the type of basin development. Tectonic subsidence increases northwards and eastwards away from the London Brabant Platform. To the north it increases over the Market Weighton Block and Vale of Pickering Fault Zone into the Yorkshire Basin. Eastwards it increases over the Dowsing Fault Zone into the differentially subsiding Sole Pit Basin. These results illustrate that despite inversion and partial basin destruction (figure 3.31) reconstruction of the pre-inversion sedimentary thicknesses has facilitated analysis of the variations of subsidence forms between the Yorkshire, Sole Pit and East Midland Basins.

4.5.2. Tectonic Subsidence in the Yorkshire Basin.

Four, representative backstripped tectonic subsidence curves from the Yorkshire Basin are presented in figure 4.22. They reflect the changes in tectonic subsidence along a north-south traverse of the basin and have all been compen-

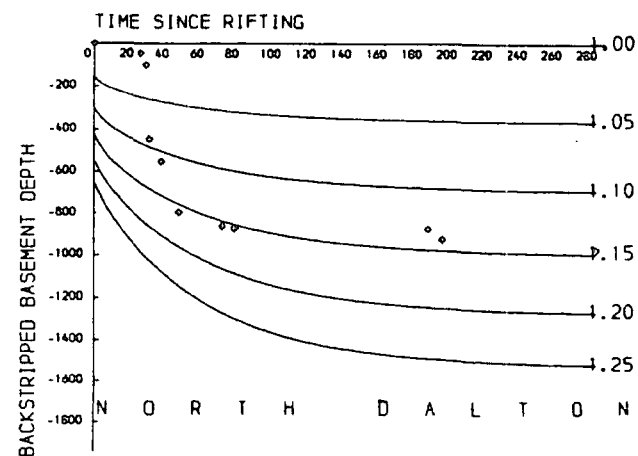
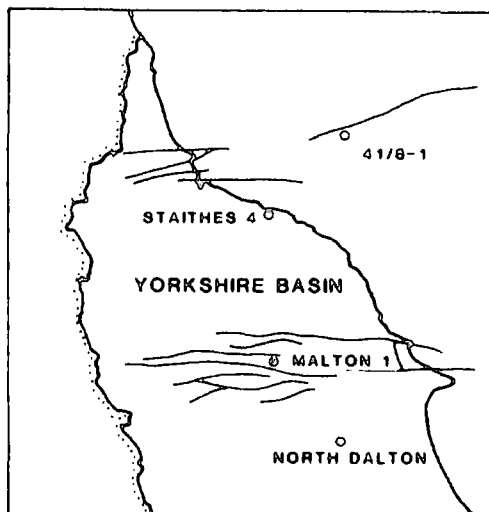
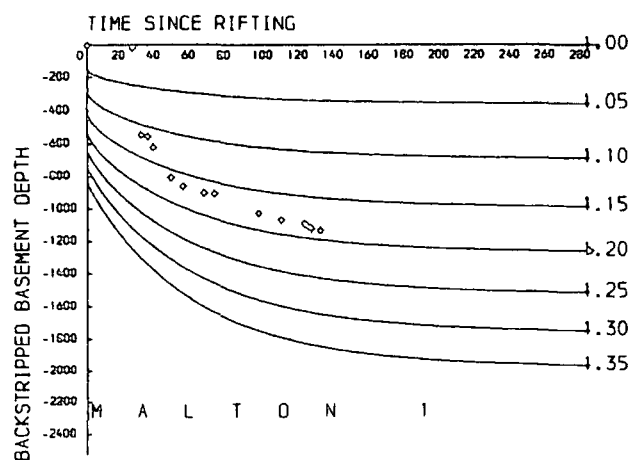
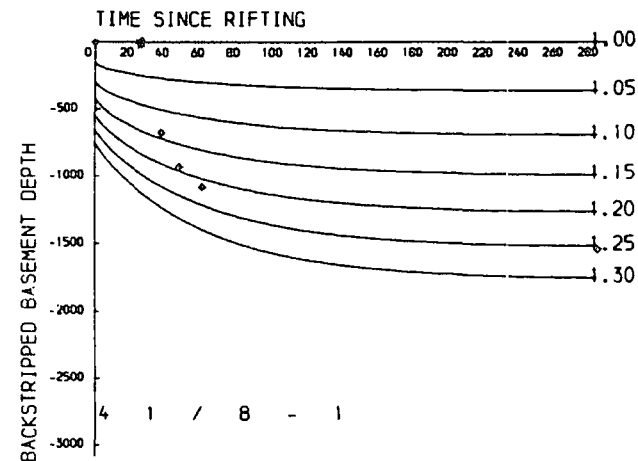
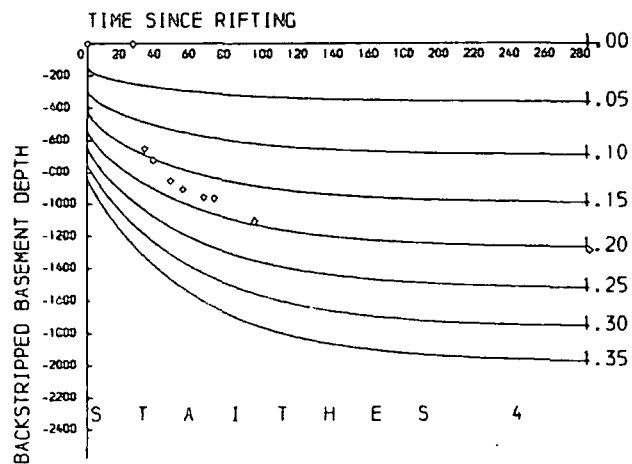


Figure 4.22. Representative selection of tectonic subsidence curves across the Yorkshire Basin. Curves are compared to theoretical curves for uniform lithospheric stretching.

sated for the removal of overburden. The more detailed or complete nature of the boreholes in the south of the area reflects lesser inversion of the southern margin of the Yorkshire Basin, as discussed in Chapter 3 (figure 3.31). In general, the tectonic subsidence curves correlate well with the predicted or theoretical curves for uniform one layer stretching. All curves imply that one major subsidence, extension or stretching event occurred in late Permian to Triassic followed by a generally more gentle subsidence which closely mirrors the expected component of thermal subsidence. However, this is an oversimplification of the observed tectonic subsidence and represents an overview of the postulated background or controlling tectonic forces. Superimposed on both of the two major components or stages of tectonic subsidence are a number of individual events which require further study.

4.5.2A. Permian.

The detailed Permian lithostratigraphic variations within the Yorkshire Basin have not been recorded in all the boreholes studied (Appendix C4). Where they are recorded, accurate chronostratigraphic marker horizons are difficult to obtain due to the diachroneity and lateral variations in the Permian facies (Smith, 1974; Anderton et al, 1979 and Kent, 1980b). The four representative boreholes in figure 4.22, have been differentiated into Lower and Upper Permian and where possible have been additionally subdivided according to facies changes within the Upper Permian. Dating of facies is approximate but implemented using data from Smith, 1974; Anderton et al, 1979; Taylor, 1984 and Holloway, 1985).

The Permian is an important period within the Yorkshire Basin (and Sole Pit and East Midland Basins) as it corresponds with the commencement of subsidence and sedimentation after the Variscan Orogenic episode (Ziegler, 1982 and Glennie, 1984). It thus represents the onset of basin formation and response of the crustal and sub-crustal lithosphere to the change from a compressional to extensional tectonic regime (Bott, 1982; Glennie, 1984).

The Southern North Sea Basin began subsiding in the Lower Permian, but parts of the Yorkshire Basin display a delay in subsidence until the Upper Permian (figures 4.22 and 4.23) when the Zechstein Sea flooded the area (Smith, 1974). In the south of the Yorkshire Basin, tectonic subsidence is extremely subdued during the Lower Permian (North Dalton and Malton 1 boreholes, figure 4.22). The observed tectonic subsidence curve transects the predicted curves. In the north of the Yorkshire Basin (borehole 41/8-1, figure 4.22) thin basal Permian sediments are recorded. The tectonic subsidence curve reflects a similar response as described for the southern margin of the present Yorkshire Basin. Within the central part of the Yorkshire Basin (Staithes 4 borehole, figure 4.22) the absence of Lower Permian sediments reveals the influence of the preceding Late Carboniferous inversion and uplift over the subsidence that occurred within the Southern North Sea Basin during the Lower Permian. Rifting and break up of the Pangaea supercontinent during the Lower Permian created an east - west extensional regime within the Southern North Sea area (Dewey, 1982 and Glennie, 1984). This initiated a north - south trending graben system including the Viking, Oslo, Horn and Central Grabens. Concurrently, the Variscan Massif to the south may have imparted a load on the lithosphere creating a foreland, flexural basin ie. the Southern North Sea Basin (Glennie, 1984; Karner et al, 1987). The Yorkshire Basin was an area of basinal development during the Carboniferous (Kent, 1980a) but it was inverted and uplifted prior to the Permian causing removal of Westphalian and Namurian sediments. The absence of Lower Permian sediments in the central parts of the Yorkshire Basin is postulated to resemble the presence of a Pre-Permian structural inversion high that was slowly subsiding, but still an area of positive relief (figure 4.23). Surrounding this area, but in less inverted terrain, thin Lower Permian sediments accumulated. Further evidence for this hypothesis is supplied by Smith and Francis (1967), who recount that the basal Permian sediments in the Teeside and south Durham area represent deposits derived from the

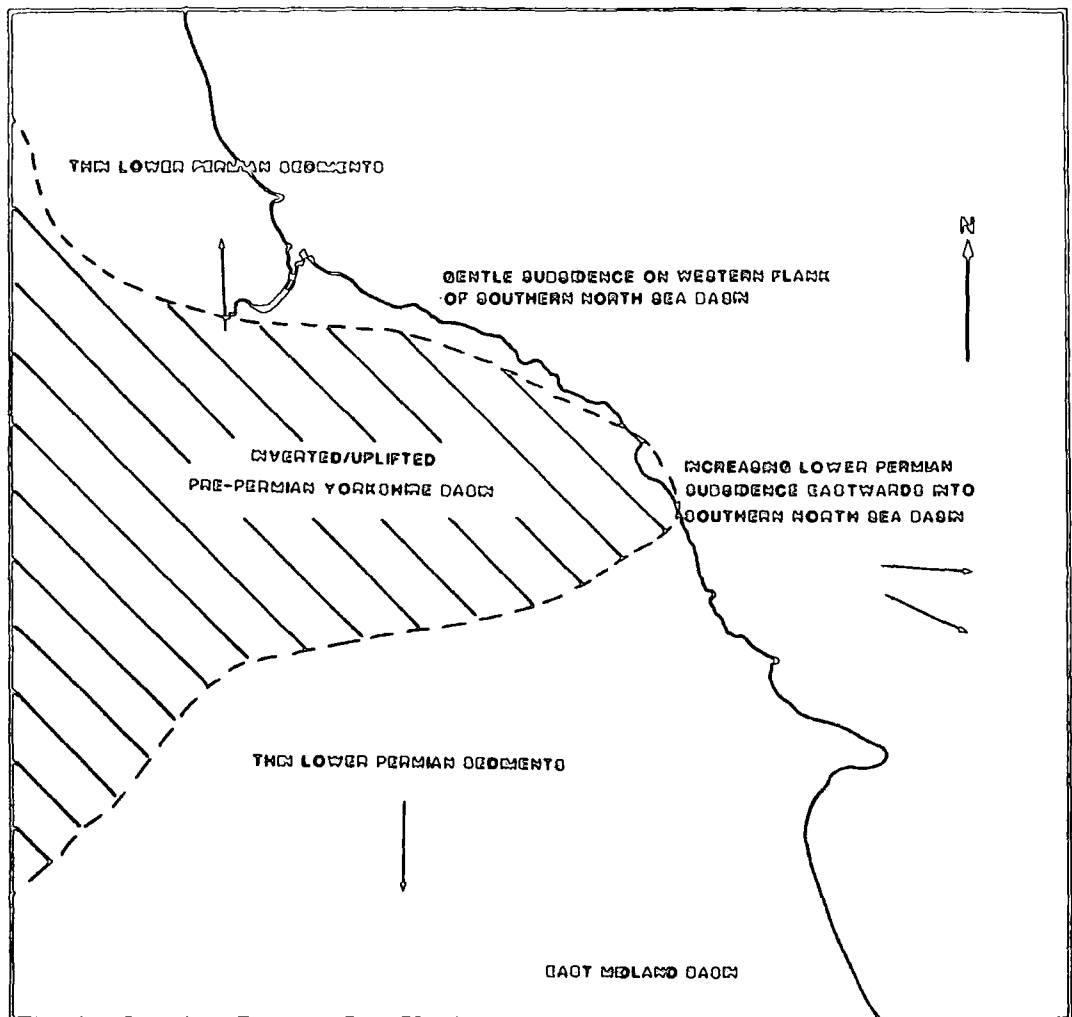


Figure 4.23. Pre-Permian basement topography causes initial subsidence in the Southern North Sea Basin to be subdued or delayed. A component of the initial subsidence may be taken up in removing pre-existing highs.

Lower and Middle Carboniferous of the inverted Carboniferous Yorkshire Basin to the south (figure 4.23).

The Lower Permian sediments of the Yorkshire Basin reveal no evidence of fault control, although most Carboniferous basement faults do displace them in the Durham area (Smith and Francis, 1967). They thicken eastwards into the Southern North Sea Basin, where Glennie and Boegner (1981) recognised some faulted control of the basal Permian Rotliegendes Sandstone on the eastern margin of the north-west - south-east trending Dowsing Fault Zone. This is analogous with east - west orientated extension (Dewey, 1982 and Glennie, 1984). The lack of similarly orientated faults within the onshore area may explain in part the apparent non-differentiation of the Yorkshire and East Midland Basins at this time (Whittaker, 1985) and the absence of observed rapid or instantaneous tectonic subsidence as predicted by the curves for McKenzie's uniform stretching model (figure 4.22). Lower Permian subsidence is subdued and represents one, or a combination of:-

1. Thermal and mechanical readjustment of the lithosphere following inversion, uplift and shortening.
2. Gentle, unfaulted (thermal?) subsidence on flanks of north - south trending, east - west extending faulted rift system.
3. Gentle, flexural subsidence in foreland of the Variscan Massif.

Following lithospheric shortening and thickening in the Late Carboniferous the cool, thick lithosphere would inherit flexural strength and oppose initial rapid or instantaneous subsidence. Continued lithospheric extension may reset the flexural rigidity (Lake, 1985) and allow subsidence as predicted by McKenzie (1978).

The first major increase in tectonic subsidence occurs in the Upper Permian

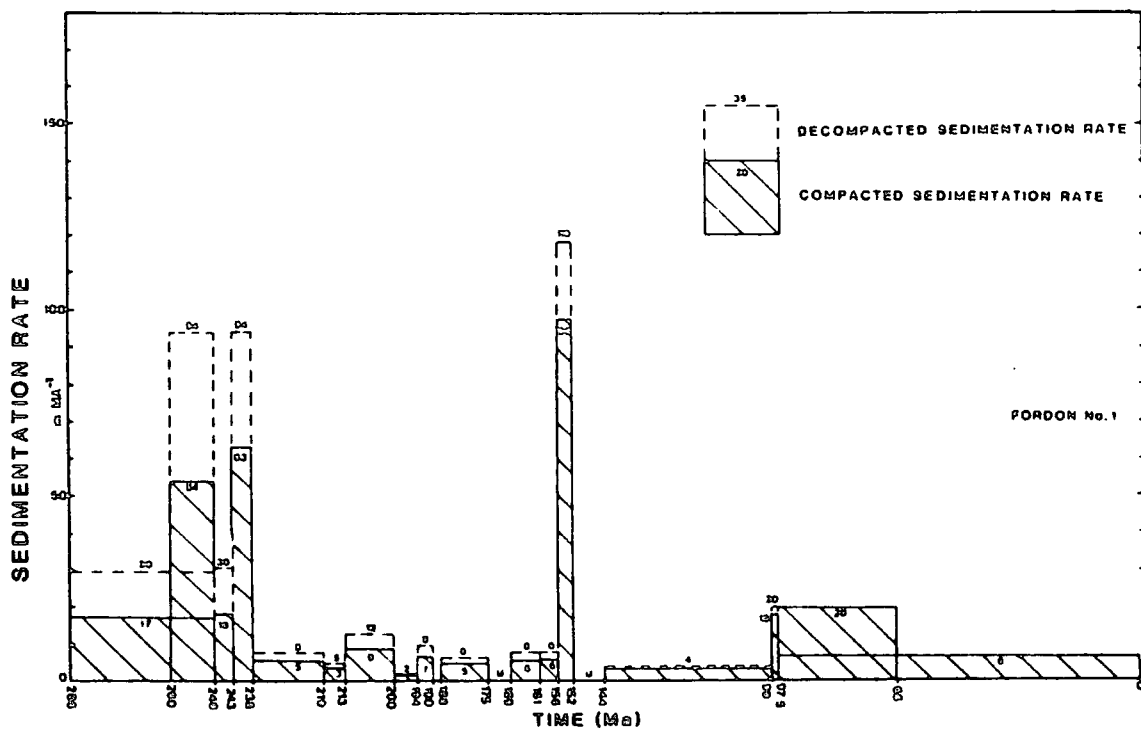
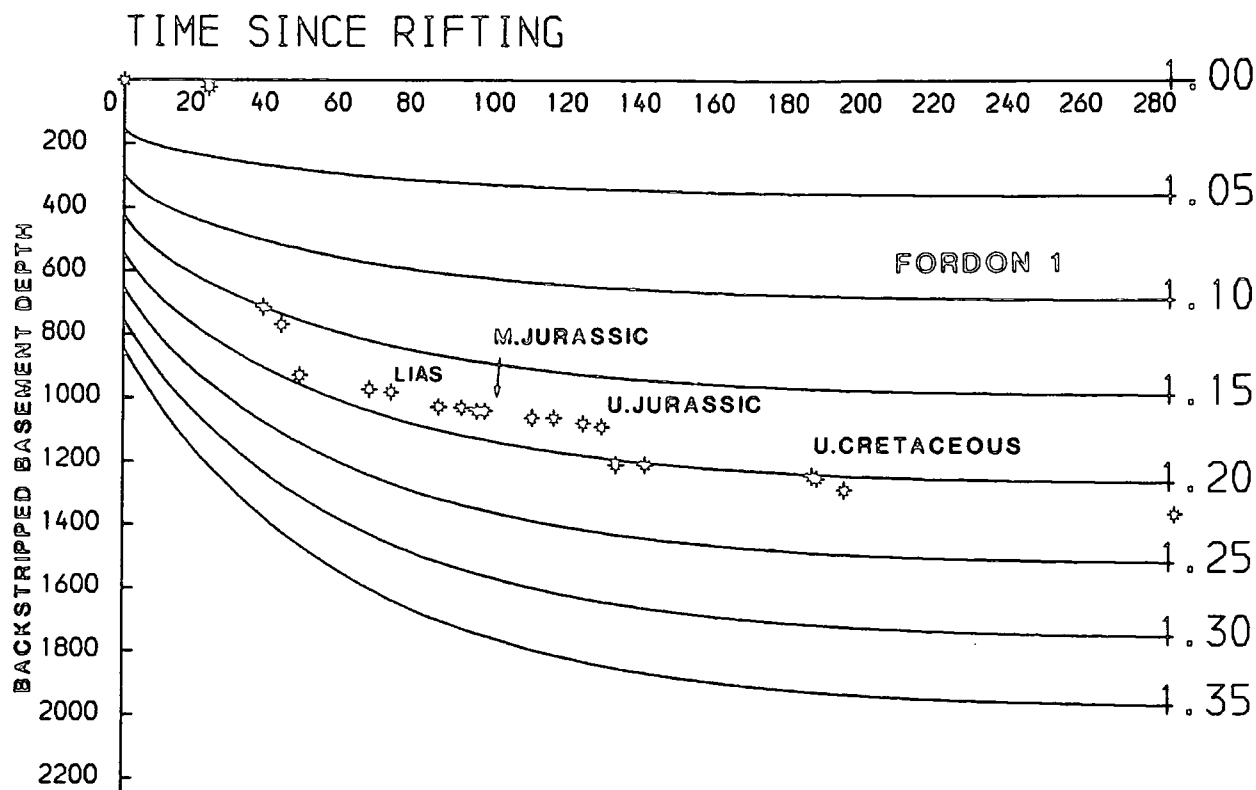


Figure 4.24. Backstripped tectonic subsidence curve correlated with compacted and decompact sedimentation rates for Fordon 1 in the south of the Yorkshire Basin.

as the boreholes in figure 4.22 illustrate. Subsidence associated with this event is synchronous throughout the basin and the structural high of the central Yorkshire Basin was breached. The basement responded uniformly to this rapid subsidence event timed at 12Ma. Where enough chronostratigraphic data points are available backstripping reveals a general reduction in the rate of tectonic subsidence towards the end of the Upper Permian (figure 4.22). Figures 4.24 and 4.25 illustrate that in addition to the increased tectonic subsidence at this time, sedimentation rates (compacted and decompacted) were exceptionally high. Only Early Triassic and Kimmeridgian (Upper Jurassic) sedimentation rates match those computed for the Upper Permian. Thus, the rapid tectonic subsidence was exaggerated by rapid infilling of the basin and loading of the already subsiding basement. Evidence for the control of sedimentation by extensional faults is not clear, at least not along existing or known structural lines. Sediment isopach maps (Whittaker, 1985) reveal a gradual, rather than sudden increase northwards from the East Midland Basin into the Yorkshire Basin. The Yorkshire Basin, at this time, appears not to have been the tectonically distinct unit it was to become during the Mesozoic.

Although the form of Permian tectonic subsidence curves reveal a rapid initial subsidence characteristic of the predicted subsidence at the onset of rifting, the lack of differential fault controlled subsidence in the area appears to contradict this. Isopach maps for the Southern North Sea Basin (Glennie and Boegner, 1981 and Taylor, 1981 and 1986) reveal a similar pattern of subsidence. Furthermore, the major fault zone at the southern margin of the Yorkshire Basin, ie. the Vale of Pickering Fault Zone appears not to exert a control over subsidence or sedimentation until the Jurassic (Holloway, 1985 and Whittaker, 1985). Rather, this fault zone utilises the Permian sediments as a decollement horizon for relaying north-south orientated extension during the Jurassic to Lower Cretaceous (see seismic section, figure 4.41). Extensional basin formation, eg. Cheshire and Worcester Basins and volcanic activity are recorded during the Permian within the United

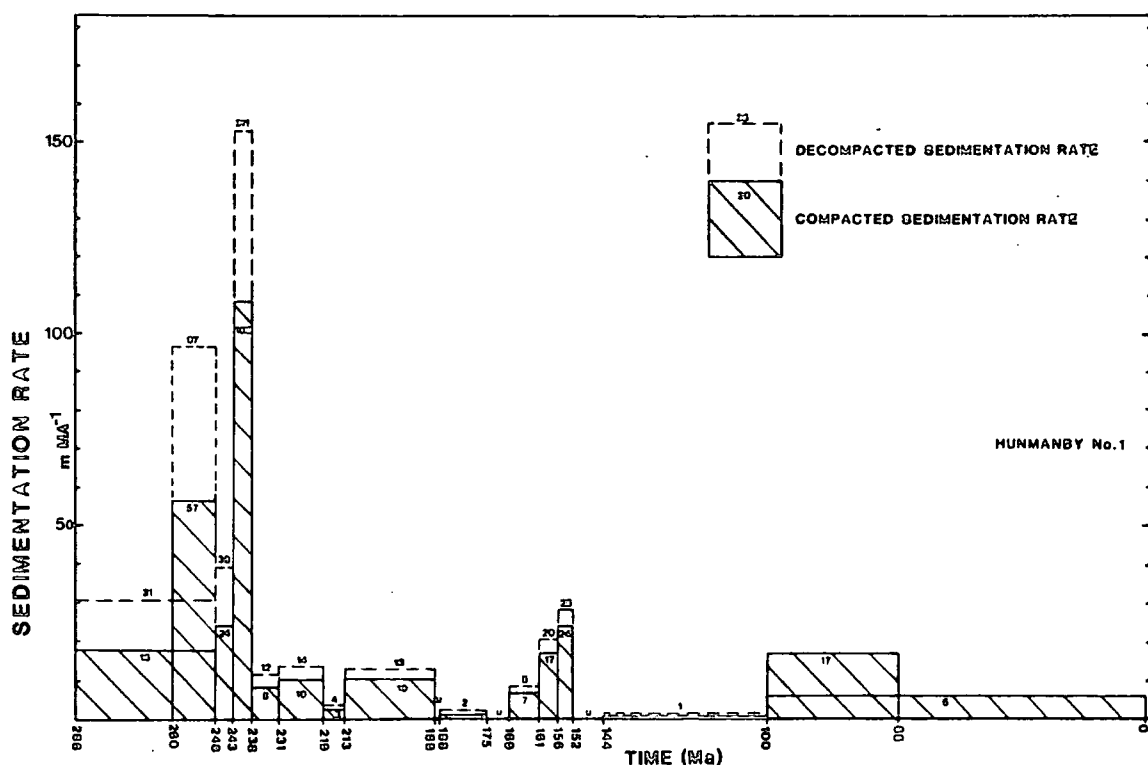
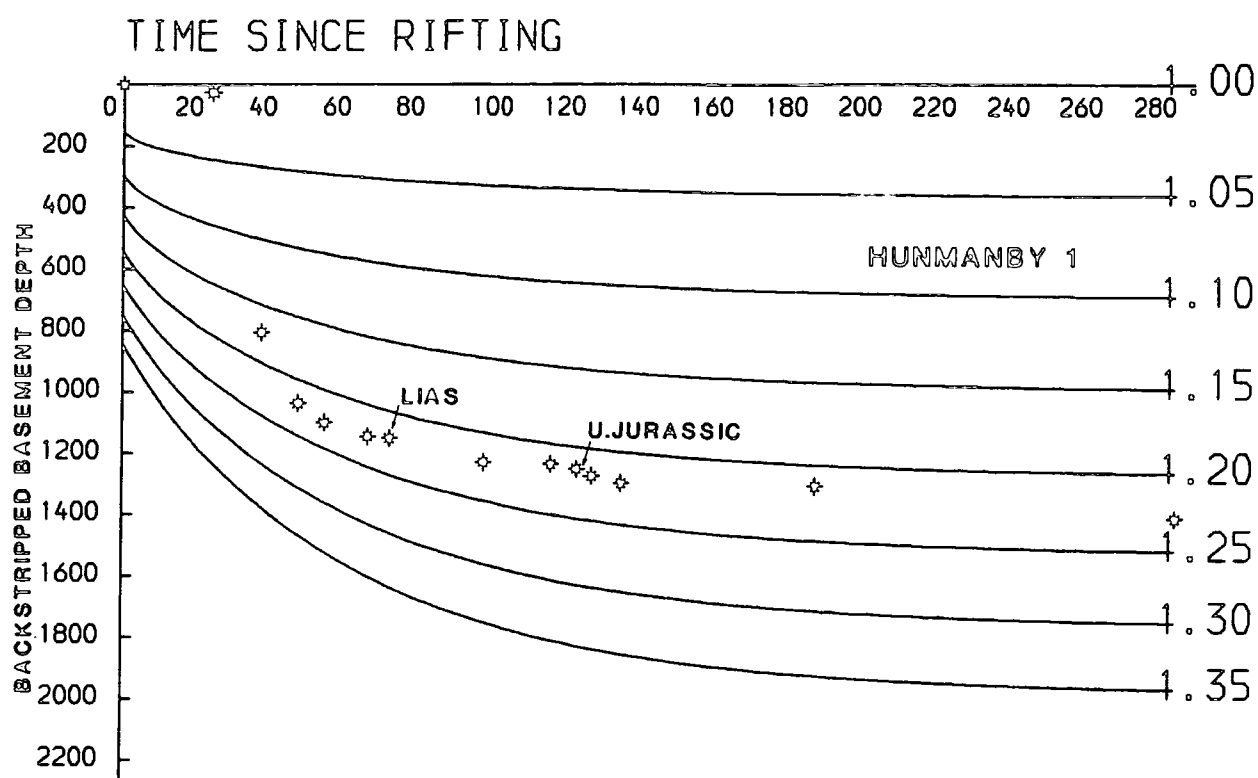


Figure 4.25. Backstripped tectonic subsidence curve correlated with compacted and decompact sedimentation rates for Hunmanby 1 in the south of the Yorkshire Basin.

Kingdom and North Sea areas (McGregor and McGregor, 1948; Rundle, 1981; Olsen, 1983; Penn et al, 1985; Skjerven et al, 1983; Glennie, 1984 and Holloway, 1985) the inference being that these events record the onset of continental rifting in the Lower Permian. The Yorkshire Basin, which displays general negatively exponential, tectonic subsidence curves, appears to record a strong component of thermal subsidence and thus significant involvement of both crustal and sub-crustal lithosphere.

4.5.2B Triassic.

The Triassic marks the onset of differential subsidence within the North Sea area (Ziegler, 1978; Sclater and Christie, 1980) and the control of subsidence within a mainly north - south trending graben system (Fisher, 1984). Within the study area differential subsidence, bound by major faults, eg. Dowsing Fault Zone, occurred in the Sole Pit Basin (Glennie and Boegner, 1981). Extension was orientated east - west and the Yorkshire and East Midland Basins were still subsiding as one unit (Whittaker, 1985). Dating the Triassic sequences is achieved using data from figure 4.19 (Harland et al, 1982) and facies correlations in Anderton et al (1979).

The Triassic period in the Yorkshire Basin commences with rapid tectonic subsidence and high sedimentation rates (figure 4.24, 4.25 and Appendix C4). They decrease into the Upper Triassic and become similar in magnitude to the majority of the succeeding subsidence history. The observed tectonic subsidence curves closely resemble the theoretical rapid or instantaneous subsidence curves followed by the commencement or early stages of gentle thermal subsidence, which with some interruptions is observed to continue throughout the Mesozoic (figures 4.22, 4.24, 4.25 and Appendix C4). Appendix C4 includes the tectonic subsidence plots for boreholes in the Yorkshire Basin assuming that the onset of rifting was the base of the Triassic. The excellent correlation of these curves, to the theoretical

curves for uniform lithospheric stretching and particularly the rapidity of the early mechanical faulting during the Triassic stresses the importance of the Triassic extension event to the evolution of the basin (figure 4.26).

Tectonic subsidence, on the scale of that computed in the Late Permian to Early Triassic is not encountered in the succeeding subsidence history of the Yorkshire Basin. It is postulated that these extensional events occurring during this time period created a stretched and thermally unequilibrated lithosphere, which continued to subside in response to thermal re-equilibration. Superimposed on this are additional mechanical extension episodes (figures 4.22, 4.24, 4.25 and Appendix C4), which occurred through the Jurassic and Lower Cretaceous in response to a dominating north - south orientated extensional stress field (Livermore and Smith, 1986; Lake, 1985).

4.5.2C. Jurassic to Lower Cretaceous.

Inversion, uplift and removal of sediment has largely unaffected the Permian and Triassic sediments within the Yorkshire Basin. They retain their original sedimentary, if not structural, configuration and thus their detailed subsidence history (tectonic and total) can be investigated once an approximation of the removed younger overburden is computed. The same cannot be assumed of the Jurassic and Cretaceous sediments within the Yorkshire Basin as inversion has removed much of these from, in particular, the northern, western and eastern margins of the basin. Nevertheless, by assuming that the computed figure of removed sediment is accurate and adding it to the inverted sequence, the general form of the tectonic subsidence curve will remain the same (figure 4.22, Staithes 4 and 41/8-1). The end point representing the time and total sedimentary thickness of maximum loading on the basement is constant whether the detailed sedimentological variations within the amount of sediment removed are known or not. Although the total tectonic subsidence between two points is the same, the detailed components of

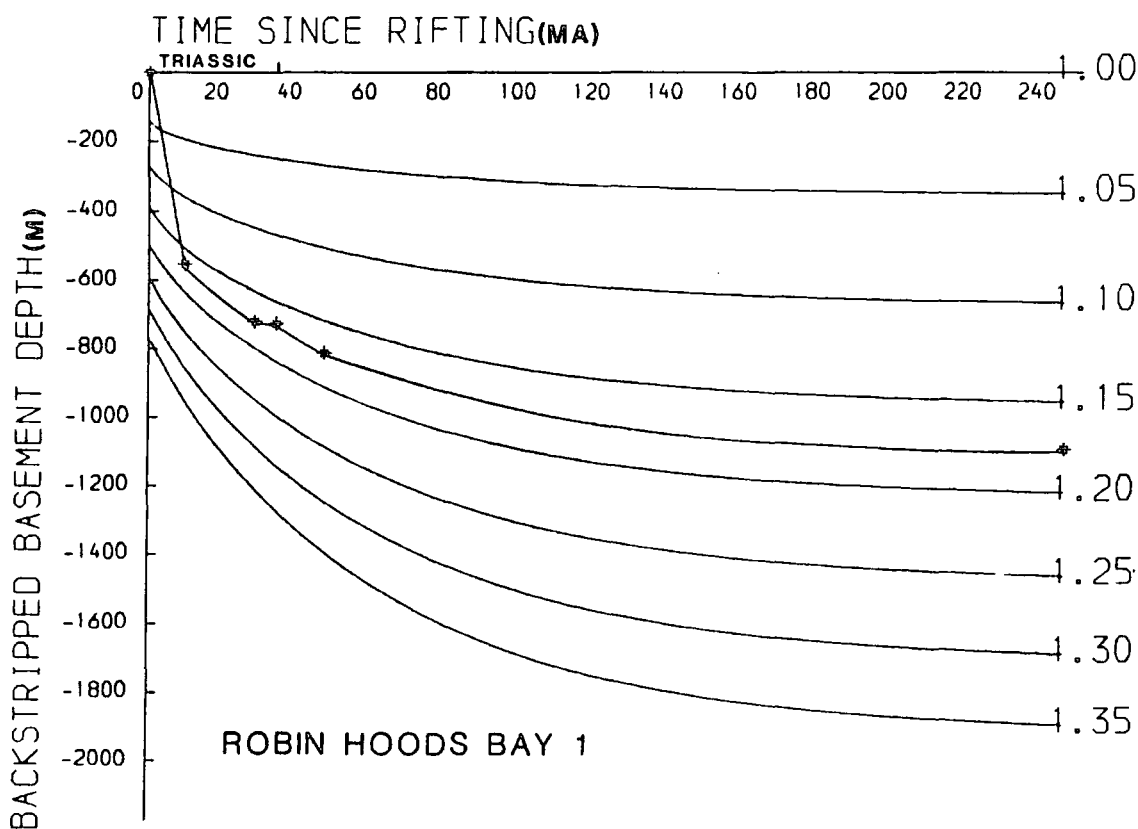
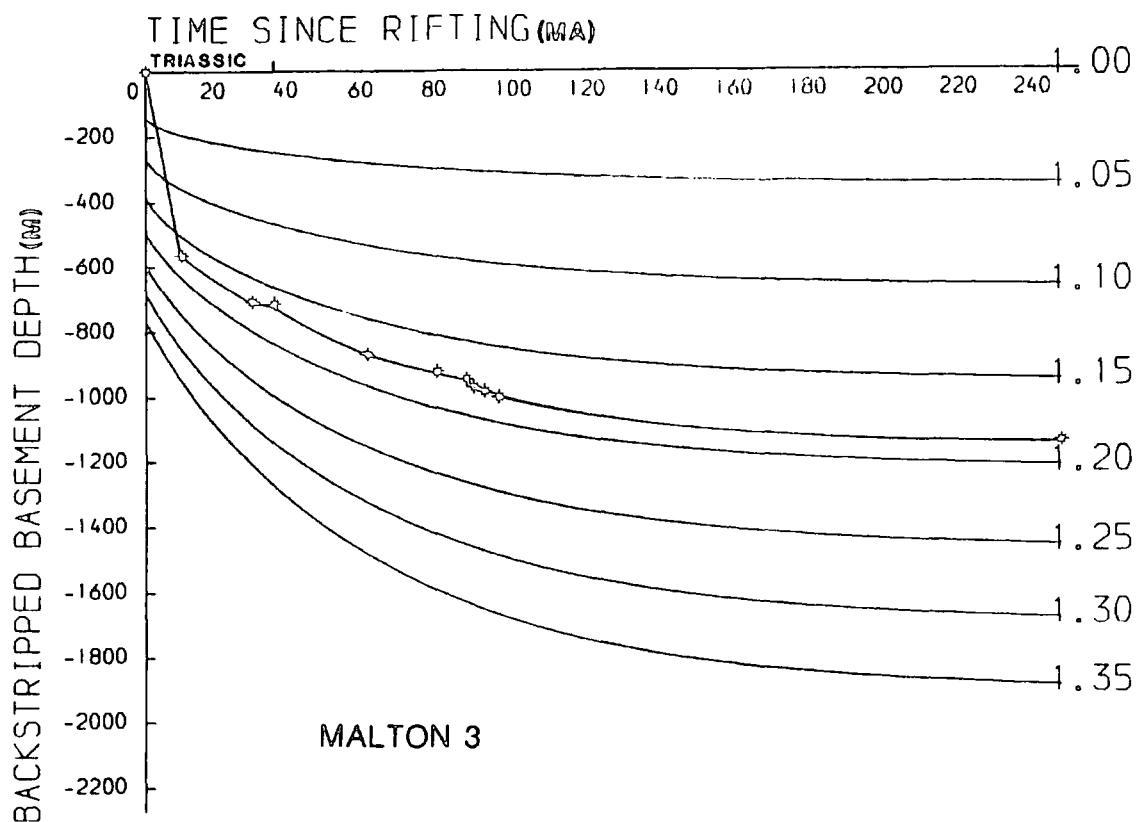


Figure 4.26. Tectonic subsidence curves in the Yorkshire Basin assuming the onset of rifting proper is at the start of the Triassic (Sclater and Christie, 1980).

subsidence are not represented in the data (compare Staithes 4 with Malton 1 in figure 4.22). The association of increased tectonic subsidence with facies changes and increased sedimentation rates cannot therefore be made where inversion is significant. This can be crucial within a period of subsidence such as the Jurassic when changes of facies were more regular than in either the preceding or ensuing subsidence phases of the basin.

Fortunately, the southern margin of the Yorkshire Basin remains relatively uninverted and the more detailed structure of the tectonic subsidence curve can be analysed (figures 4.22, 4.24 and 4.25). Tectonic subsidence curves within the central, more inverted parts of the basin provide correlation in the Lower and Middle Jurassic and valuable information on the total pre-inversion extension (β).

The Jurassic to Lower Cretaceous tectonic subsidence curves (figures 4.22, 4.24, 4.25 and Appendix C4) reveal a rather subdued subsidence relative to the rapid subsidence of the Permian and Triassic. Subsidence rates (figures 4.24 and 4.25) also reveal a more steady, thermal type of subsidence. Relative increases and decreases in sedimentation rates also coincide with analogous changes in the tectonic subsidence curves. The Jurassic to Lower Cretaceous tectonic subsidence curves within the southern parts of the Yorkshire Basin infer two main increases in tectonic subsidence, notably in the Lower Jurassic and Upper Jurassic (Kimmeridgian) as illustrated in figures 4.22, 4.24, and 4.25. Within the central part of the Yorkshire Basin, inversion has removed much of the sediments above the Middle Jurassic. Both the Lower and Middle Jurassic sediments thicken towards the centre of the Yorkshire Basin (Whittaker, 1985). Backstripped tectonic subsidence curves that include a component of these sediments reveal corresponding kicks representing phases of increased, possibly mechanical, subsidence (figure 4.27). The Middle Jurassic sequence is incomplete within the Lockton 8 bore-

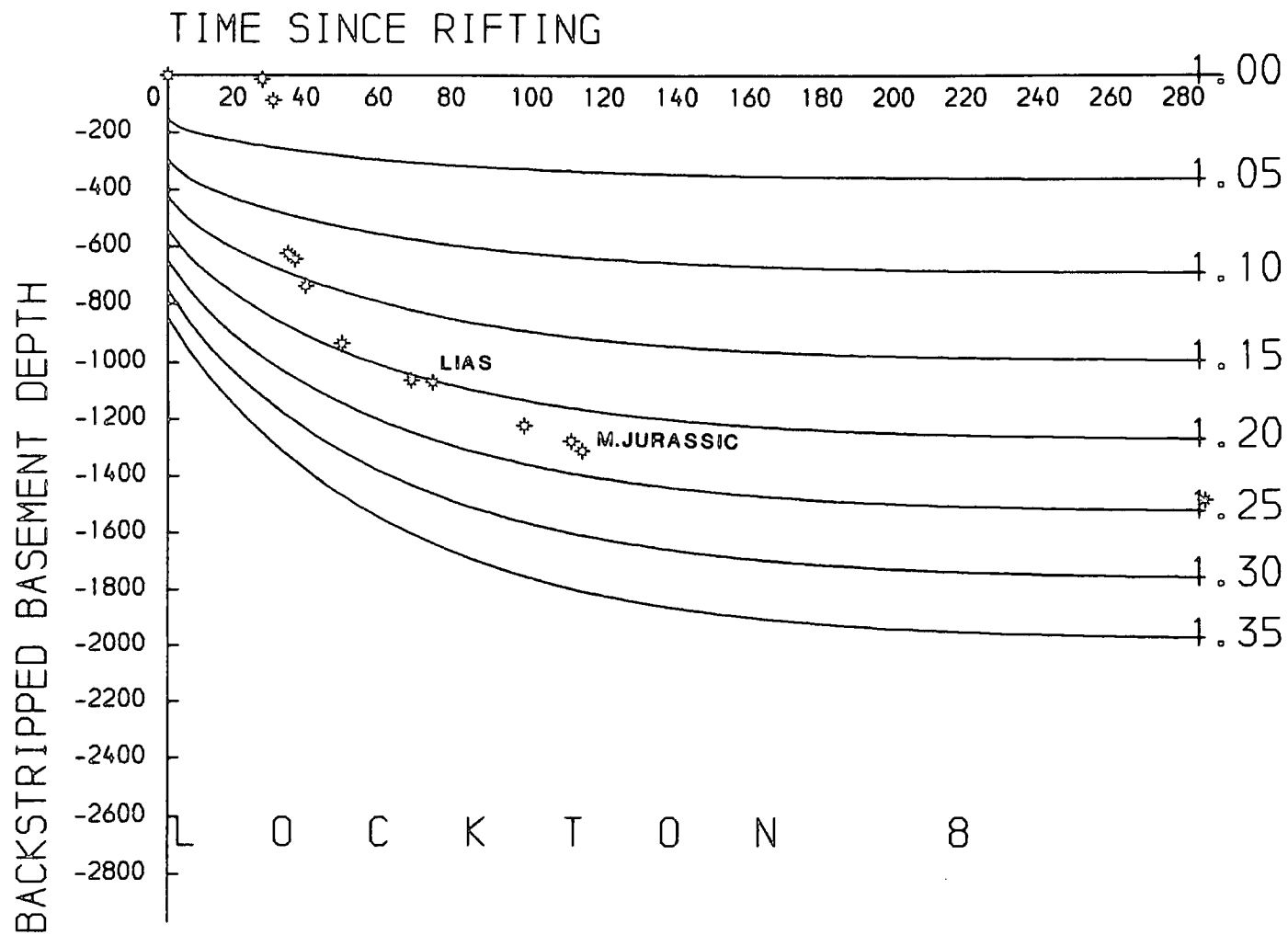


Figure 4.27. Lockton 8, central Yorkshire Basin. Late Permian to early Triassic initial rapid subsidence. Additional subsidence events in the Lias and Middle Jurassic, although the latter has been partially removed by inversion.

hole (figure 4.27), but an increase in tectonic subsidence is nevertheless recorded. Southwards, towards the Vale of Pickering area, Middle Jurassic sediments thin, but still correspond with an increase in tectonic subsidence (Malton 1 in figure 4.22, Fordon 1 in figure 4.24 and Hunmanby 1 in figure 4.25).

During Lower and Middle Jurassic, the Yorkshire Basin became a differentially subsiding unit due to the initiation and influence of a zone of relative positive relief, on the footwall or southern side of the Vale of Pickering Fault Zone (figure 4.28). This region has been termed the Market Weighton Block or Axis (Versey, 1948; Kent, 1955, 1974, 1980a, b; Jeans, 1973; Bott et al, 1978), and formed a barrier between the Yorkshire Basin to the north and East Midland Basin to the south during the Jurassic to Lower Cretaceous. Sediments of this age thin from these two basins towards the Market Weighton Block (figure 4.28). The backstripped tectonic subsidence curve for the North Dalton borehole (figure 4.22) aptly summarizes the transformation of this area of significant Permian and Triassic subsidence to one of Jurassic non-deposition.

The northern margin of this zone of uplift does not correspond exactly to the southern limit of the Vale of Pickering Fault Zone (figure 4.28). Across the latter, Jurassic sediments thicken rapidly northwards. Indeed, the Lower Jurassic tectonic subsidence event, discussed above for the area within and to the north of the Vale of Pickering Fault Zone (figures 4.22, 4.24 and 4.25), is almost insignificant in the area between the Market Weighton Block and the aforementioned fault zone (figure 4.29). Greater extension and hence subsidence occurs on the hangingwall side of these faults or within the Yorkshire Basin to the south. Lithospheric tectonic stretching will cause rapid mechanical or brittle extension which will be recorded by both fault displacement and increased tectonic subsidence and sedimentation rates. It is postulated therefore, that the patterns of tectonic subsidence and sedimentation characteristic of the Yorkshire Basin during the Lower

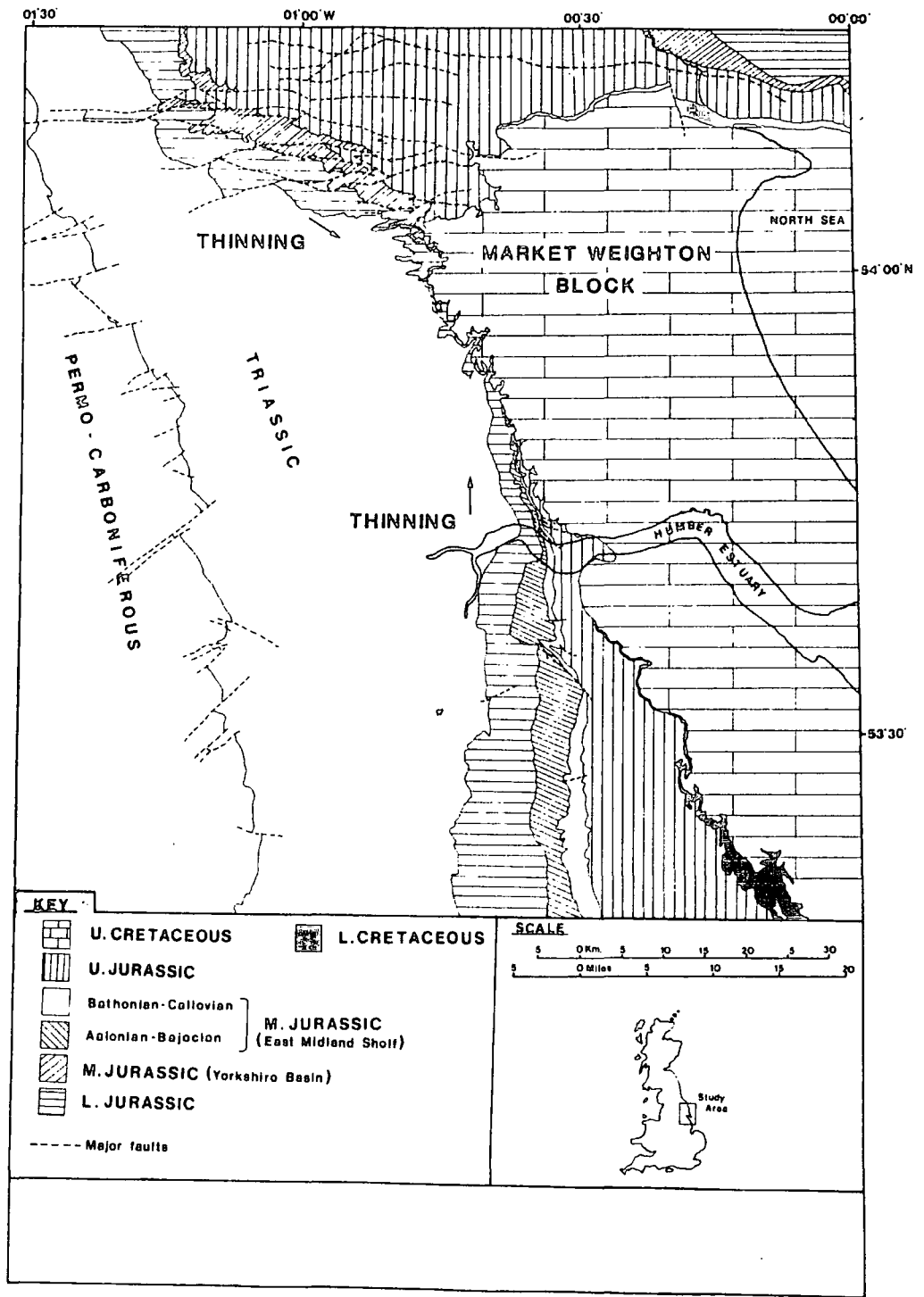


Figure 4.28. Geological map of the Market Weighton area showing thinning of Jurassic and Lower Cretaceous sediments across it.

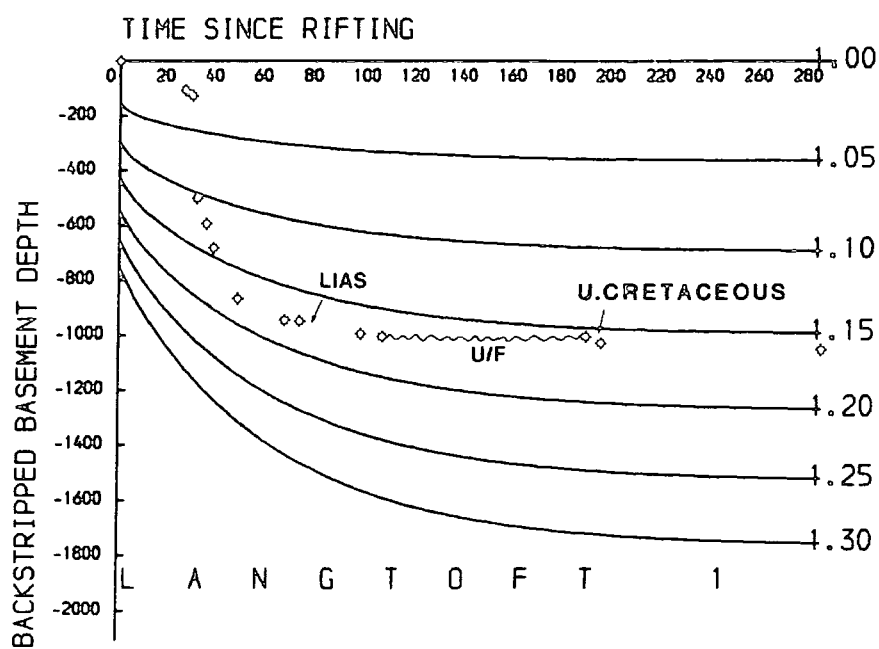


Figure 4.29. Representative tectonic subsidence over the northern margin of the Market Weighton area. Note unconformity and normal Permian to Triassic subsidence.

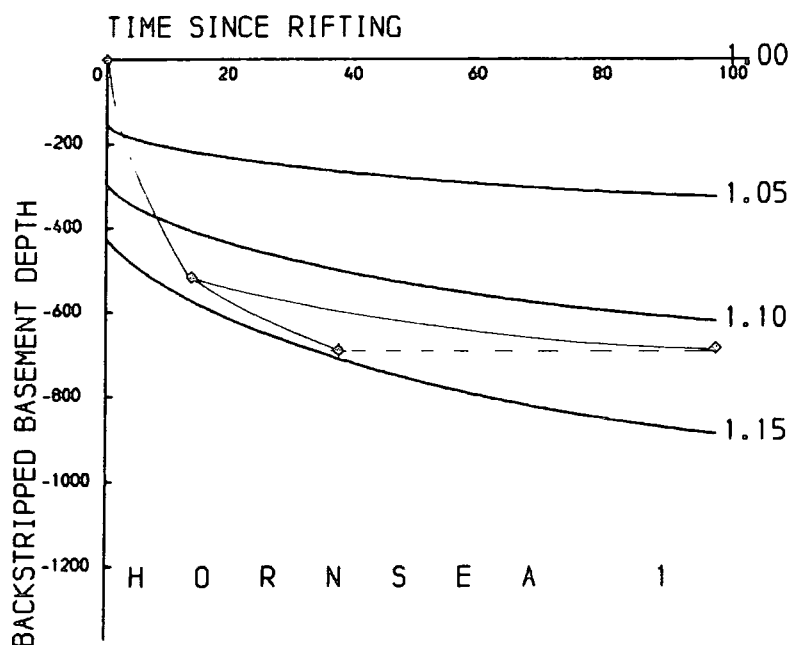


Figure 4.30. Tectonic subsidence of the Upper Cretaceous chalk in the Yorkshire Basin.

and Middle Jurassic reveal the creation of the Vale of Pickering Fault Zone, its subsequent accommodation of extension and influence on basin development.

Upper Jurassic and Lower Cretaceous sediments are preserved in the southern half of the Yorkshire Basin (figure 4.28) predominantly within the Vale of Pickering Fault Zone, in which they are downthrown and protected from inversion. Sequences recorded in boreholes Malton 1, Fordon 1 and Hunmanby 1 (figures 4.22, 4.24 and 4.25 respectively) show that the Upper Jurassic was a time of increased tectonic subsidence and sedimentation. This is particularly pronounced during deposition of the Kimmeridge Clay (figures 4.24 and 4.25). The severity of this tectonic subsidence episode in the Fordon 1 borehole relative to that in the Hunmanby 1 borehole, the accompanying difference in Kimmeridge Clay thickness, ie. 390 m and 97 m respectively, and their close proximity to and separation by faults within the Vale of Pickering Fault Zone implies that this area was subjected to increased extension and mechanical fault controlled subsidence at this time.

Deposition of the Speeton Clay in the Lower Cretaceous does not coincide with any notable increase in subsidence (figures 4.24 and 4.25). However, Jeans (1973) and Neale (1974) have both postulated that laterally variable thickness changes of the Speeton Clay are controlled by faulting. Thus, not all phases of mechanical accommodation of upper crustal extension may be represented in the form of distinctive changes in the pattern of tectonic subsidence or increases in sedimentation rate. The relatively long period of deposition of the Speeton Clay, approximately 47Ma and the lack of reasonable and datable sub-units within it, may contribute to the masking of internal variations in subsidence rates, if indeed they occur. The Lower Cretaceous in the Yorkshire Basin is the youngest unit to be demonstrably affected or controlled by extensional faulting during subsidence.

Thus, although the general form of the Jurassic to Lower Cretaceous tectonic

subsidence is subdued and similar to the theoretically predicted pattern of thermal subsidence (McKenzie, 1978) a number of discrete subsidence events or episodes are superimposed. This suggests the combination of continuous mechanical/brittle lithospheric extension or stretching during exponentially decreasing, post Permo-Triassic thermal subsidence.

4.5.2D. Upper Cretaceous.

Upper Cretaceous sedimentation, within the Yorkshire Basin is represented by the relatively, lithologically monotonous chalk. Subsidence was slow and unfaulted and did not differentiate between the Yorkshire and East Midland Basins, but rather transgressed the pre-existing basin margins, eg. Market Weighton Block (figure 4.28). The chalk is preserved, like the Upper Jurassic and Lower Cretaceous sediments, to the south of the Yorkshire Basin, but its subsidence form can also be examined over the Market Weighton Block which once more subsided non-differentially as in the Permian and Triassic. These sequences are assumed to reflect the history of Upper Cretaceous within the whole of the Yorkshire Basin since:-

1. Chalk isopach data does not display rapid changes.
2. Chalk subsidence is not apparently fault controlled.
3. The computed amount of removed overburden from the more inverted northern part of the Yorkshire basin infers that Upper Cretaceous sedimentary thicknesses were of similar magnitude to those presently recorded in boreholes in the study area. Figures 4.22, 4.23, 4.24 and 4.29 each illustrate a similar and distinct form of exponentially decreasing Upper Cretaceous tectonic subsidence. The Upper Cretaceous subsidence has further been isolated by assuming it was a distinct subsidence event, as the above examples support. Figure 4.30 models the post - Lower Cretaceous subsidence in the Hornsea

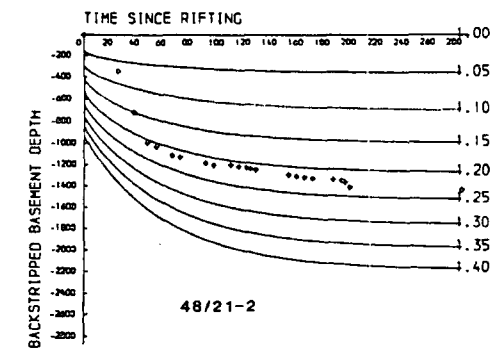
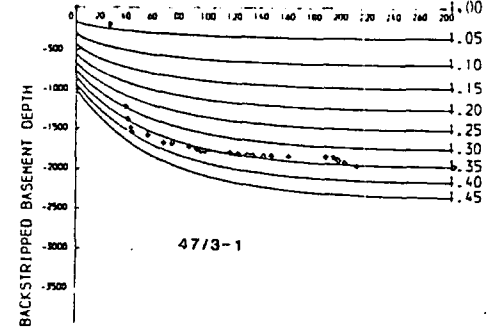
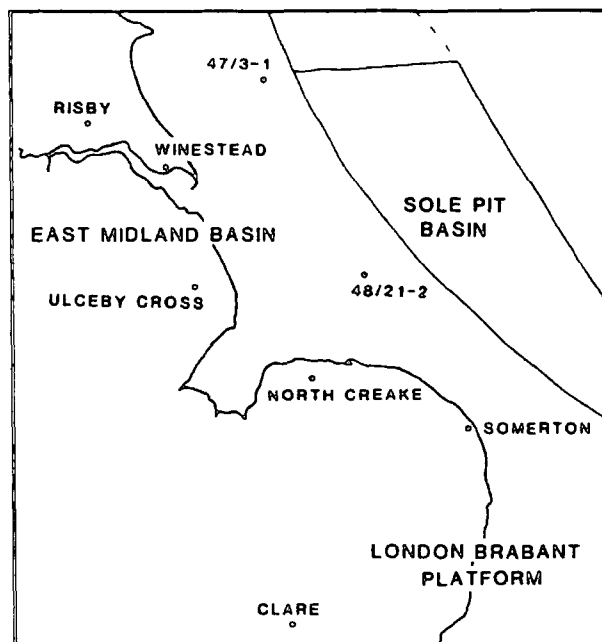
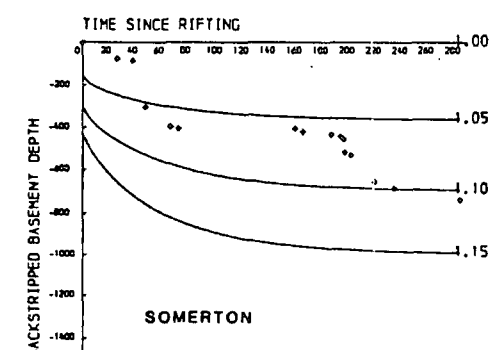
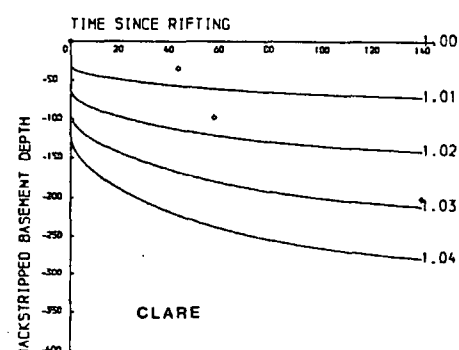
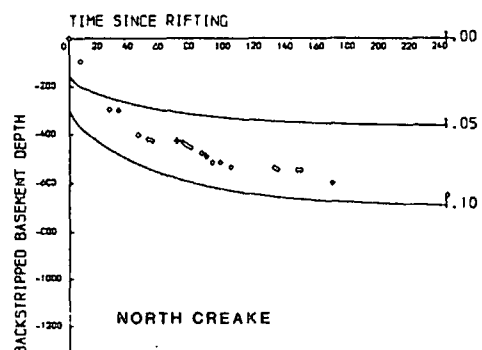
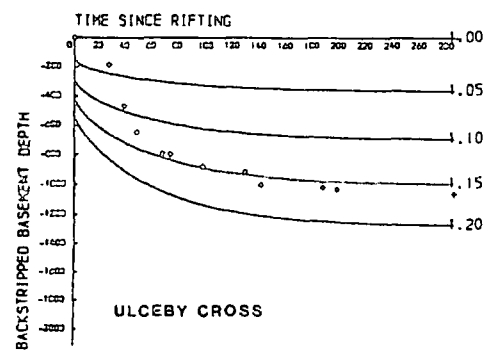
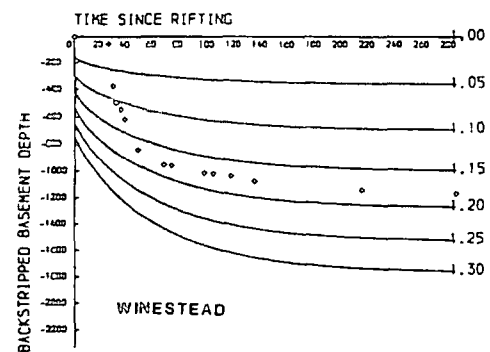
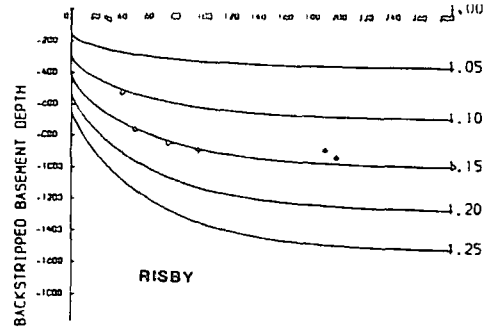


Figure 4.31. Tectonic subsidence in the East Midland Basin.

borehole against theoretical uniform one layer stretching curves. Onset of subsidence is assumed to be the base of the Upper Cretaceous, ie. 97.5Ma (Harland et al, 1982).

Two manifestations of the observed tectonic subsidence are portrayed:-

- A. Assuming the minimum computed post - Lower Cretaceous sediment thickness represents the maximum subsidence from the Upper Cretaceous to Recent (figure 4.30).
- B. Assuming inversion commenced or subsidence ceased in the Late Cretaceous to Early Tertiary.

Cretaceous subsidence curves portray quite good correlations with the theoretical curves, the Upper Cretaceous curve being truncated at the end of the Cretaceous. This resembles the cessation of subsidence in the Yorkshire Basin due to uplift and inversion. The latter are postulated to have begun in the Late Cretaceous to Early Tertiary in the Sole Pit Basin (Glennie and Boegner, 1981; Van Hoorn, 1987). Thermal subsidence within the surrounding North Sea Basin continued throughout the Tertiary (Beaumont, 1978; Sclater and Christie, 1980; Wood, 1981 and Barton and Wood, 1984). It is postulated that the form of Upper Cretaceous tectonic subsidence in the Yorkshire Basin (figures 4.20, 4.22, 4.24, 4.29 and 4.30) suggests that thermal re-equilibration and subsidence of the lithosphere following rifting was not necessarily complete and that subsidence was locally curtailed by a change in the tectonic stress (Livermore and Smith, 1986).

4.5.3. Tectonic Subsidence in the East Midland Basin.

The variation in the amounts and forms of tectonic subsidence in the East Midland Basin are illustrated in figures 4.21 and 4.31. Present and pre-inversion depth to the basement (figures 4.1 and 4.2 respectively) are similar due to the

relatively minor uplift that affected the East Midland Basin (figure 3.31). The sedimentary sequences within the present extent of the basin are therefore more complete than for example, those in the more inverted parts of the Yorkshire Basin (figure 4.22 and Appendix C4). This provides a more precise insight into the subsidence history of the East Midland Basin.

The London Brabant Platform (figures 4.21 and 4.31) formed the southern margin to the East Midland Basin throughout most of its subsidence history. Delay in the onset of subsidence around its margin with the East Midland Basin, corresponding with a change in the form of the tectonic subsidence curves (figure 4.31 - Clare, North Creake and Somerton boreholes), support this and reflect the influence of this structurally positive region. To the north of the East Midland Basin, the Market Weighton Block formed a relatively uplifted boundary between the former and the Yorkshire Basin during the Jurassic to Lower Cretaceous (figure 4.28). The truncation of tectonic subsidence in the Risby borehole (figure 4.31) is the manifestation of this period of uplift on the southern edge of the Market Weighton Block. Although the magnitude of tectonic subsidence decreases westwards (figure 4.21) the form of the tectonic subsidence (figure 4.31 - Risby, Ulceby Cross) does not infer the close proximity of a western margin to the East Midland Basin, like it does to the south of the basin (figure 4.31 - North Creake, Somerton, Clare). Rather, the form of the tectonic subsidence is similar to that in the east of the basin (figure 4.31 - 47/3-1 and 48/21-2) but of smaller magnitude. The observed curves correlate well with the theoretically derived thermal subsidence curves for uniform lithospheric stretching ($\beta = \delta$). β values increase eastwards towards the Sole Pit Basin. The similarity or uniformity of the form of tectonic subsidence within the East Midland Basin is postulated to reflect the absence of local structural control on basement subsidence.

4.5.3A. Permian.

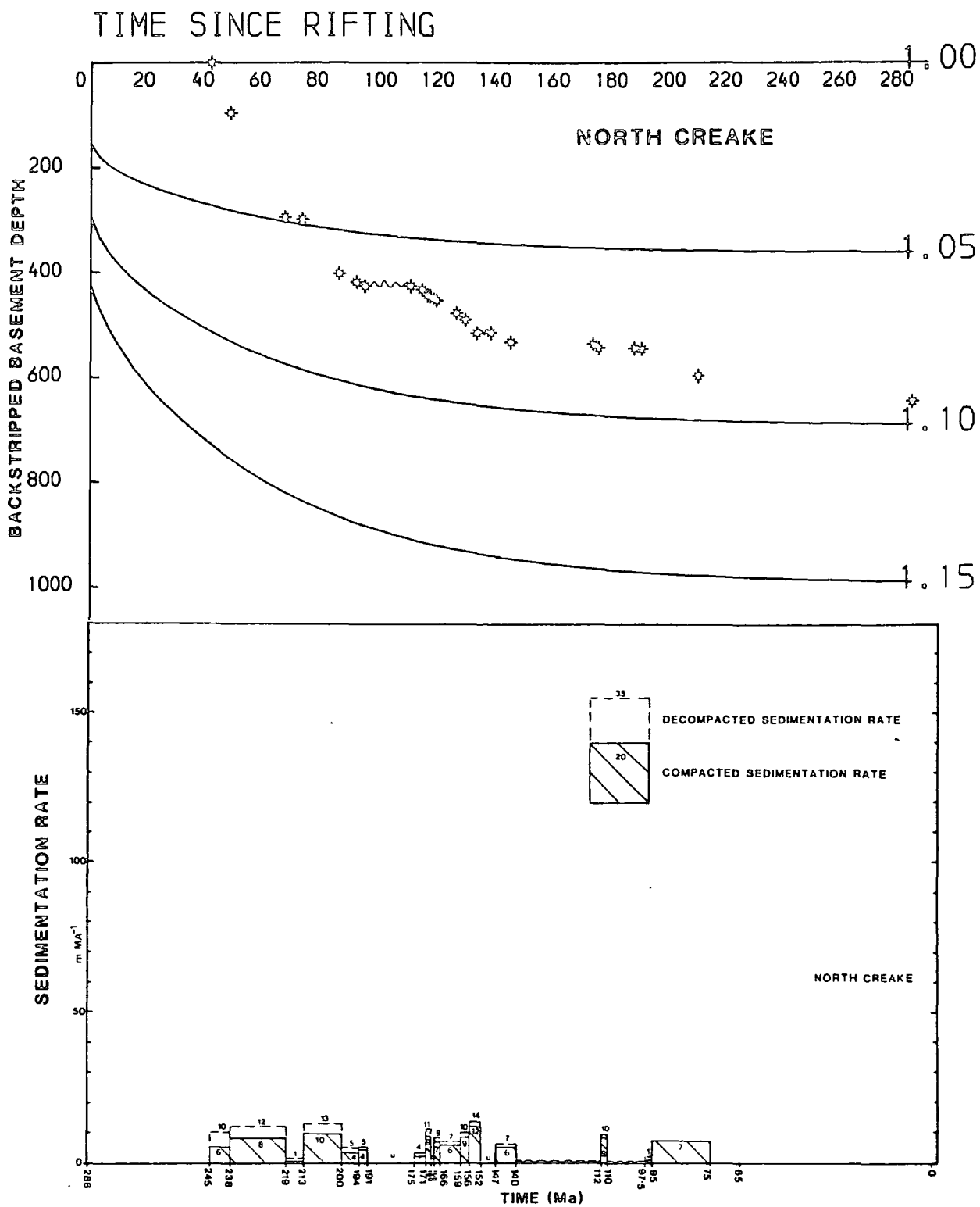


Figure 4.32. Tectonic subsidence correlated with compacted and decompact sedimentation rates on the margin of the London Brabant Platform in the East Midland Basin. Flexure is not accounted for in the modelling but may influence subsidence particularly at the basin margins.

The East Midland Basin formed the southern part of a regionally subsiding western margin of the Permian Southern North Sea Basin. It was not separated structurally from the Yorkshire Basin to the north. Unlike the Yorkshire Basin, in which delayed, early Permian subsidence reflected the pre-Permian structural configuration, the whole East Midland Basin subsided with the exception of the London Brabant Platform area (figures 4.31, 4.32, 4.33 and 4.34).

The first period of rapid subsidence occurs in the Upper Permian (figures 4.31, 4.33 and 4.34) and is analogous to the subsidence in the Yorkshire Basin at this time (figure 4.22). The severity of the Upper Permian subsidence is more pronounced offshore (figures 4.31 and 4.34) and signifies the regional increase in subsidence towards the centre of the Southern North Sea Basin.

4.5.3B. Triassic.

The early Triassic, as in the Yorkshire Basin, represents a period of increased tectonic subsidence and sedimentation rates (figures 4.31, 4.32, 4.33 and 4.34). Subsidence propagated further southwards onto the London Brabant Platform (figures 4.31 and 4.32 - North Creak). This period represents the most pronounced and widespread subsidence during formation of the East Midland Basin. Mechanical fault control on subsidence or sedimentation is not evident within the East Midland Basin. It subsided on the footwall of the Dowsing Fault Zone, east of which, in the hangingwall, the Sole Pit Basin was differentially subsiding at this time (figure 3.30). East - west extension of the Southern North Sea Basin utilised suitably orientated crustal fractures, eg. the north-west - south-east Dowsing Fault Zone. The lack of faulting however, does not appear to have restricted subsidence within the East Midland Basin inferring that some other mechanism, such as thermal or flexural subsidence, was involved. The close approximation of the observed tectonic subsidence curves to the theoretical curves for equal upper crustal (brittle) and sub-crustal (ductile or thermal) lithospheric stretching

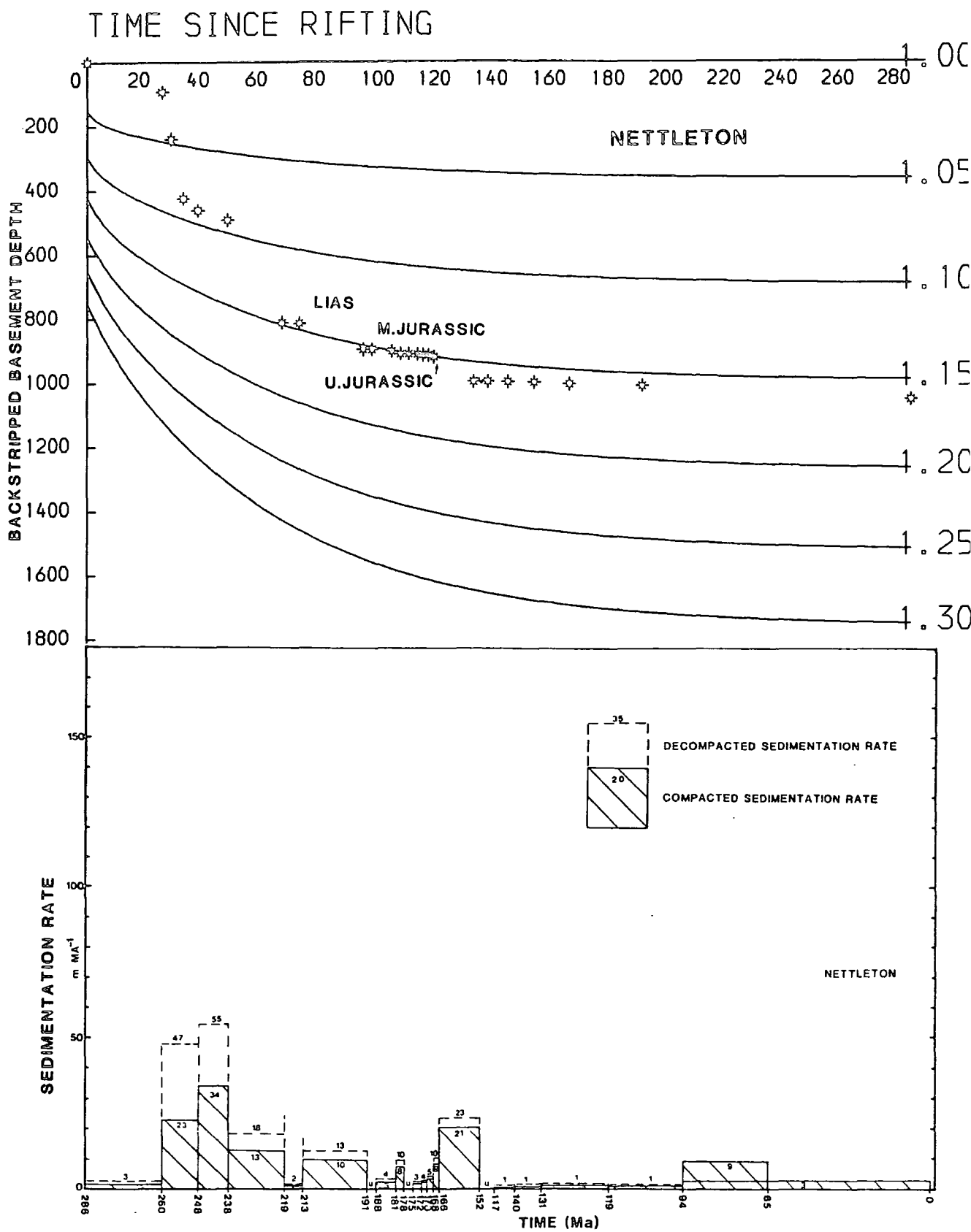


Figure 4.33. Tectonic subsidence correlated with compacted and decompact sedimentation rates in the central, onshore East Midland Basin.

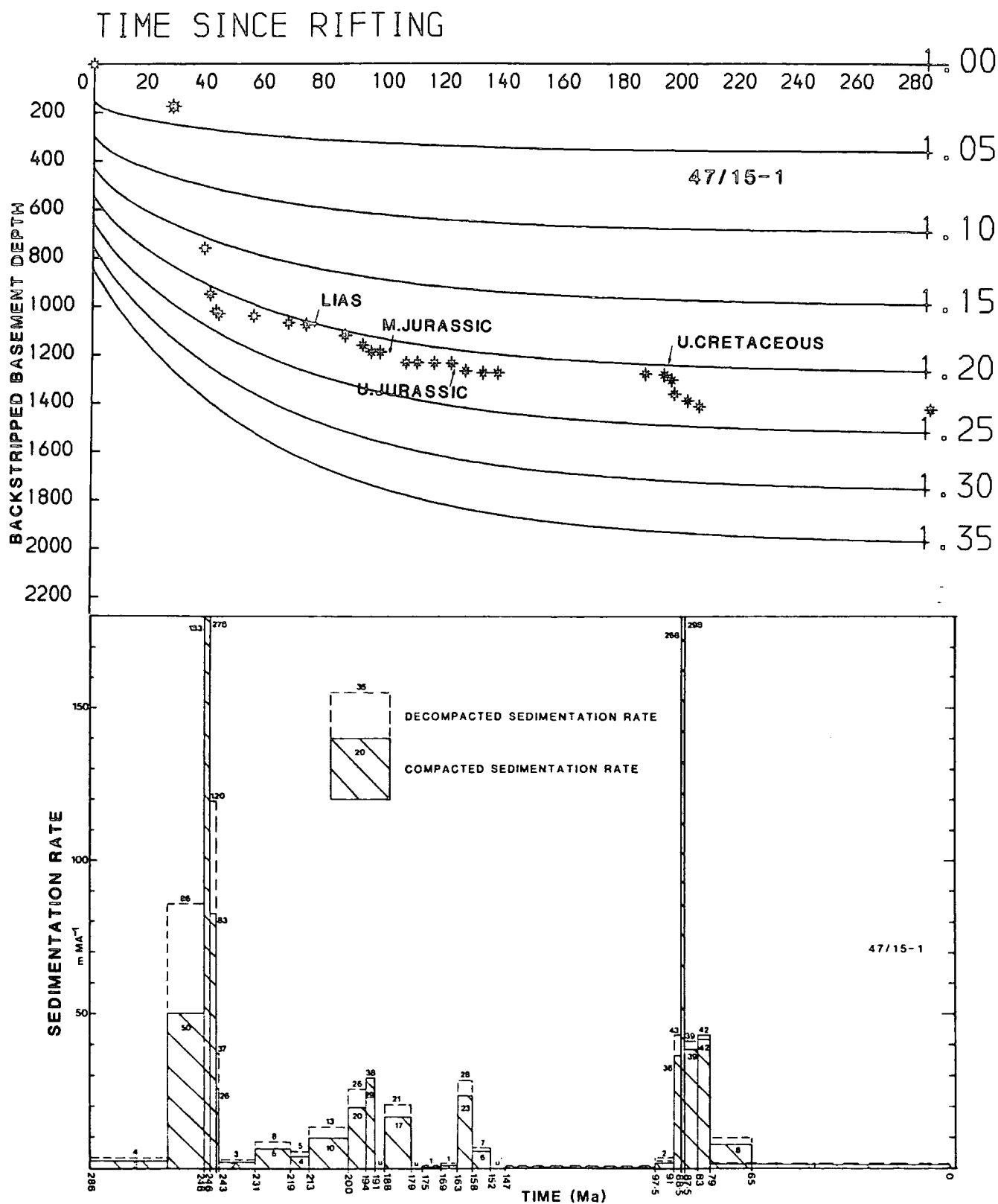


Figure 4.34. Tectonic subsidence correlated with compacted and decompact sedimentation rates for the offshore East Midland Basin.

supports this hypothesis (figures 4.31, 4.32, 4.33, 4.34 and Appendix C4).

Tectonic subsidence and sedimentation rates depreciate in the Late Triassic and merge into the more subdued subsidence of the Jurassic (figures 4.32, 4.33 and 4.34).

4.5.3C. Jurassic to Lower Cretaceous.

Jurassic to Lower Cretaceous subsidence in the East Midland Basin followed a gentle exponentially decreasing path punctuated by a number of increased subsidence events. The observed trend is remarkably similar to theoretical thermal subsidence curves (figures 4.31, 4.33 and 4.34). Subsidence was extremely gentle and constant on the margin of the London Brabant Platform (figure 4.32). Here, the observed tectonic subsidence is more linear and transects the theoretical curves (figure 4.31 - Clare and figure 4.32). Within the central and eastern parts of the basin, subsidence rates fluctuated much like in the Yorkshire Basin (figures 4.24 and 4.25). The most notable fluctuations are in the Lower and Middle Jurassic (figures 4.33 and 4.34). Although more subdued than in the Yorkshire Basin, they do occur despite the apparent lack of extensional faulting in the basin, to which the Yorkshire events seem to be linked. This may represent either the regional, more subdued response to extensional tectonics in the upper crust which is the strongest and most notable within the hangingwall of major extensional faults (figure 4.21). Alternatively, it may represent some other phenomenon which increases the load on the basement and hence the tectonic subsidence, such as an increase in eustatic sea-level. The interaction of these two mechanisms in the context of the observed tectonic subsidence of the Yorkshire, Sole Pit and East Midland Basins will be discussed in section 4.6.

4.5.3D. Upper Cretaceous.

Upper Cretaceous tectonic subsidence was a regional, unfaulted event which

coincided with a marked rise in eustatic sea-level (Vail et al, 1977). The form of Upper Cretaceous subsidence in the East Midland Basin is similar to that already described in section 4.5.2D. It represents a marked increase over Lower Cretaceous subsidence which was minor in the East Midland Basin (figures 4.31, 4.32, 4.33 and 4.34). The London Brabant Platform was transgressed (figure 4.31 - Clare). The Upper Cretaceous was the last major subsidence event to affect the East Midland Basin. Its form is very consistent and is distinguishable in all parts of the basin (figures 4.31, 4.32, 4.33, 4.34 and Appendix C4). Offshore, where chronostratigraphic subdivisions of the chalk are recognised in borehole sequences, subsidence and sedimentation rates are extremely rapid and match the magnitude of those observed in the Early Triassic (figure 4.34). These are the two major periods of subsidence in the East Midland Basin.

4.5.4. Tectonic Subsidence in the Sole Pit Basin.

The basement of the Sole Pit Basin has suffered substantial uplift resulting in basin inversion and partial destruction (figure 3.31). This is reflected in the present and estimated pre-inversion depth to basement in the Sole Pit Basin (figures 4.1 and 4.2). Because of this, much of the detailed subsidence and sedimentological variation that occurred in the basin has been lost. However, the amount of estimated sediment removed has been made for each borehole such that:-

1. The general form of the tectonic subsidence and postulated pre-inversion lithospheric stretching or extension (β or δ) can be analysed.
2. The preserved sediments and the detailed tectonic subsidence they represent can be accurately assessed in time. Failure to account for removal of sediment causes less representative results due to errors in estimating variation of sediment density through time, and hence the maximum load on the basement. An example from the Yorkshire Basin, where the sediment removed is not

compensated for is illustrated in figure 4.17.

A representative selection of tectonic subsidence curves along a north-west - south-east transect of boreholes in the Sole Pit Basin is illustrated in figure 4.35. The youngest sediments preserved in the boreholes are Lower Jurassic in age except for borehole 47/5-1 in the north of the basin where they are Triassic. It is clear from comparison of the tectonic subsidence curves in figure 4.35 with those in the East Midland Basin (figures 4.31, 4.32, 4.33 and 4.34) and the less inverted parts of the Yorkshire Basin (figures 4.22, 4.24 and 4.25) that the detailed fluctuations in the Jurassic and Cretaceous subsidence in the Sole Pit Basin have been lost. Despite this, the general form of the subsidence curves between the three basins are similar.

4.5.4A. Permian.

Lower Permian tectonic subsidence is more substantial in the Sole Pit Basin than in the Yorkshire and East Midland Basins. However, Lower Permian subsidence is still not as rapid an event as Upper Permian and Triassic events. This is a common feature to all three basins. Isopach data (Glennie and Boegner, 1981) reveal that the Dowsing Fault Zone on the western margin of the Sole Pit Basin (figure 4.35) had an influence on Lower Permian sedimentation. Despite this initial, fault controlled subsidence, the observed tectonic subsidence is not instantaneous or rapid (figure 4.35). This infers some component of thermal subsidence which would extend the duration of the initial rifting event (figure 4.20).

Upper Permian tectonic subsidence is more rapid and appears to form a general exponentially decreasing, but initially rapid, subsidence event with the Triassic (figure 4.35). Upper Permian isopach data (Glennie and Boegner, 1981) suggest that the influence of the Dowsing Fault Zone was reduced and differential subsidence within the Sole Pit Basin was part of a more regional rapid subsidence

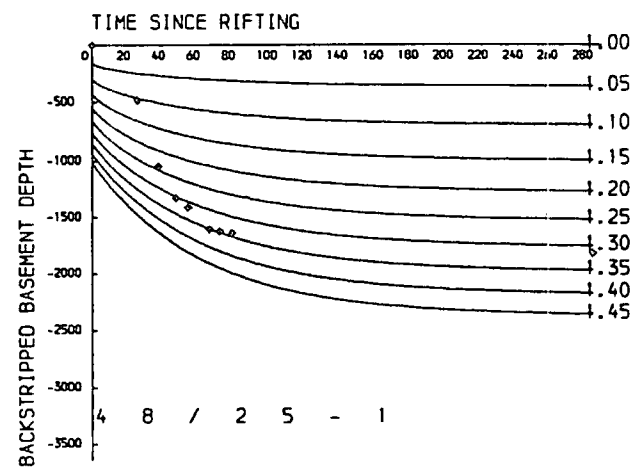
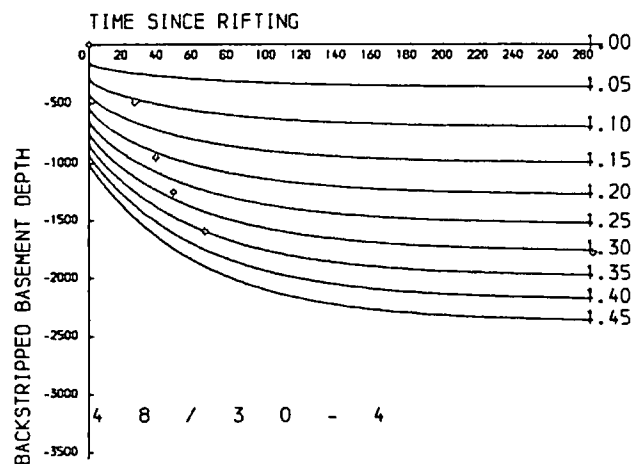
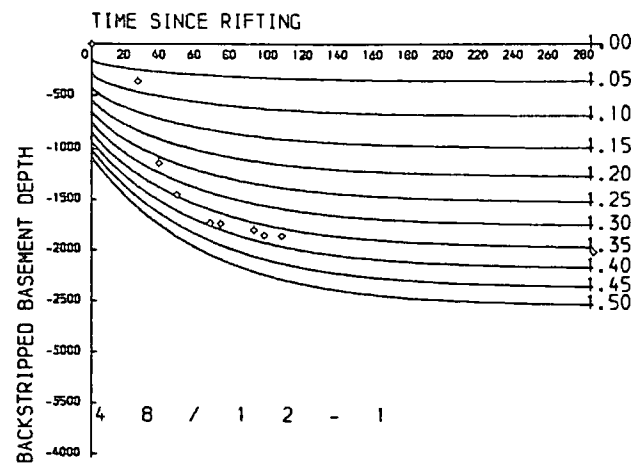
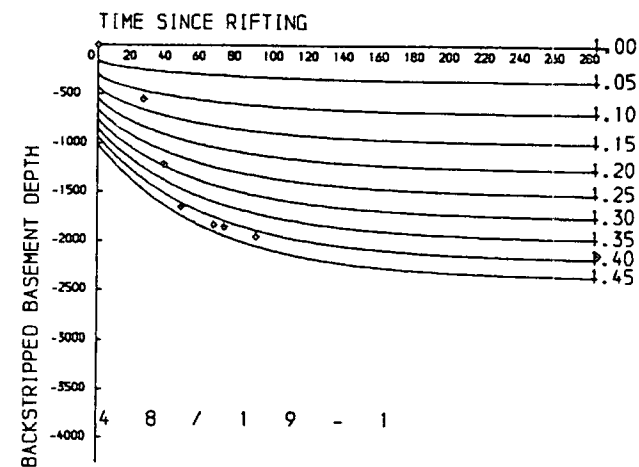
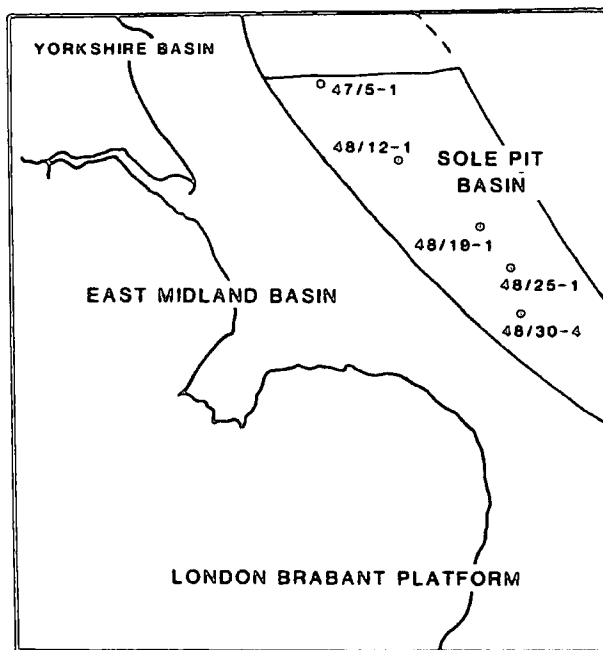
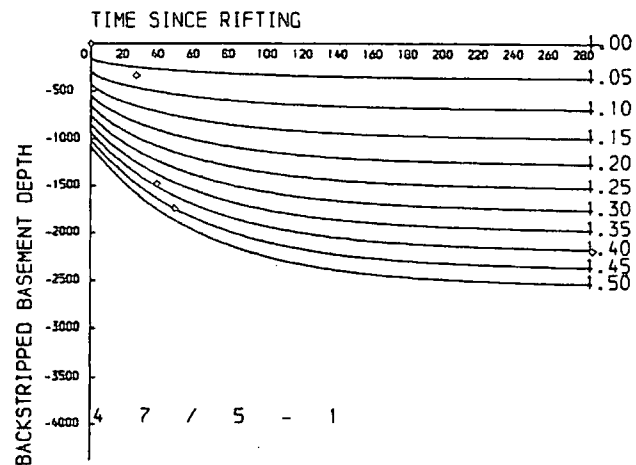


Figure 4.35. Tectonic subsidence curves for the Sole Pit Basin.

in the Permian Southern North Sea at this time.

4.5.4B. Triassic.

During the Triassic, the Sole Pit Basin once more became a differentially subsiding unit (Glennie and Boegner, 1981). The onset of Triassic subsidence is rapid but does not appear to conform to theoretical tectonic subsidence curves. However, if one assumes that the Triassic marks the initiation of rifting in the Southern North Sea Basin (Sclater and Christie, 1980) or the initiation of a finite rifting event, the form of the Triassic subsidence more clearly approximates to the theoretical initial rapid subsidence during basin formation. This is found to be a consistent observation throughout the study areas and is illustrated in Appendix C4.

As in the Yorkshire and Sole Pit Basins, the end of the Triassic marks the decline in the severity of tectonic subsidence (figure 4.35:- 48/12-1, 48/19-1 and 48/25-1).

4.5.4C. Jurassic.

The late Triassic and early Jurassic tectonic subsidence closely matches the predicted thermal subsidence curves. However, erosion has removed much of the Lower Jurassic from the area which restricts one's ability to interpret the observed tectonic subsidence. Borehole 48/12-1 (figure 4.35) reveals a small subsidence event in the Lower Jurassic, a feature common to the Yorkshire and East Midland Basins.

Further interpretation of the tectonic subsidence of the Sole Pit Basin is not possible from boreholes within the inverted basin. However, isopach data (Glennie and Boegner, 1981) and comparisons of computed removed sedimentary thicknesses with preserved sedimentary thicknesses on the east of the Dowsing Fault

Zone (Chapter 3, this study), suggests that the subsiding Sole Pit Basin may have extended further north, beyond the present extent of the inverted Sole Pit Basin. The Outer Silver Pit Fault, which bounds the inverted Sole Pit Basin to the north (figure 4.35), may be a posthumous structure related to compressive inversion and/or diapirism.

Borehole 42/30-1 (Appendix C4), located in figure 4.35 is postulated to represent a lesser inverted equivalent of the sequences in the Sole Pit Basin. Sediments of Upper Jurassic age are preserved and an estimation of removed overburden (2000 feet) has been made. The form of the tectonic subsidence and predicted stretching (β) are similar to those illustrated in figure 4.35. The characteristic punctuated Jurassic subsidence curve is observed.

4.5.5. Two Layer Lithospheric Stretching.

The magnitude of the observed backstripped tectonic subsidence curves for the Yorkshire, Sole Pit and East Midland Basins remain constant for uniform and non-uniform lithospheric stretching. In sections 4.5.2. - 4.5.4. this driving tectonic subsidence has been compared to theoretical subsidence curves for uniform lithospheric stretching. Uniform lithospheric stretching assumes that brittle and ductile accommodation of extension in the crustal and sub-crustal lithosphere respectively is equal ie. the amount of extension in both is equal, and $\delta = \beta$. The model recognises the occurrence of the two layer situation but assumes that both the upper and lower layers behave uniformly. Thus, the uniform lithospheric stretching model assumes brittle accommodation of extension is confined to the crust (thickness = 31.2 km, Royden and Keen, 1980; Dewey, 1982; Lake, 1985) and ductile accommodation of extension is confined to the sub-crustal lithosphere.

From analysis of the observed tectonic subsidence curves for the Yorkshire, Sole Pit and East Midland Basins in Appendix C4 and in illustrated examples in

sections 4.5.2. - 4.5.4., it is evident that, as a rule, they correlate very closely to the theoretical curves for the situation mentioned above. The majority of boreholes in these basins display what may be classified as a thermal or negative exponential subsidence similar to the uniform lithospheric stretching model. Thus, the overall, regional mechanism of basin formation seems to be consistent.

Nevertheless, problems still arise in that most researchers recognise that brittle accommodation of extension is confined to the upper crust (Montadert, 1979; Chen and Molnar, 1983; Chadwick, 1985a) where faults are observed to sole out. This represents the transition between brittle and ductile behaviour and is assumed to be at 15 km in the study area. Additionally, within the Yorkshire and Sole Pit Basins some major faults appear to sole out at a depth of 3.5 - 4km on weak Permian evaporite horizons. Clearly, brittle accommodation of extension will not be confined to the upper 4km but it may serve to compartmentalize it where these faults occur.

The two layer stretching model has been applied to the backstripped tectonic subsidence curves in the Yorkshire, Sole Pit and East Midland Basins. The model allows specification of the depth of decoupling, but the product of the stretching or the whole lithospheric stretching/extension is the same. Values for β or sub-crustal lithospheric stretching were chosen, for which tectonic subsidence curves and expected crustal extension or δ were computed. Some representative best fit curves are illustrated in figures 4.36, 4.37 and 4.38.

Figure 4.36 illustrates a selection of two layer stretching models for borehole Hunmanby 1 in the Yorkshire Basin. The excellent fit of the uniform stretching model (analogous to $\beta = \delta$ for two layer stretching) is in marked contrast to the curve for no sub-crustal involvement, $\beta = 1.0$. The form of the observed tectonic subsidence infers a component of thermal subsidence. Imparting a component of sub-crustal lithospheric involvement, $\beta = 1.1$, improves the correlation but

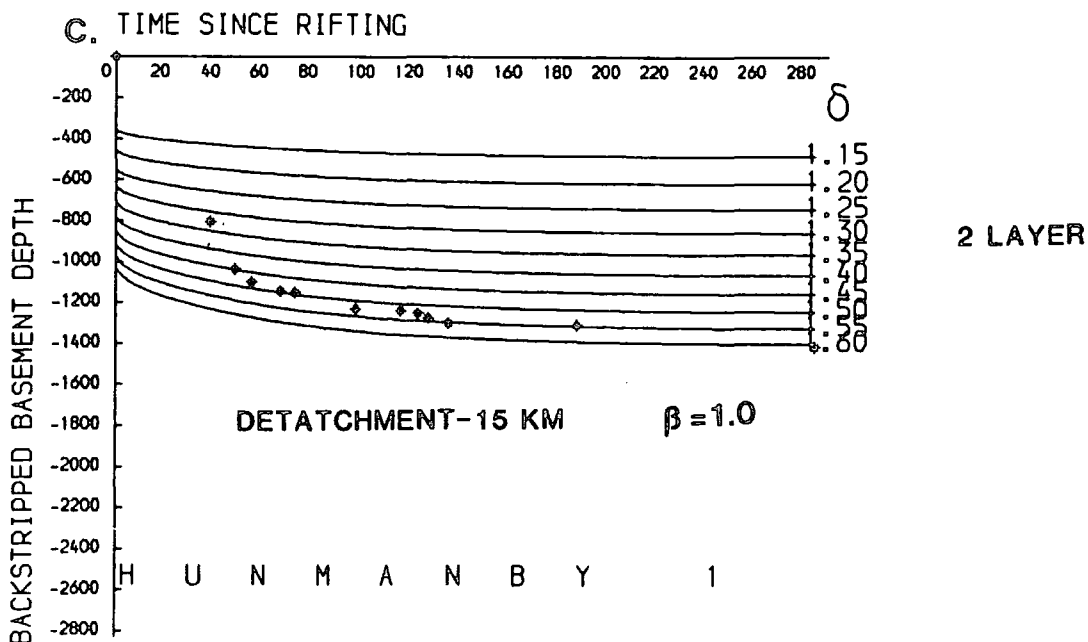
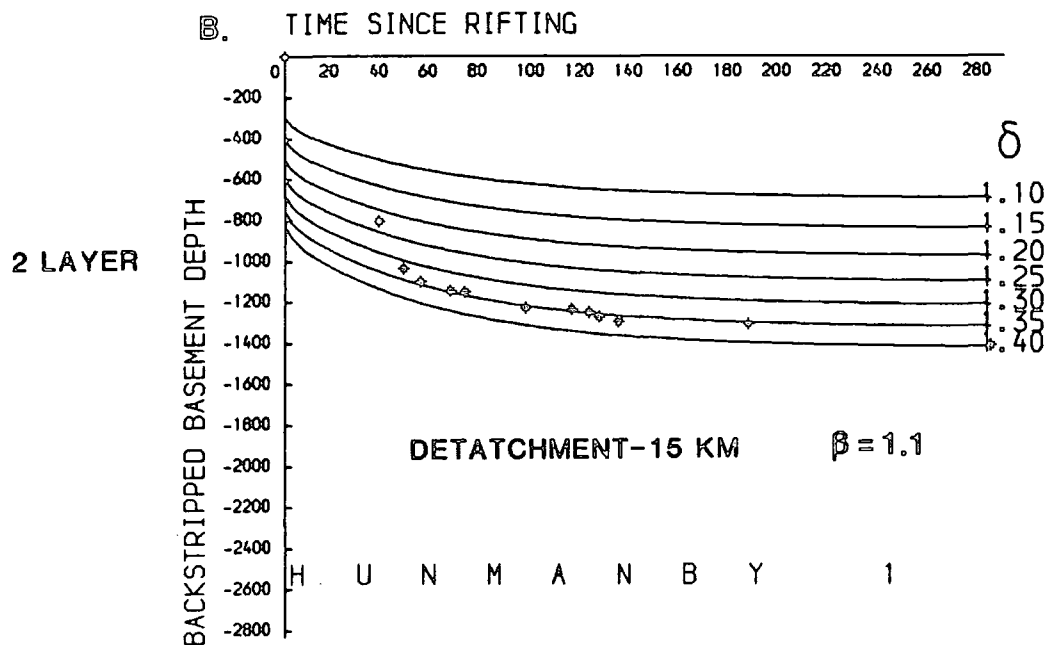
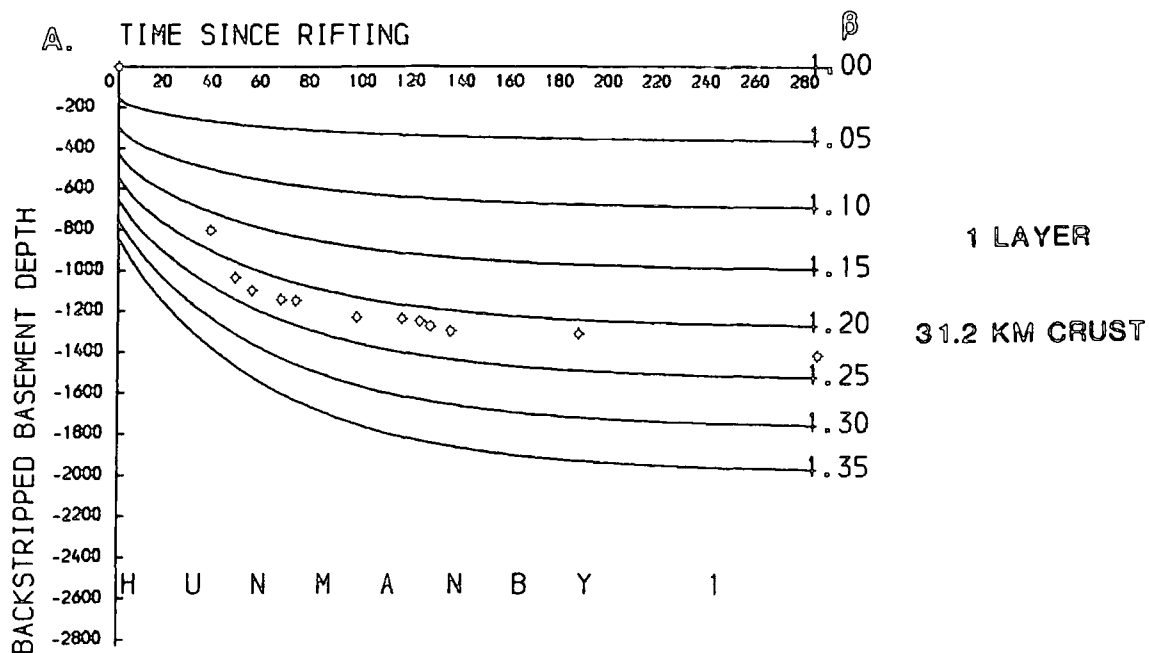


Figure 4.36. Correlation of 1 and 2 layer, uniform and non-uniform lithospheric stretching in the Yorkshire Basin.

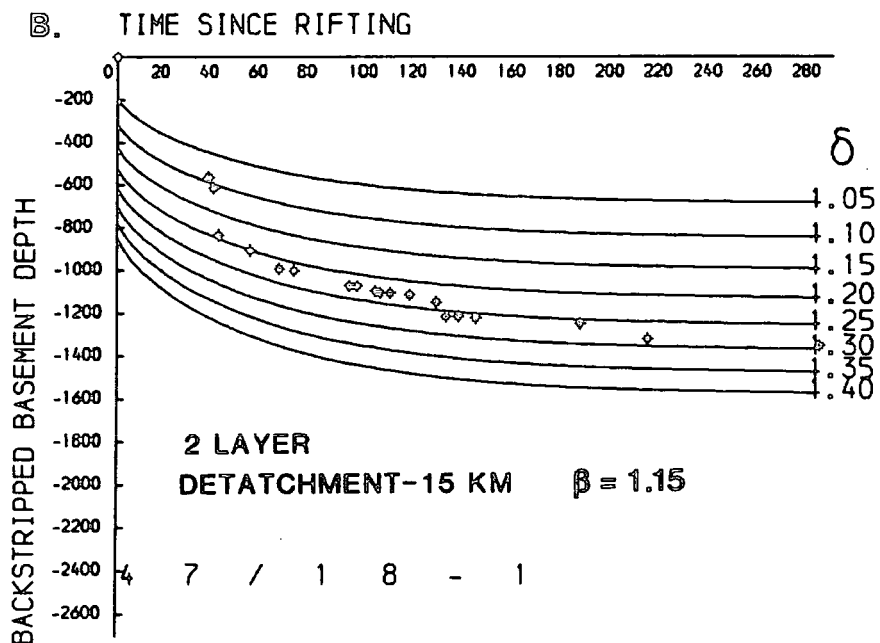
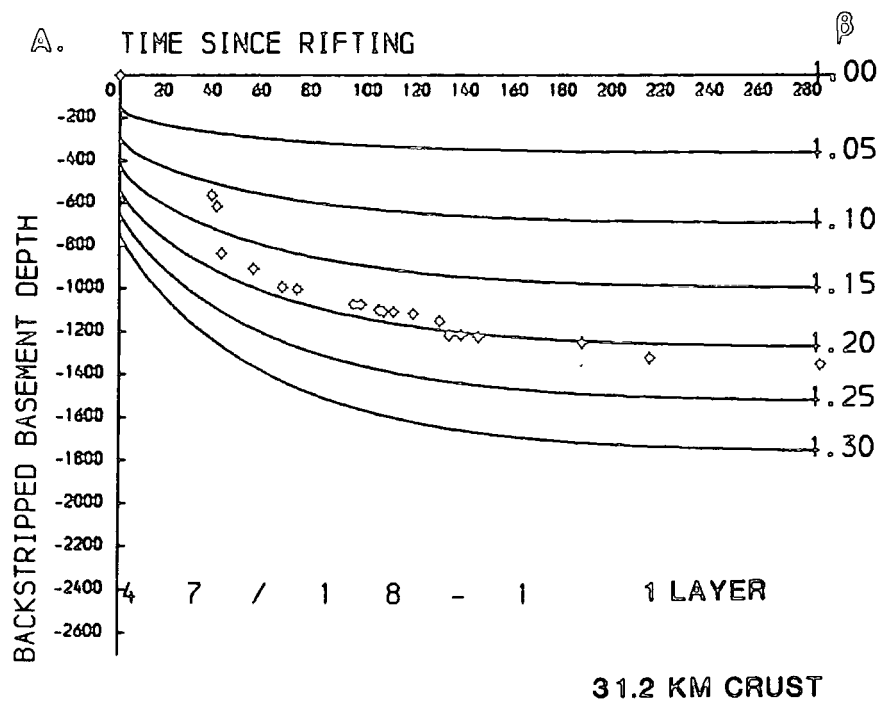


Figure 4.37. Correlation of 1 and 2 layer, uniform and non-uniform lithospheric stretching in the East Midland Basin.

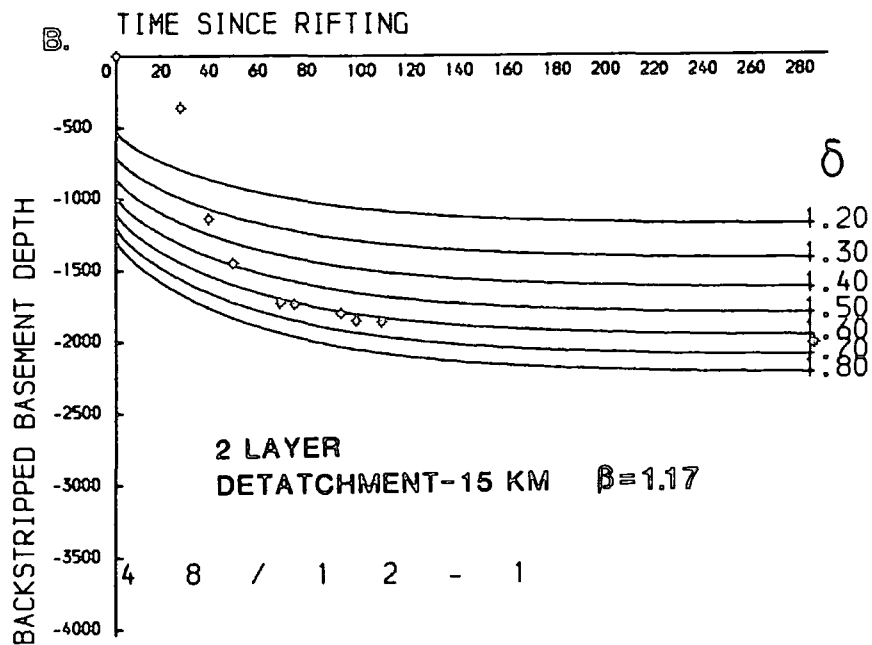
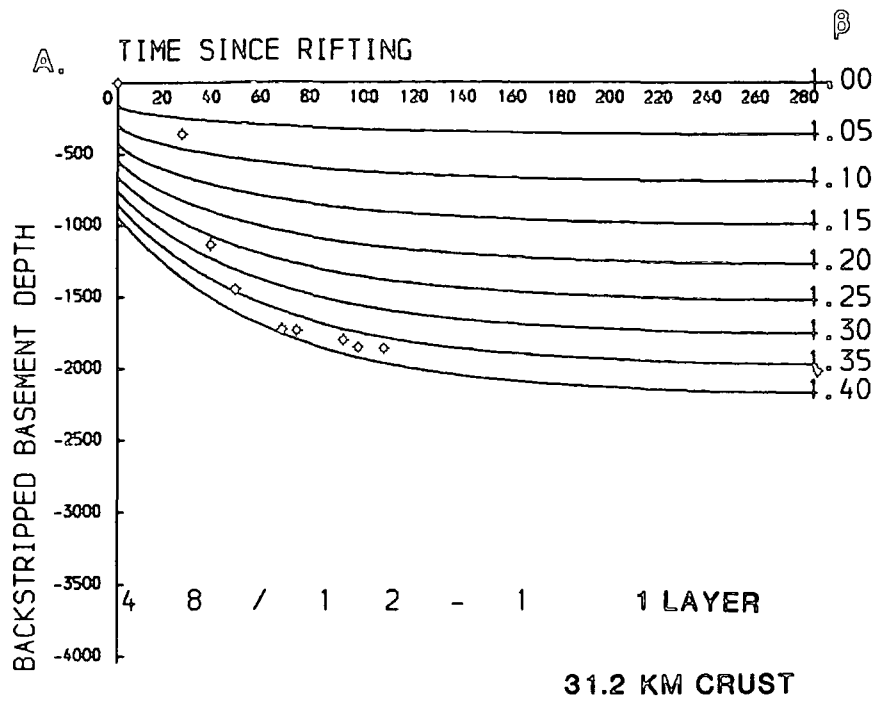


Figure 4.38. Correlation of 1 and 2 layer, uniform and non-uniform lithospheric stretching in the Sole Pit Basin.

not sufficiently to warrant recognition as the lithospheric conditions during basin formation. Continuous rearrangement of the starting conditions (β and depth to the lithospheric detachment) provides no better correlation of the observed and predicted forms of tectonic subsidence than the uniform stretching model.

Similar conditions apply to the East Midland and Sole Pit Basins (figures 4.37 and 4.38). The uniform lithospheric stretching model provides an excellent correlatory basis from which the components of subsidence during basin formation can be analysed. Interestingly, several tectonic subsidence curves in the Sole Pit Basin reveal quite good correlation to two layer stretching with a depth of 15 km to the crustal detachment (figure 4.38). The uniform stretching model is a good fit but assuming a significant component of sub-crustal lithospheric involvement ($\beta = 1.22$) gives an equally good fit, notably after initial Permo-Triassic subsidence. Upper crustal extension increases proportionally $\delta = 1.63$. This value greatly exceeds estimations of extension in the Southern North Sea Basin. However, this may be difficult to prove in the Sole Pit Basin by analysis of extensional fault offsets, since significant inversion and shortening may have reduced the maximum values reached.

Non-uniform two layer stretching does not reproduce a more accurate prediction of the components of observed tectonic subsidence. It facilitates the specification of preferential upper crustal, brittle accommodation of extension. Postulated wrench motion during formation of the Sole Pit Basin (Glennie and Boegner, 1981) may explain the prediction of preferential upper crustal extension, $\delta > \beta$, in some tectonic subsidence curves (figure 4.38).

All the variations on the models applied to the observed subsidence predict significant sub-crustal lithospheric stretching during formation of the Yorkshire, Sole Pit and East Midland Basins. This is analogous to results from other basins within the North Sea (Sclater and Christie, 1981; Wood, 1981; Wood and Barton,

1983; Leeder, 1983) but is in contrast to predictions from depth dependent studies in the Wessex Basin (Lake, 1985). The driving mechanism for basin formation (stretching) or how it is accommodated in specific locations must therefore vary.

The above discussion serves to outline the form of tectonic subsidence in the Yorkshire, Sole Pit and East Midland Basins and how by applying theoretical models for basin formation the postulated components of observed tectonic subsidence can be isolated. The following discussion aims to create a geological model for basin formation by applying the above theoretical approaches to the observed structural and sedimentological evolution of the Yorkshire, Sole Pit and East Midland Basins.

4.6 Geological Model for the Development of the Yorkshire, Sole Pit and East Midland Basins.

Uniform lithospheric stretching is accommodated by initial rapid or instantaneous, mechanical, fault controlled subsidence followed by regional, thermal, unfaulted subsidence in response to thermal re-equilibration and increasing flexural strength of the lithosphere (McKenzie, 1978). The model assumes initial Airy isostasy or zero flexural strength of the lithosphere such that basin formation by upper crustal brittle extension is locally compensated by sub-crustal stretching and upwelling of similar magnitude. This creates a thermally non-equilibrated lithosphere (figure 4.7).

The form of the backstripped tectonic subsidence in the Yorkshire, Sole Pit and East Midland Basins has been proved to closely resemble the predicted tectonic subsidence form for uniform lithospheric stretching (section 4.5 and Appendix C4). Initial rapid Permo-Triassic tectonic subsidence corresponds to a period of rifting in the North Sea and is followed by more gentle late Triassic to Cretaceous subsidence which closely matches predicted thermal subsidence curves

and partly coincides with postulated thermal subsidence in the Central Graben (Sclater and Christie, 1980). This is a characteristic feature of subsidence in the three basins apart from the basin margins, eg. Clare, Rocklands, Culford on the London Brabant Platform, which have a linear rather than exponential subsidence. This region was outside the zone of demonstrable lithospheric or crustal thinning and may represent a flexural subsidence form due to greater lithospheric strength outside the main rifted basins. The observed tectonic subsidence curves display a punctuated nature particularly through the Jurassic and Cretaceous. These small scale subsidence events and their relation to and interaction with the general regional subsidence, will be discussed below.

The observed subsidence curves consistently reveal that initial subsidence in the Lower Permian was not rapid or instantaneous but is subdued or even truncated. This implies a component of residual lithospheric strength or rigidity following Late Carboniferous compression and lithospheric shortening. Initial extension and subsidence may be partly consumed in areas of pre-Permian structural highs and by resetting the flexural strength of the lithosphere. After this initial period of subdued subsidence and readjustment, basement subsided rapidly (section 4.5).

The apparent uniform lithospheric stretching of the Yorkshire, Sole Pit and East Midland Basins implies that whole lithospheric failure occurred at the onset of rifting. In the Wessex Basin, Lake (1985) disqualified uniform lithospheric stretching despite apparent thermal tectonic subsidence curves within the depocentres, eg. Winterborne Kingston Trough. These are isolated occurrences in the Wessex Basin and the general form of tectonic subsidence is linear and truncates the theoretical trends. In addition to the apparently inconsistent subsidence mechanisms, the timing, duration and magnitude of the initial rifting event varies across the basin. Lake (1985) concluded that subsidence was accommodated by a number of finite rifting episodes involving negligible thermal subsidence. How-

ever, the fit of predicted depth dependent finite rifting tectonic subsidence curves to the observed tectonic subsidence in the Wessex Basin is not greatly improved.

These observations for the intra-continental Wessex Basin are anomalous to the subsidence modelled in the Yorkshire, Sole Pit and East Midland Basins suggesting that different mechanisms were responsible for basin formation between the two areas. Uniform lithospheric stretching assumes that the initial rift episode is a rapid, basin wide event, although it may be more significant within the basin centres or hangingwall sides of major upper crustal extensional faults. Thus, sub-crustal lithospheric involvement and hence thermal subsidence will be greater in the basin centres. Within the Yorkshire, Sole Pit and East Midland Basins the initial major subsidence event is rapid, synchronous and similar in form. It occurs in the Upper Permian to early Triassic (section 4.5 and Appendix C4). The Lower Triassic resembles the first major period of active normal faulting and coincides with the maximum sedimentation rates inferring that both basement subsidence and sedimentary loading were not severe at this time. The onset of rifting in the Central Graben is assumed to be at the start of the Triassic (Sclater and Christie, 1980). Modelling the tectonic subsidence curves assuming onset of rifting is at 248Ma reveals a close fit to both the initial mechanical and secondary thermal tectonic subsidence predicted by the uniform stretching model (figure 4.26 and Appendix C4). The regional estimation of lithospheric (upper and lower) stretching or extension, β , for a base Triassic rift time are illustrated in figure 4.39. This can be compared to figure 4.40, which represents regional β for a base Permian rift time (286 Ma). The duration of Upper Permian to early Triassic rifting is approximately 15 to 20Ma although the main Triassic episode lasts approximately 5Ma where precise chronstratigraphic boundaries are recorded (figures 4.22, 4.24, 4.25, 4.31, 4.33, 4.34, 4.35 and Appendix C4). This study suggests that this period represents the main rifting event in the initiation of the Yorkshire, Sole Pit and East Midland Basins. The thermal subsidence of this event is manifested

in the form of the tectonic subsidence curves but it is punctuated by local and basin wide events. Although the initial subsidence is rapid, because it is finite and not instantaneous this is postulated to represent a combination of inherent lithospheric flexural strength and early thermal subsidence which will affect the rift time (figure 4.20). Stretching factors, although quite significant, particularly in the Sole Pit and Yorkshire Basins (figure 4.39 and 4.40), are not great enough, ie. $\beta > 2$, to have significantly reset the flexural rigidity of the lithosphere and allowed perfect Airy or local isostatic compensation of subsidence (Kuznir and Karner, 1985).

The apparent lack of significant lithospheric strength during rifting will appear in the free-air or bouger gravity anomaly over such basins. Karner et al (1987), postulated that the positive free-air gravity anomaly of the Sole Pit Basin may reflect just such a mechanism for basin formation. This is a characteristic common to other basins of demonstrable sub-crustal lithospheric thinning, stretching and upwelling (Watts et al, 1982), eg. Central and Viking Grabens. The northern part of the Yorkshire Basin also has a positive bouger gravity signature (Kent, 1980b). These positive gravity anomalies coincide with the more inverted parts of the Yorkshire and Sole Pit Basins (figure 3.31) and hence may be created by lithospheric shortening and removal of low density sediments (figure 3.31). In the lesser inverted south of the Yorkshire Basin and East Midland Basin, gentle negative bouger anomalies are recorded. This does not preclude the possibility that sub-crustal lithospheric involvement was less significant than postulated by the tectonic subsidence curves. Such conditions may be dissipated by lithospheric re-equilibration, inversion and eg. flexural strengthening. Furthermore, demonstrable sub-crustal lithospheric thinning and mantle upwelling has been imaged from gravity and refraction data in the Central Graben of the North Sea (Barton and Wood, 1983; Leeder, 1983; Thomas, 1984). This is inferred to have influenced subsidence of the Central Graben since the Triassic. The magnitude of such sub-

crustal lithospheric stretching, which represents an approximation to McKenzie (1978) uniform stretching conditions, and its close proximity to the Yorkshire, Sole Pit and East Midland Basins infers that the thermal subsidence in the latter are influenced by such a mechanism. Deep profiling of the Moho topography in the study area is not available although studies in the Pennine area (Bott et al, 1985) suggest that it is insignificant. In southern England (Wessex Basin) a similar configuration is profiled (BIRPS and ECORS, 1986) and Lake (1985) postulated minor sub-crustal stretching.

The influence of heat and hence thermal subsidence during basin formation appears to be significant. Palaeogeothermal gradients during basin formation are therefore expected to have been accordingly high (figure 4.7). This may help to explain the discrepancies between estimations of maximum removed overburden from the Yorkshire Basin. Hemingway and Riddler (1982) from estimations of maximum palaeotemperatures believe this figure to be 2.5 km. Physical, compaction related changes in the sediments predict 1 - 1.5 km maximum (this study), which correlates with known stratigraphic variations (Kent, 1980b). This discrepancy may be accounted for by a raised geothermal gradient during basin formation and also raised temperatures associated with Tertiary volcanism in north-west Britain (Anderton et al, 1979).

The uniform stretching model predicts that stretching in the crust and sub-crustal lithosphere is equal, ie. $\delta = \beta$. β therefore represents the maximum upper crustal, brittle extension. The contoured, regional variation of β from the uniform lithospheric stretching model (Appendix C4) is illustrated in figure 4.40. β values generally mirror the main structural trends and increase across the major fault zones into the Yorkshire and Sole Pit Basins. Reduced β values (1 - 1.05) define the marginal London Brabant Platform to the south. β values also decrease westwards towards the Pennines suggesting the gradual encroachment of a former

basin margin.

If the uniform lithospheric stretching model is assumed to be representative of the basin formation mechanism in the study area, then the upper crustal extension, β , predicted in figure 4.40, should correlate with observed brittle extension of faults. However, a problem is that the present basin configuration has suffered a component of inversion, uplift and shortening. Basinal fault offsets may not represent the maximum mechanical extension since they have been reactivated in a reverse sense to accommodate compressional tectonics. Figure 4.41 is a line drawing of a seismic section. The figure comprises a cross-section through the offshore continuation of the Vale of Pickering Fault Zone. As will be illustrated in Chapter 5 and specified in figure 4.40, this set of extensional faults has not suffered a significant amount of shortening and mechanical reactivation. The faults have retained a significant component of their original extensional offset. Quantitative estimation of extension from fault offsets in the less inverted southern margin of the region predict approximately 15 - 20% ($\beta = 1.15 - 1.20$) extension. This figure is slightly smaller than the predicted extension for the area which is approximately 25% ($\beta = 1.25$). This may reflect the following:-

- (a) A component of shortening in the area = 5 - 10% (Chapter 5)
- (b) Not all faulted extension is accommodated for by the faults picked on in the section.
- (c) There may be a component of east - west orientated Permo-Triassic mechanical extension which would not be imaged in a north - south orientated section.

The observations and predictions of mechanical extension are however significantly close to warrant recognition of the postulated mechanism of basin formation.

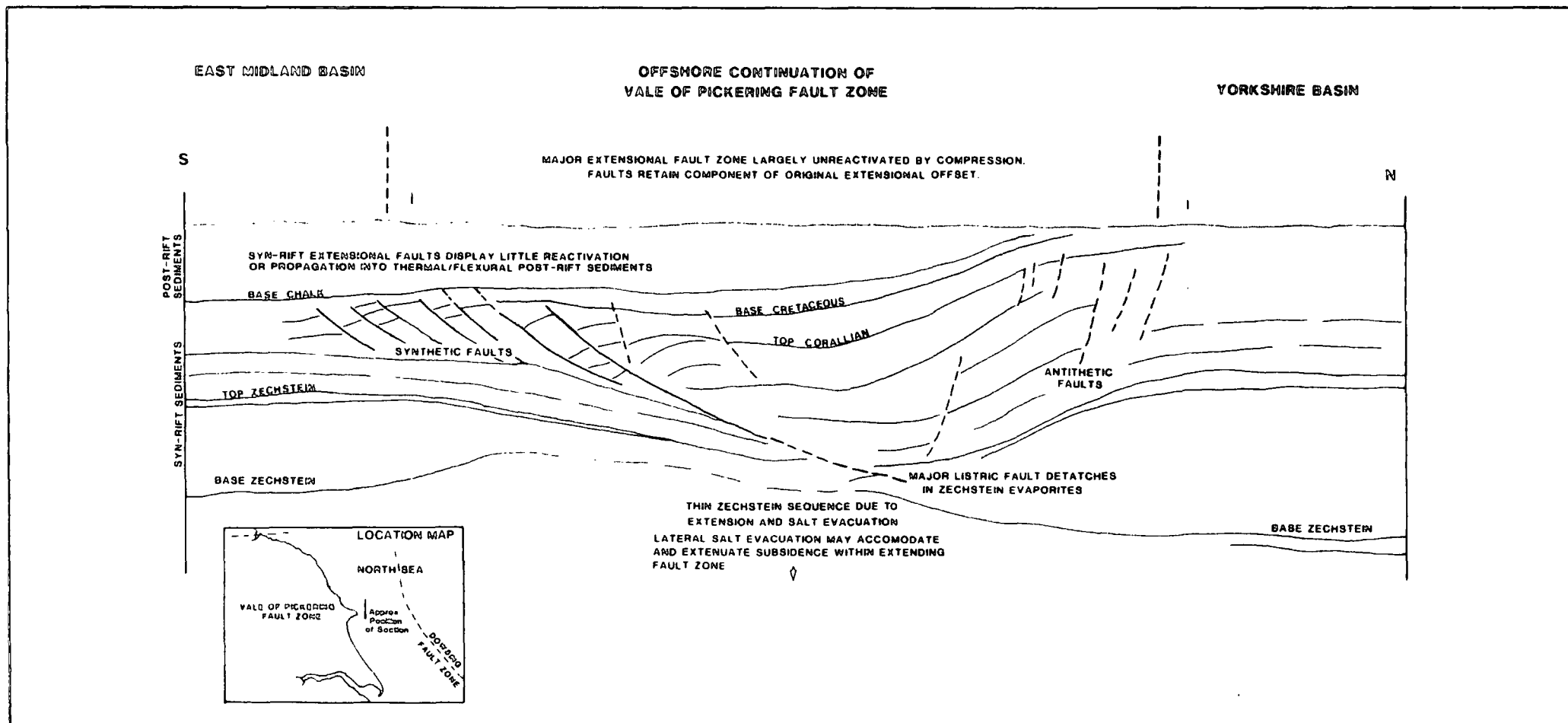


Figure 4.41. Seismic section (source-British Petroleum) across the southern less inverted margin of the Yorkshire Basin. Reveals some of the structural controls on and relationships between syn-rift and post-rift subsidence and sedimentation.

McKenzie (1978) developed the uniform stretching model to explain the common observation that subsidence and sedimentation within basins often occurs initially within a faulted graben system followed by regional overlap of the original graben system, during unfaulted subsidence. These two phases correspond to mechanical and thermal subsidence. Sediments deposited within the basin are termed syn-rift and post-rift sediments respectively. The result is the formation of the classic steer's head form of subsidence (figure 4.9). This model has been shown to correspond to the distribution of subsidence and sedimentation in the Central North Sea (Sclater and Christie, 1980; Barton and Wood, 1984; Thomas, 1984).

Figure 4.42 illustrates the structural and sedimentological configuration across the southern and northern margins of the Yorkshire and Sole Pit Basins respectively, and the intervening Market Weighton Block or Axis which formed a margin to these two basins during the Jurassic to Lower Cretaceous. The north - south profile (figure 4.43) is parallel and analogous to the structural cross-section offshore (figure 4.41). It is evident from figures 4.41, 4.42 and 4.43 that Jurassic to Lower Cretaceous basin initiation, mechanical faulting, syn-rift type sedimentation and offlap due to graben infilling was followed by regional, unfaulted Upper Cretaceous post-rift type sedimentation and onlap and overlap of the syn-rift sediments and basin margins respectively. Inversion to the north has curtailed subsidence and removed both syn- and post-rift sediments from the Yorkshire Basin. However, the general similarities between the predicted and observed sedimentological configurations are clear.

4.7 Summary and Conclusions.

The thermal and mechanical evolution of the Yorkshire, Sole Pit and East Midland Basins has been analysed by isolating the tectonic driving subsidence and comparing it to theoretically derived models for basin formation. Basin formation

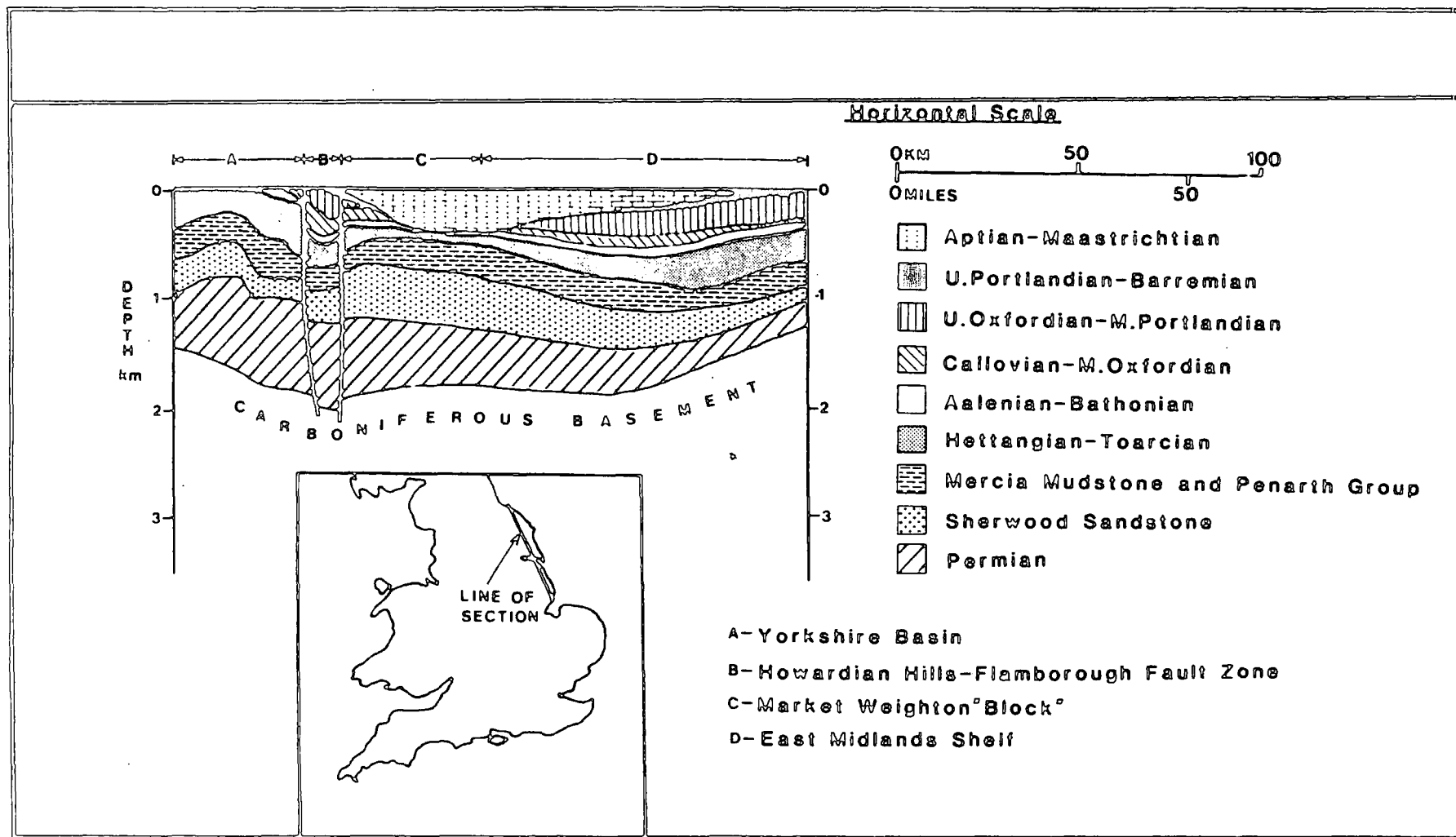


Figure 4.43. Simplified cross-section of the Yorkshire and East Midland Basins. Inversion has removed much of the post-rift Upper Cretaceous sediments from the Yorkshire Basin but onlap over the basin margins is preserved.

is assumed to be initiated and propagated by lithospheric stretching. The form of the driving tectonic subsidence (backstripped subsidence) is a measure of the degree of crustal and sub-crustal lithospheric involvement.

1. The driving tectonic subsidence has been isolated by backstripping the basement and removing the load due to sediments.
2. Significant basin inversion of the Yorkshire and Sole Pit Basins has removed variable amounts of the original sedimentary sequence. The present day depth to the basement does not represent the maximum depth to basement.
3. Inversion, uplift and removal of sediment will offset the variation of porosity and hence density of the sediments with depth.
4. To accurately reconstruct the driving tectonic subsidence requires the maximum load on the basement to be removed. Thus, the pre-inversion depth to basement must be calculated and the porosity/density trend reset.
5. The above has been achieved by utilising the observed and predicted porosity (compaction) trends to calculate the amount of removed sediment. Thus, the maximum depth to basement is calculated and the porosity/density curve reset by the same method.
6. The tectonic subsidence in the basins assumes a typically negative exponential form characteristic of the uniform stretching model.
7. The good agreement between observations and predictions fortify the above statement.
8. The onset of rifting is a synchronous and rapid basin wide event. Its magnitude is comparable across the basins. This confirms the importance of wholesale lithospheric involvement during rifting, ie. $\beta = \delta$.

9. Inclusion of a finite strength lithosphere will explain the non-instantaneous but rapid initial subsidence.
10. Predicted stretching factors are insufficient to theoretically reset the flexural rigidity and create Airy isostatic conditions, ie. $\beta < 2$. However, rapid basin wide initial subsidence does infer thermal subsidence and appreciable sub-crustal involvement.
11. Predicted crustal extension (β) accords with observed extension from fault geometries.
12. The observed distribution of sediments accords with the characteristic steer's head geometry of uniform lithospheric stretching.
13. Crustal stretching factors increase into the basin centres over the hangingwall of major faults. This infers some local mechanical fault control on basin subsidence.
14. The tectonic subsidence curve comprises of one major initial subsidence event followed by a number of smaller subsidence events which punctuate the thermal subsidence curve. These may be local tectonic events or cyclic changes in load such as eustatic sea-level variations.
15. Initial Permo-Triassic rifting and extension is orientated east - west. NW - SE Dowsing Fault Zone accommodates extension. N - S faults in the Yorkshire Basin may reflect the manifestation of older structures in younger Jurassic sediments.
16. Permo-Triassic subsidence is rapid but apparently not confined to individual sub-basins or grabens. Preferential mechanical accommodation of extension, ie. depth dependent, non-uniform stretching, is expected to create varying types and amounts of subsidence within a graben system, eg. Wessex Basin

- (Lake, 1985). Non-uniform lithospheric stretching is not a satisfactory mechanism for initiation of the Yorkshire, Sole Pit and East Midland Basins.
17. The Jurassic to Cretaceous includes a number of subsidence events which occur regionally but vary locally in magnitude (section 4.5).
 18. Lower Jurassic subsidence event is more pronounced in the Yorkshire and Sole Pit Basins, but is also recorded in the East Midland Basin. A general increase in eustatic sea-level in the Lower Jurassic is coincident with extensional, differential subsidence in the Yorkshire and Sole Pit Basins. The local tectonic control will mask regional or global changes which are not of particularly strong magnitude in the Lower Jurassic (Vail et al, 1977).
 19. Middle Jurassic subsidence is particularly pronounced in the Yorkshire Basin. The East Midland Basin subsided more gently and inversion has removed most occurrences of Middle Jurassic sediments from the Sole Pit Basin. Middle Jurassic rifting occurred in the Central North Sea. Alexander (1986) has recognised the influence of major fault control over subsidence and sedimentation during the Middle Jurassic, eg. Peak Fault. Small scale syn-sedimentary growth faulting is also recorded in the Yorkshire Basin at this time (figure 4.44). The Middle Jurassic subsidence event appears to be controlled in the upper crust by extensional, brittle faulting. This subsidence event is superimposed on the general background thermal subsidence curve. It is recorded that sub-crustal involvement was significant during Central North Sea rifting at this time (Barton and Wood, 1983)
 20. In the late Middle Jurassic (173 Ma) the relative motion of Africa to Europe created a north - south extensional stress system. This lasted until the end of the Lower Cretaceous. During this time, the east - west orientated Vale of Pickering Fault Zone displays significant control on sedimentation (Swallow

and Kirkby, 1987).

21. The Upper Jurassic (Kimmeridgian) is another subsidence event recognised by the tectonic subsidence. It is most strongly portrayed within the Vale of Pickering Fault Zone. This supports evidence for a period of mechanical extension preferentially accommodated within, or by, suitably orientated fault systems (as discussed in 20. above).
22. These Jurassic subsidence events represent local extensional tectonic episodes. They may in turn impart an additional component of thermal subsidence, eg. Middle Jurassic.
23. Upper Cretaceous tectonic subsidence represents continued thermal relaxation subsidence after Permo-Triassic rifting. North - south orientated extension had ceased and unfaulted regional, thermal subsidence occurred. Basin margins were overlapped.
24. The Upper Cretaceous coincides with a major eustatic sea-level rise. This will exaggerate the effects of thermal subsidence due to a regional increase in load on a flexurally strengthening lithosphere.
25. Thermal subsidence continues in the Central North Sea during the Tertiary.
26. Subsidence in the Yorkshire, Sole Pit and East Midland Basins is terminated in the Late Cretaceous due to the creation of North - south compression (Livermore and Smith, 1986). This caused sub-Hercynian - Laramide (Ziegler, 1978) inversion and basement uplift of the Yorkshire and Sole Pit Basins by compressive reactivation of major faults..

CHAPTER 5

INVERSION OF THE YORKSHIRE, SOLE PIT AND EAST MIDLAND BASINS

5.1 Introduction.

The destruction or partial destruction of former basinal areas is an increasingly studied phenomenon as geologists' appreciation and understanding of local and regional crustal and lithospheric deformation increases. Its affects are recorded in a number of studies from wholesale foreland basin inversion, as in many basins in north-west Europe, to local or small scale deformation associated with accomodation of stresses along individual faults and their subsequent reactivation (Chapple, 1978; Dewey, 1982; Gillchrist et al, 1987; Lake and Karner, 1987; Ziegler, 1987).

It has been recognised that the Yorkshire, Sole Pit and East Midland Basins have suffered various amounts of destruction (Kent, 1980a, 1980b; Glennie and Boegner, 1981; Hemingway and Riddler, 1982; Van Hoorn, 1987). The deformation associated with this destructive episode has been quantified in Chapter 3 as a finite amount of basement uplift which has caused the removal of a proportional amount of overlying basin fill. The severity of the basement uplift is a measure of the degree of destruction of the former basin.

In Chapter 3 this basement uplift has been objectively quantified in an attempt to recreate the original sedimentary thickness, and hence load, for evaluation of basin formation mechanisms (Chapter 4). The causes of the uplift have only briefly been speculated upon. The results from Chapter 3 refer to the deformation as uplift or sediment removed. It is evident from these results (figure 3.32) that the deformation causing this uplift has been preferentially accommodated within the basinal areas, particularly on the hangingwall of the major basinal faults. It

is thus assumed in this Chapter that the dominant component of the basement uplift recognised in the study area is due to positive inversion or the conversion of a former structural low (basin) into a structural high (Harding, 1985). Where uplift is referred to, it is in the context of basement uplift associated with inversion and therefore basin destruction.

It is the objective of this chapter to qualitatively and quantitatively identify the deformation associated with inversion of the Yorkshire, Sole Pit and East Midland Basins. Basin inversion, manifested partly by basement uplift and sediment removal, is primarily a response to lateral lithospheric stresses (Dewey, *op. cit.*). Two major periods of lithospheric compression and basin inversion are recognised in the study area; one in the late Carboniferous or Variscan, and a younger event in the late Cretaceous to Tertiary (Sub-Hercynian to Laramide - Ziegler, 1978). The general effects of the earlier event will be briefly discussed in this introduction, and have been cited in Chapter 3 and Chapter 4. This study is, however, primarily concerned with the younger tectonic event which is partly quantified and identified in Chapter 3.

Basin inversion can be recognised and studied in a number of ways, from which its nature or form, and magnitude may be elucidated. As in basin formation the mechanisms of basin inversion may be controlled by both the mechanical and thermal, or brittle and ductile, deformation of the lithosphere. The theory behind the expected forms of inversion is outlined to put into context the following study of the observed inversion of the Yorkshire, Sole Pit and East Midland Basins.

The vertical and lateral or horizontal deformations inflicted by compression within the study area are subsequently modelled using stratigraphic data, as in Chapter 4. These deformations are manifested in the total basement uplift, the tectonic basement uplift, and lithospheric and crustal shortening or thickening. These components are quantified and qualitatively assessed with respect to the

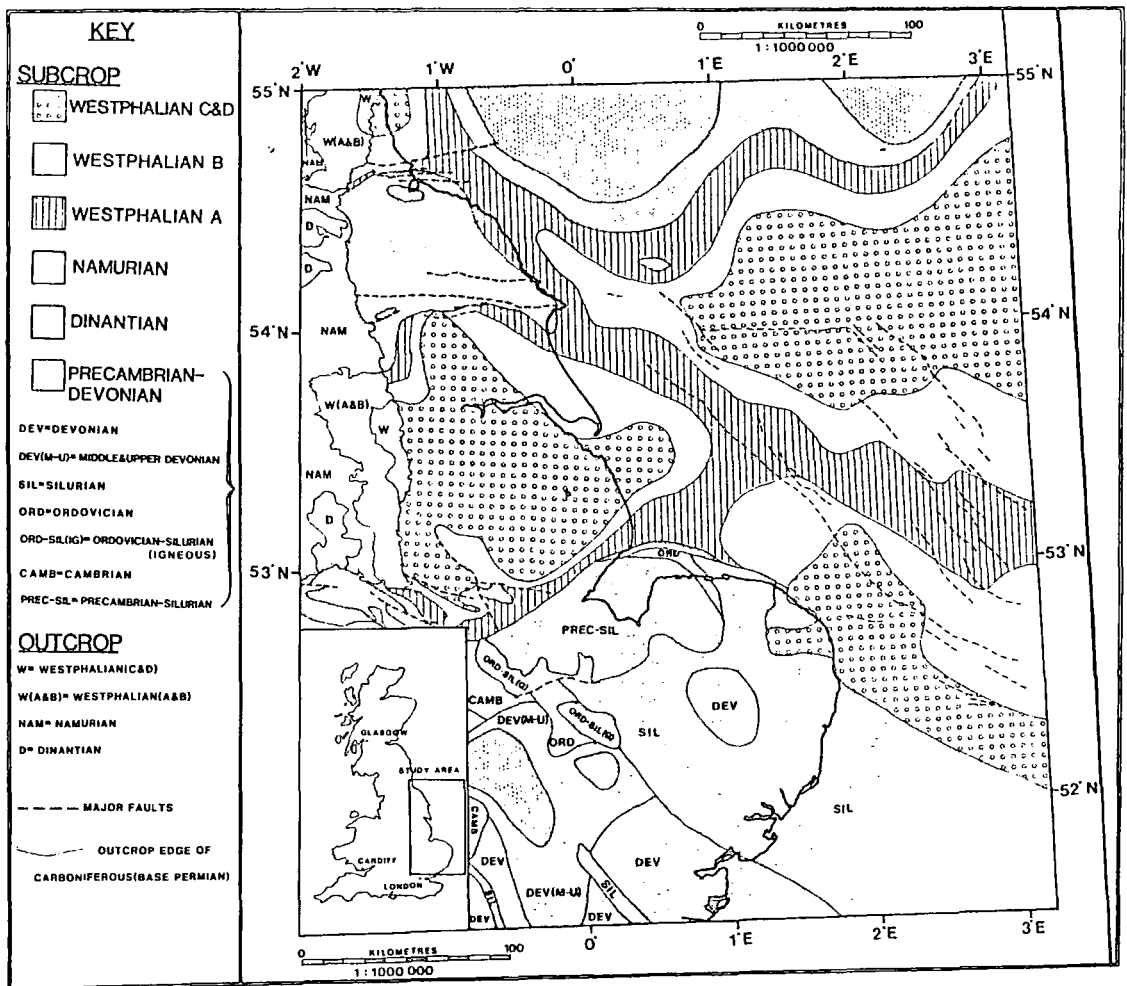


Figure 5.1. Regional distribution of Carboniferous sediments in the study area reflects late Carboniferous (Variscan) differential basin inversion. Carboniferous inversion appears to be restricted to similar structural areas as the later Mesozoic basin inversion, quantified in Chapter 3 (figure 3.31).

structural style and evolution of the study area. The results are supplemented by analysis of field data as evidence for local, brittle structural deformation and accommodation of inversion. Finally these results, and those from lineament analysis of satellite imagery in Chapter 2, are integrated to assess the regional stress regime in operation during inversion.

5.2. Overview of Inversion in the Yorkshire, Sole Pit and East Midland Basins.

Prior to the initiation of the late Palaeozoic to Mesozoic Yorkshire, Sole Pit and East Midland Basins, compression in the late Carboniferous associated with the Variscan Orogeny, caused the inversion of many contemporary basins by re-activation of former extensional faults as thrust, reverse or strike-slip faults. Bordering the study area a number of such basins (figure 5.1) were affected by this approximately north - south orientated compression eg. Craven Basin, Stainmore Trough (Anderton et al, 1979; Arthurton, 1983; Underhill et al, 1988). Deep borehole data and facies analysis (Versey, 1948, Brunstrom, 1962; Kent, 1980a and 1980b) suggests that similar Carboniferous basins exist beneath the present Yorkshire, Sole Pit and East Midland Basins (figures 5.1 and 5.2). For example, the ages and distribution of the subcropping Carboniferous sediments (figure 5.1) illustrate that beneath the younger inverted Yorkshire Basin lies an older inverted basin. Westphalian sediments are absent and Namurian and Dinantian sediments (Lower and Middle Carboniferous respectively) subcrop in an area defined by the same or similar structural trends as manifested in the younger Permian to Cretaceous basin (figures 5.1 and 5.2).

Similar conclusions can be made about the Sole Pit Basin area, although the Carboniferous inversion appears to be slightly offset from the younger limits of inversion, defined by the Dowsing Fault Zone (figures 5.1 and 5.2, Kent, op. cit. , Glennie and Boegner, op. cit.). The East Midland Basin was an area of relatively

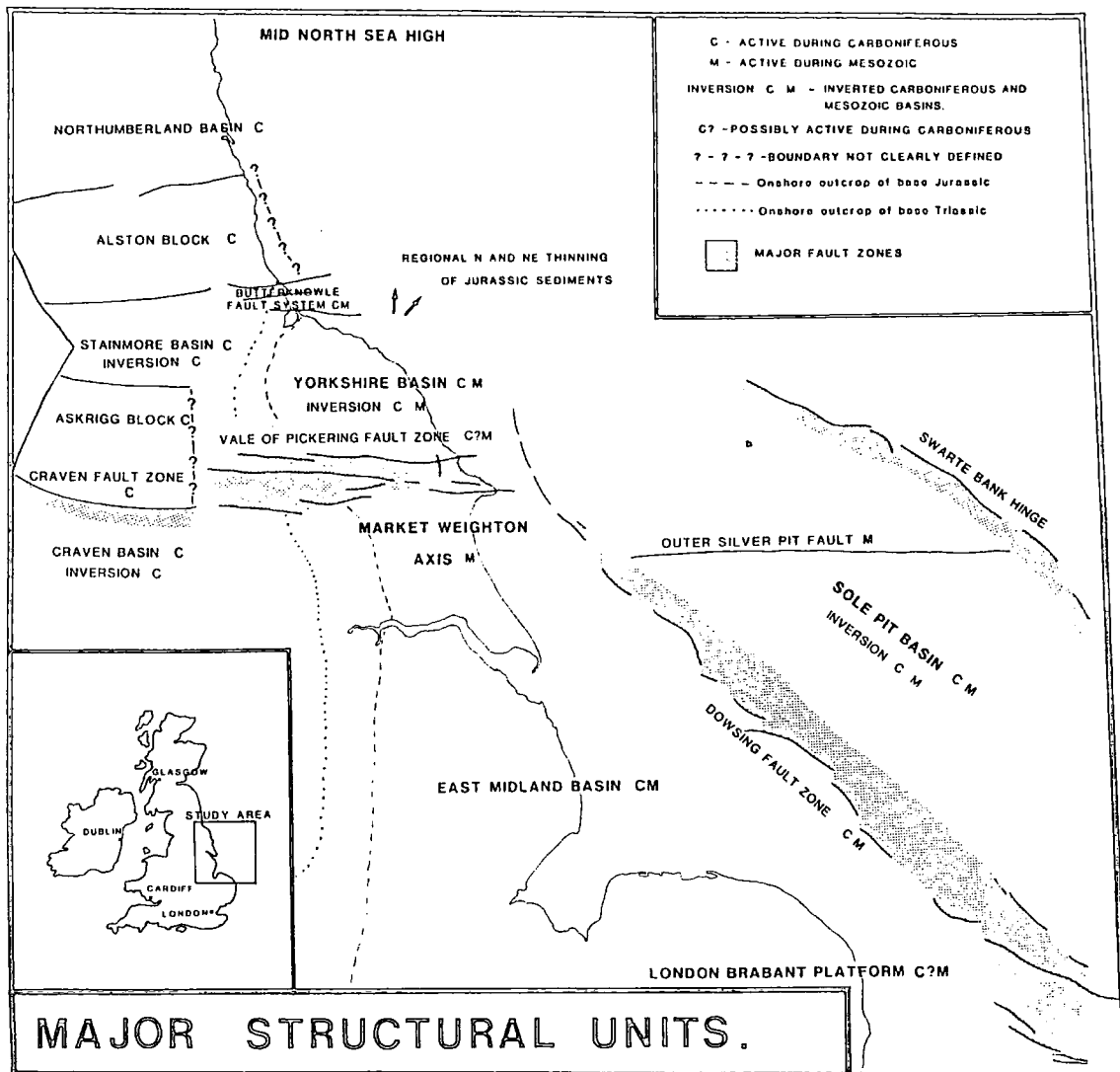


Figure 5.2. The evolution and influence of the major structural units in the Yorkshire, Sole Pit and East Midland Basins. The history of structurally superimposed basins and inversion axes highlights the influence of major basement structures in time. These structures are continuously reactivated to accommodate the specific tectonic stresses being applied regionally to the area.

less intense subsidence and inversion in the Carboniferous. This is analogous to its post-Carboniferous evolution (Chapters 3, 4, 5, and 6, this study, and Kent *op. cit.*).

Thus, the different constituents of the study area appear to have responded to extension and compression in similar forms and relative magnitudes in time. The super-position of basins and inversion highs reflects some over-riding basement control on the tectonic evolution of the area.

The phenomenon of fault reactivation is an important process by which tensional and compressional stress is accommodated in the crust and lithosphere since less work is required to reactivate a pre-existing fracture or weakness than create a new one. This may not always be the case, particularly in areas more proximal to the deformation front, eg. thrust sheets in the Alps (Butler, 1983 and 1985). In the south of England, major lithospheric detachments are suggested to propagate through the crust and control the evolution of the Wessex Basin (Chadwick *et al*, 1983; Brooks *et al*, 1984; Whittaker and Chadwick, 1984; Lake, 1985). The main faults or fault zones in the Yorkshire, Sole Pit and East Midland Basins, eg. Dowsing, Vale of Pickering, Hartlepool-Butterknowle and Swarte Bank Fault Zones, that control the late Palaeozoic to Mesozoic basin evolution, have developed in the basin fill above older, intrinsic basement structures (figures 5.1 and 5.2). However, they do not appear to link directly to the basement faults, but rather sole out on Permian or Triassic evaporite horizons (Chapter 4-figure 4.42, later in this chapter, figure 5.22, and Van Hoorn, 1987). In the north of the Yorkshire Basin, the Butterknowle Fault, which controlled Carboniferous basin formation and inversion (Smith and Francis, 1967), is the only definite onshore link between structures in the older and younger basins. Deep structural evidence for crustal and lithospheric detachments, like those in southern England, is not available. Hence, the manner by which the high level crustal faults in the York-

shire, Sole Pit and East Midland Basins are the manifestation of deeper structures is purely speculative.

Late Cretaceous to early Tertiary inversion due to a change from lithospheric tension to compression (Livermore and Smith, 1986), caused regional and differential basement uplift and partial destruction of the Yorkshire, Sole Pit and East Midland Basins. The main component of the inversion (figure 3.33) was restricted to the hangingwall or basinal sides of the major fault zones discussed above.

The following discussion focuses attention on the quantitative and qualitative nature of the last major inversion or uplift event in the Upper Cretaceous-Tertiary, and its regressive effects on the basinal development studied in Chapter 4.

5.3 Inversion Theory.

5.3.1. Introduction.

In Chapter 3, the partial destruction of the Yorkshire, Sole Pit and East Midland Basins was been referred to as being due to basement uplift which caused the removal of a proportional amount of overburden. The mechanism by which this uplift occurred and the manner in which it was accommodated by the structures in each basin has largely been ignored. However, the regional pattern of uplift has been identified and quantified (Chapter 3). This is utilised in a study of the thermal and mechanical evolution of the region during basin formation (Chapter 4).

Inversion is a term which is used to describe a reversal in the vertical sense of movement of, for example, a basinal area, that may occur during or after subsidence or may terminate the subsidence itself (Dewey, 1982; Lake and Karner, 1985; Kent, 1980a; Chadwick, 1985a, 1985b; Jackson, 1980; Stoneley, 1982; Etheridge, 1986). Harding (1985) defines two inversion types, namely, positive and negative

inversion, which are distinguished by the relative change in structural relief that occurs. Positive inversion involves the conversion of the basin into a structural high. Negative inversion, a lesser documented occurrence, involves conversion of a structural high into a structural low (basin). Thus, positive inversion is a mechanism by which a former basin is destroyed and hence, it can be applied to the tectonic evolution of the study area. This chapter, therefore, concentrates on the causes and consequences of positive inversion and the manner in which it is accommodated within, and between, the Yorkshire, Sole Pit and East Midland Basins.

5.3.2. Mechanisms of Inversion and Uplift.

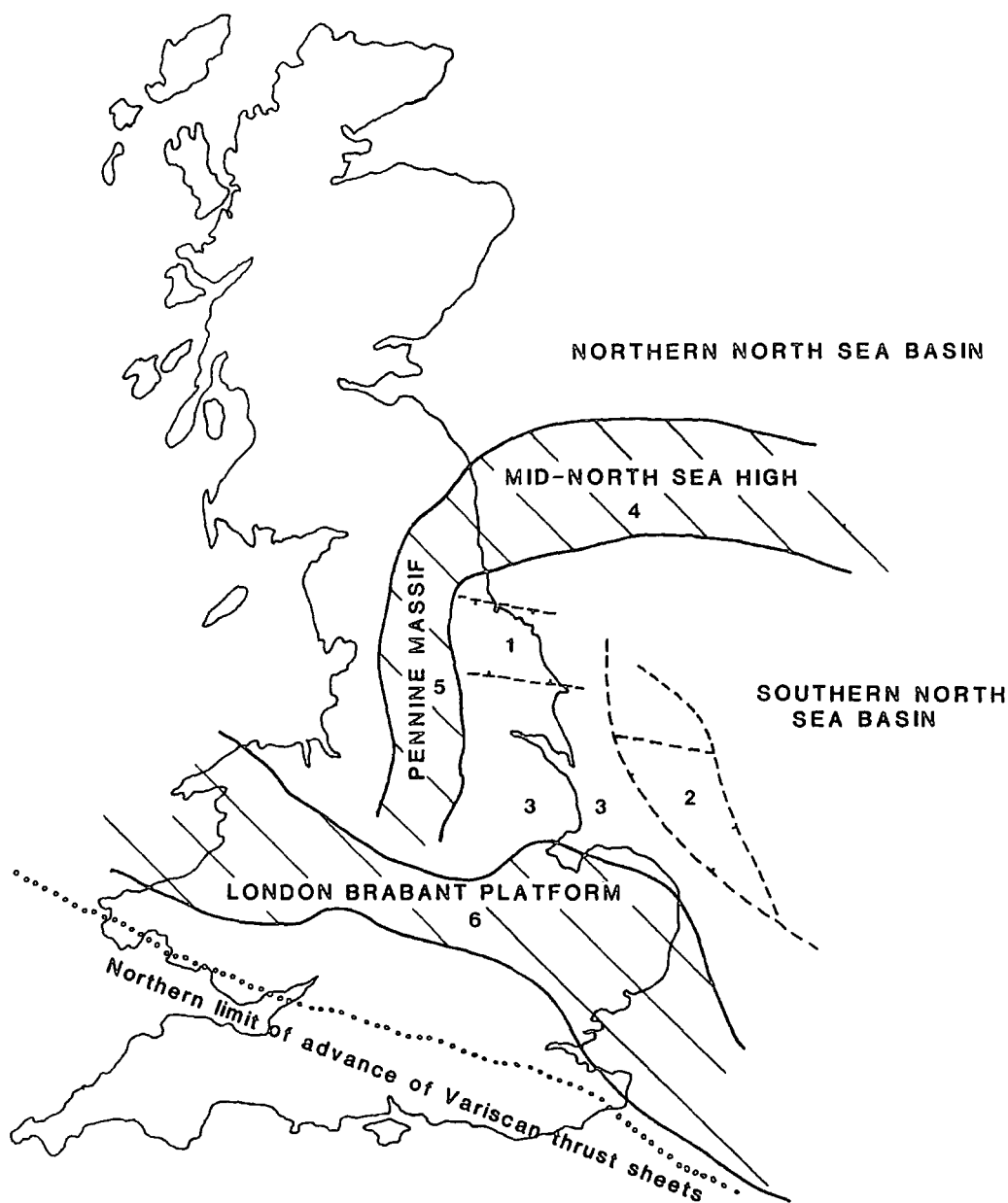
The uplift or positive inversion that is recognised in the Yorkshire, Sole Pit and East Midland Basins in this study and others (Kent, 1974; Glennie and Boegner, 1981; Marie, 1975; Hemingway and Riddler, 1982; Jeans, 1973; Neale, 1974) might be attributed to a number of causal processes. These include:-

1. Diapiric uplift.
2. Flexural uplift.
3. Isostatic uplift due to upper crustal and sub-crustal lithospheric extension and thinning.
4. Reactivation of pre-existing extensional structures under lateral compressive stress.

Each of these processes could cause the uplift or positive inversion of a previously subsiding area. Diapirism in the thick Zechstein evaporite deposits of the Permian Southern North Sea Basin which encloses the Yorkshire, Sole Pit and East Midland Basins, is a well documented occurrence (Glennie and Boegner, 1981; Jenyon, 1984; Jenyon et al, 1984;). Its contribution to uplift in the study

area has been accounted for in Chapter 3. Its effects are localised, eg. diapiric walls coinciding with the Outer Silver Pit Fault (figure 5.1), and it is not a process which is regarded as having significant influence on the regional uplift or inversion that is recognised in the study area (figures 3.33 and 5.10). Additionally, the regional uplift, particularly in the Yorkshire and Sole Pit Basins, does not have to be explained by diapiric uplift because the contemporaneous inversion of basins within the north-west Europe (Ziegler, 1987) has affected basins both with and without major evaporite deposits, eg. Yorkshire and Sole Pit Basins, and Weald Basin respectively. It is this basement uplift and the corresponding release in isostatic pressure associated with removal of overburden, which may have initiated some of the diapiric bodies found in the study area. In general, diapirs are found in these more inverted areas which were originally subject to greater subsidence and sedimentation, and hence have been affected by the greatest changes in pressure.

Flexure undoubtedly has an influence on uplift, particularly of basin margins due to the effect of sediment loading and increasing lithospheric flexural strength during rifting and basin formation (Thomas, 1984; Lake, 1985; Watts et al, 1982; Steckler and Watts, 1978; Bodine et al, 1981). The interaction between loading and lithospheric strength may be represented in the subsidence patterns observed within a basin (Chapter 4). Therefore flexure does not necessarily result in any basement uplift or positive basin inversion. Typically, uplift caused by flexure is of large wavelength (hundreds of kilometers). Their effects may be seen on the margins of large scale subsiding areas, eg. whole of the Southern North Sea Basin, and not necessarily on the margins of smaller sub-basins within a large subsiding area. The Mid-North Sea High and Pennine Massifs to the north and west of the study area may represent the flexurally uplifted margins of the Southern North Sea Basin as a whole. Also, the London Brabant Platform uplift may represent an interference pattern of flexural uplift due to sediment loading in the Southern North Sea Basin to the north, and Variscan thrust sheet loading to the south



- 1 - YORKSHIRE BASIN
- 2 - SOLE PIT BASIN
- 3 - EAST MIDLAND BASIN

- 1 and 2 - Differential fault controlled subsidence and major inversion axes.
- 3 - Unfaulted, thermal/flexural subsidence possibly in response to loading in major basins, 1 and 2. More pronounced westwards and southwards towards flexural margins. Largely un-inverted.
- 4, 5 and 6 - Flexurally uplifted margins of Southern North Sea Basin from Permian to Cretaceous

Figure 5.3. Location of flexurally uplifted areas marginal to the Yorkshire, Sole Pit and East Midland Basins.

(Karner et al, 1987). These relationships are illustrated in figure 5.3. Flexure has played an important part in the nature of subsidence and in defining the basin margins (figure 5.3), but it is evident that the Mid-North Sea High, Pennine Massif and London Brabant Platform were not areas undergoing subsidence from Permian to Cretaceous (Ziegler, 1978, 1982). Theoretically, their relative uplift does not represent positive inversion. Therefore, positive inversion seen in the Yorkshire and Sole Pit Basins is unlikely to represent the effects of localised flexural uplift in the study area.

Similarly, although lithospheric thinning undoubtedly occurred (Chapter 4) and may have caused localised and regional isostatic uplift within the basins (Leeder, 1983), these events occurred during rifting, subsidence and basin formation. They may be represented by unconformities within the sedimentary sequence but are subsequently overprinted by subsidence and sedimentation during both mechanical and thermal/flexural subsidence. This makes the quantification of these events very difficult (Chapter 3, section 3.6.4). Furthermore, positive inversion in the study area is demonstrated to have either caused the cessation of subsidence or occurred after subsidence had largely finished. Thus, lithospheric thinning and associated crustal uplift is not considered to be the cause of the regional but compartmentalised Upper Cretaceous-Tertiary uplift and inversion that has partially destroyed the Yorkshire, Sole Pit and East Midland Basins.

Positive inversion of the Yorkshire, Sole Pit and East Midland Basins is considered in the context of reactivation of pre-existing extensional structures under a compressive stress regime. The major inversion and uplift in the study area began in the Upper Cretaceous (Glennie and Boegner, 1981; Van Hoorn, 1987; Walker and Cooper, in press) in response to major plate tectonic movements marking the onset of the Alpine or Laramide compressive event and associated deformation within the Alps proper and in the Alpine foreland (Gillchrist, 1987). Figure 5.4

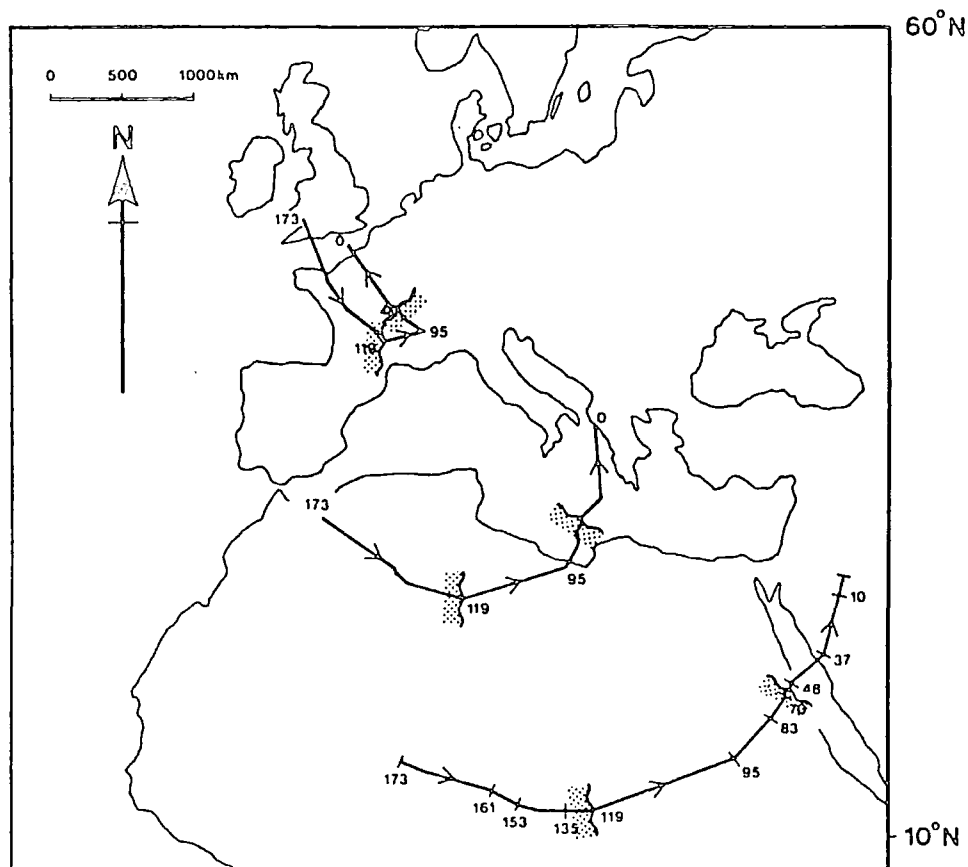


Figure 5.4. Schematic representation of the timing and orientation of the major change in tectonic stress from extension to compression in the mid-Cretaceous (Livermore and Smith, 1986).

illustrates the timing and orientation of the relative motions of the African and European plates (Smith, 1971; Livermore and Smith, 1986). Rifting in the North Atlantic in the early Tertiary added a component of relative NW-SE motion of Europe to Africa (Dewey, 1982) to the N-S or NNW-SSE relative motion of Africa to Europe described above (figure 5.4).

Thus, the vertical motions of the crust observed in the form of basin uplift and removal of overburden are a secondary response to lateral motion of the lithosphere associated with compression and lithospheric shortening or thickening. Just as basin formation has been analysed with respect to the thermal and mechanical evolution of the lithosphere in extension, their destruction or partial destruction is analysed with respect to the structural style of the inverting basins, the types and amounts of uplift that occur and the thermal and mechanical evolution of the lithosphere in compression.

5.4 Thermal and Mechanical Evolution During Basin Inversion.

5.4.1. Introduction.

Basin formation occurs in response to lithospheric extension. Initial fault controlled subsidence facilitated by collapse of the hangingwall sides of the major extensional faults, eg. listric faults, is followed by gentle, regional unfaulted subsidence in response to thermal re-equilibration and increasing flexural strength of the lithosphere (figure 4.8, and McKenzie, 1978). Although repeated subsidence or extension events may occur as opposed to one major, initial event (Chapter 4, section 4.5), the general theory and predictions of the McKenzie model are seen to be represented in real basins (Chapter 4- this study; Central North Sea Graben- Sclater and Christie, 1980). Basin destruction or inversion occurs in response to a reversal of polarity of the regional tectonic stress regime, such that the lithosphere is under compression. We may apply similar theoretical boundary

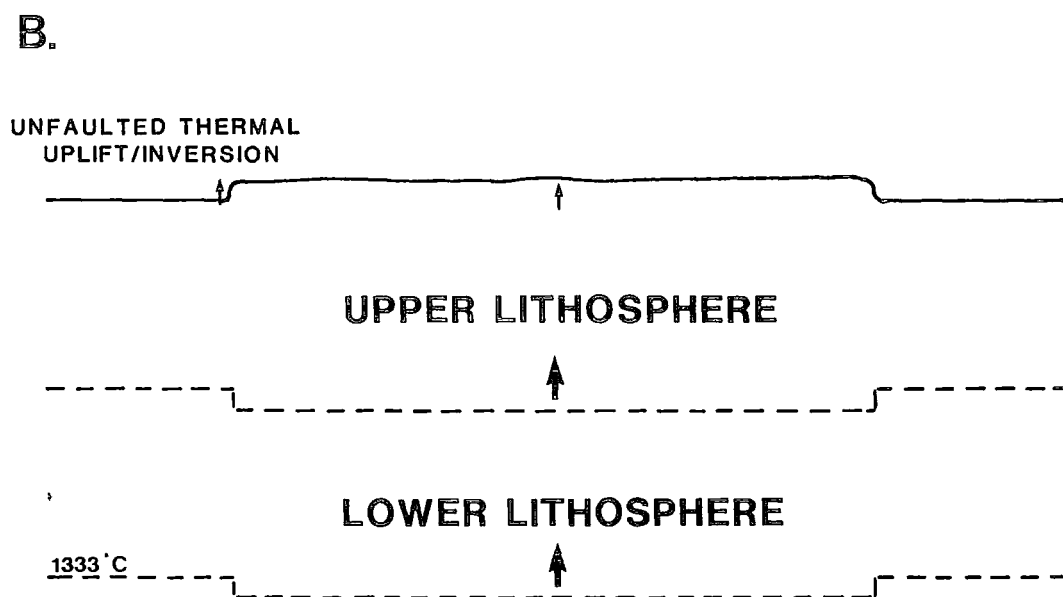
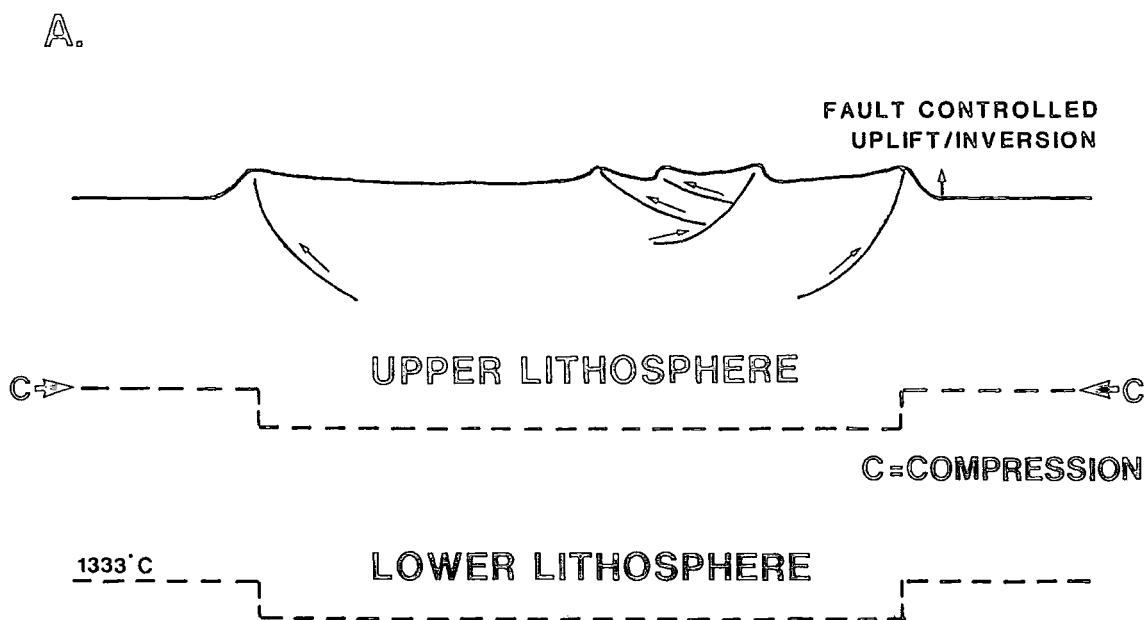


Figure 5.5. Regional lithospheric shortening. Initial fault controlled mechanical tectonic inversion (A) is followed by regional thermal inversion/uplift (B). Mechanical inversion will be recognised by fault reactivation and compartmentalisation of the deformation within the pre-existing fault bound basins

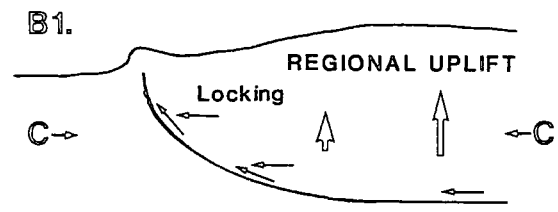
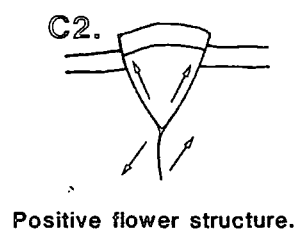
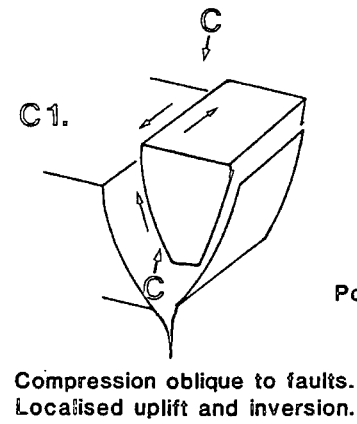
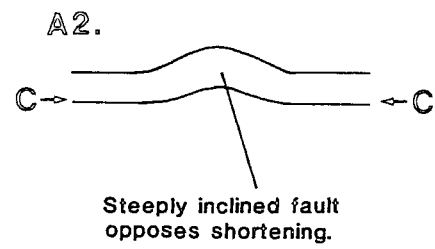
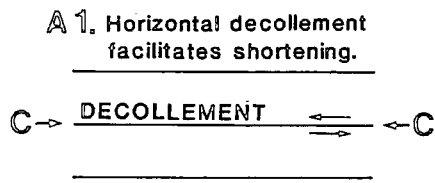
conditions to inversion as we do to subsidence in order to predict the quantitative and qualitative nature of the inversion on a local and regional scale.

Figure 5.5 illustrates the theoretical lithospheric conditions and components of uplift expected during inversion. Whole lithospheric compression causes depression of the lithospheric isotherms and subsequently lithospheric thickening. Individual basins or sub-basins within the boundaries of the shortened or thickened lithosphere become inverted and uplifted by mechanical reactivation of pre-existing faults in both the basement and basin fill. Subsequent thermal re-equilibrium and relative lithospheric thinning and heating causes gentle, regional uplift.

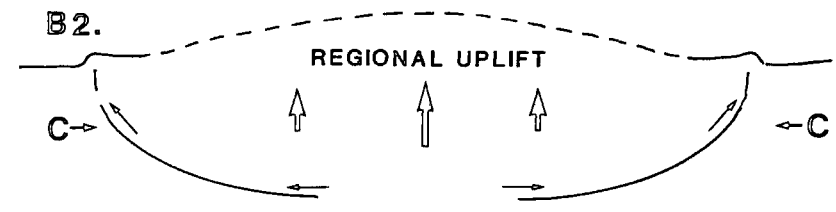
5.4.2. Mechanical Inversion.

Initial mechanical inversion is fault controlled. Pre-existing, extensional basin faults play an important part in defining areas where mechanical inversion will pre-dominate. To reactivate a fault, it must be both favourably geometrically orientated and suitably weak to move. Thus, differential uplift and basin inversion occurs by vertical reactivation along hangingwalls of preferentially orientated faults. These may include those normal or sub-normal to the lateral compressive stress. Inversion can also be facilitated by strike slip and transpressive reactivation along faults orientated parallel or sub-parallel to the compressive stress (figure 5.6.A-E). Clearly, less work is involved if faults are parallel to the compression direction or if they are of a low angle and normal to the compression direction. Conversely, more work is involved if faults are steep and perpendicular or normal to the compression direction (figure 5.6.A1, A2).

Extension during basin formation is commonly accommodated along listric, normal faults whose dip decreases downwards until the fault becomes horizontal and soles out along some decollement or detachment horizon (Barr, 1987). The



Former extensional listric fault displays variable response to shortening due to changing geometry of fault plane.



Regional uplift and inversion in centre of graben bound by listric faults. Localised deformation above reactivated fault trace at outcrop.

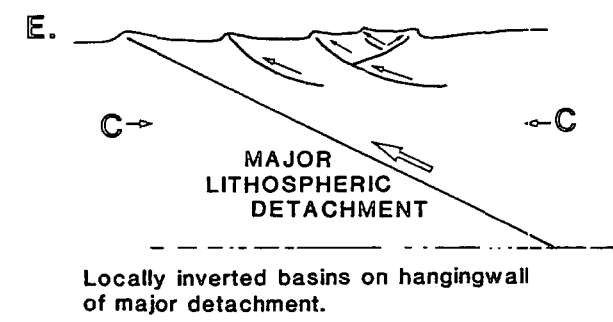
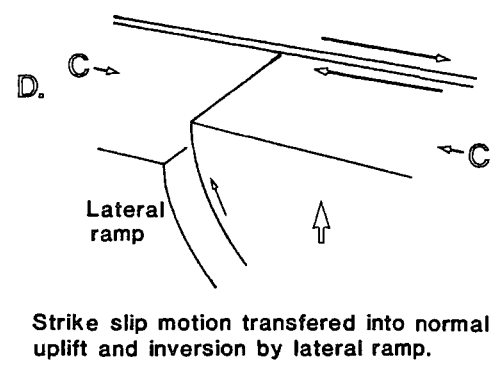


Figure 5.6. Mechanisms of fault reactivation and basin inversion.

decollement or detachment zone may be at any level in the cover sediments, if a suitably weak or accommodative sedimentary horizon occurs, and/or at deeper levels in the crust, eg. brittle-ductile transition at 15 km depth (Chadwick, 1985a). Thus, the geometry of a listric fault requires that it will display differing responses to reactivation during compression. The horizontal or sub-horizontal part (flat) will facilitate compression and shortening relatively easily (figure 5.6.A1, B1, B2). The vertical or acutely angled part (ramp) will oppose the lateral movement (figure 5.6. A2, B1, B2). Therefore, the opposition to reactivation along the vertical part of the fault may cause the system to lock or jam, causing regional uplift and bulging due to space problems over the flat of the fault where shortening is occurring (figure 5.6.B1, B2). The majority of the deformation along the fault may not be observed at its outcrop, but it may be transferred from the flat of the fault upwards into more central parts of the basin (figure 5.6.B1, B2). Deformation in or above the vertical part of the fault, or ramp, will be restricted to local folding and reverse/thrust faulting depending on the magnitude of the compression event or the success of reactivating the structure through overlying sediments (figure 5.6.B1, B2).

If one considers the structural and sedimentological configuration during basin formation, the older sediments would be subject to greater extension, whereas the amount of extension in younger sediments, or across the faults that cut the younger sediments, will be less. Also, if thermal/flexural, unfaulted subsidence has occurred, the sediments deposited during this stage of subsidence will generally not display extensional features. Thus, reactivation of earlier extensional faults from the syn-rift basin into the sediments of the post-rift basin will cause a reversal of stratigraphic separation in younger sediments. Older, more extended syn-rift sediments may retain a proportion of their extensional offset (figure 5.7). In general, faults orientated perpendicular to the compressive stress will block any attempted shortening in the crust and this can result in large wavelength folding

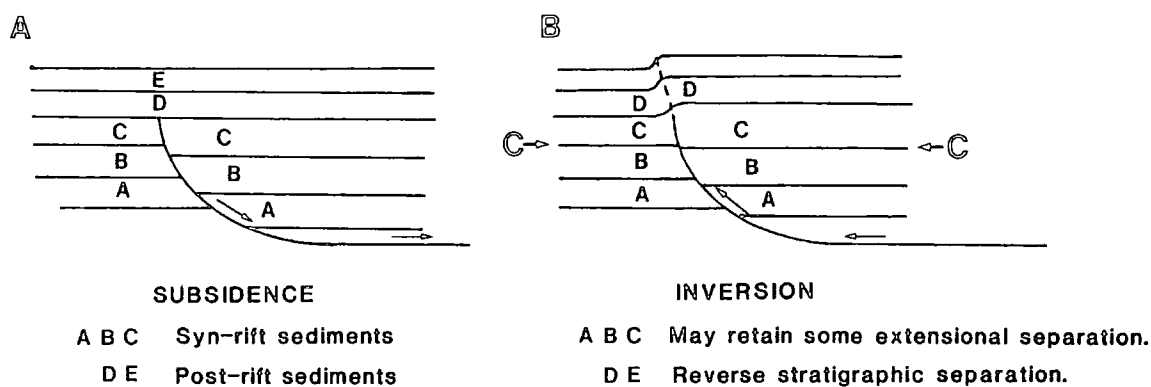


Figure 5.7. Structural positioning of syn-rift and post-rift sediments and their subsequent displacement during inversion and fault reactivation. Reverse stratigraphic offset may occur in less extended post-rift sediments.

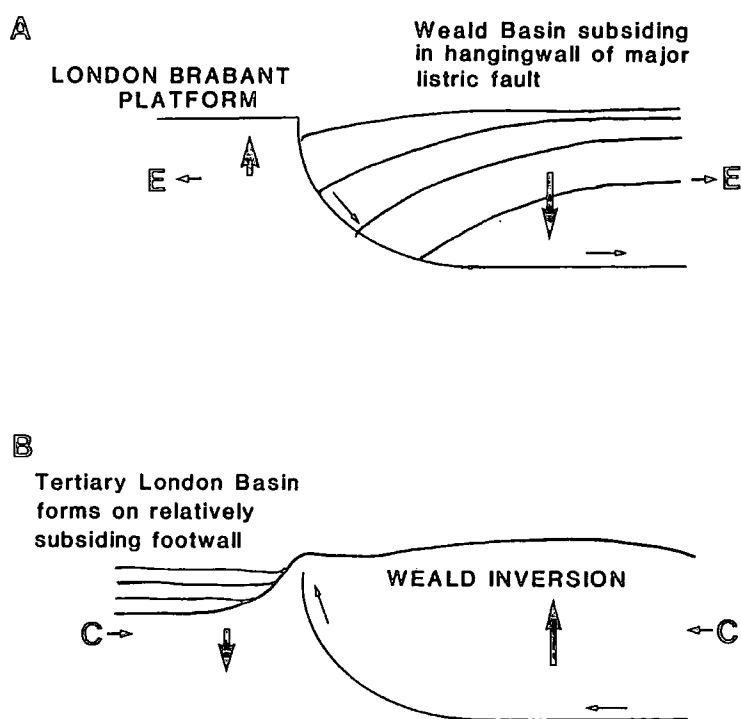


Figure 5.8. Example of Tertiary negative inversion over the London Brabant Platform due to positive inversion of the Weald Basin.

(Gillchrist et al, 1987).

Faults orientated parallel or sub-parallel to the compressive stress, whether high angle or listric will deform by pure strike-slip or transpression. Deformation, including folding and reverse or thrust faulting, is typically localised in the vicinity of the faults. The amount of basement uplift will be less than that associated with deformation about faults orientated perpendicular to the compressive stress (figure 5.6.C1, C2), but they may act as transfer faults along which the shortening deformation is passed or tram-lined until it is transformed into vertical uplift at a lateral ramp (figure 5.6.D).

The above discussion describes deformation along faults in the basin cover and basement. However, where faults in the sedimentary cover link directly to basement and lower crustal faults and detachments, compression and shortening may be preferentially accommodated (figure 5.6.E). Thus, the deformation and partial destruction of young basins may reflect a local response to widespread lithospheric compression and shortening which is accommodated along wholesale lithospheric or upper crustal lithospheric detachments (Chadwick, 1985a; Whittaker, 1985; Brooks et al, 1984; Brewer et al, 1983; Chadwick et al, 1983; Lake, 1985; Whittaker and Chadwick, 1984).

The direct relationship between upper and lower crustal structures and their continued reactivation is well documented in Southern England (above and section 5.2). Major basement thrusts and strike-slip faults link to mid-crustal detachments and were reactivated directly in the upper-most part of the crust as normal faults in extension and reverse faults and thrusts in compression. However, deep seismic data for the Yorkshire, Sole Pit and East Midland Basins is not available. Recent structural and relatively shallow, seismic studies suggest a different structural style to that in Southern England. However, this study investigates the influence of basement structures on the nature (style) and positioning

of the younger extensional basin faults. The link between and influence of both sets of structures is investigated during basin formation and inversion.

By observation, the main extensional and wrench faults in the Alpine foreland which confine the major basins on their hangingwall sides, also confine or define the main axes of inversion.

5.4.3. Regional, Thermal Uplift and Inversion.

In addition to mechanical accommodation of inversion by faulting, theory predicts a subsequent gentle, regional, thermal uplift and inversion (figure 5.5). This component of inversion, unlike the mechanical type, is not a differential uplift confined by the reactivation of faults. As illustrated in figure 5.5, both footwall and hangingwall areas will be affected by regional thickening of the lithosphere and depression of the lithospheric isotherms. However, as more shortening in the upper crust may be accommodated in the mechanically inverted basins it may be expected that a local, within basin offset of the lithospheric isotherms will occur. This would cause a greater component of thermal uplift in the more mechanically inverted basins, increasing further their observed basement uplift relative to footwall basins (figure 5.10). (figure 3.33, 5.10). Identification of this secondary inversion or uplift is more difficult if continuous compressive episodes cause a number of mechanical inversions. Thus, a regional background inversion may be obscured or overprinted by the more easily recognised mechanical inversion. Evidence for regional uplift in the study area is present as the footwall areas eg. East Midland Basin, Market Weighton Axis, do suffer some uplift which is significantly less than that in the two main inversion or uplift axes over the Yorkshire and Sole Pit Basins. This reflects differential mechanical inversion in the Yorkshire and Sole Pit Basins by preferential structural reactivation, followed by gentle regional inversion.

5.5 Negative Inversion.

A consequence of positive inversion is the development of negative inversion on the footwall of the major faults accommodating the positive inversion. Figure 5.8 illustrates a simplified situation which is analogous to such an occurrence at the southern margin of the study area during the Tertiary. Compressive reactivation of a major listric fault, bounding the northern limb of the Weald Basin on its hangingwall from the London Brabant Platform on its footwall, caused inversion and uplift of the Weald Basin and the creation of a depocentre, the Tertiary London Basin, over an area of former relative uplift from the Permian to Cretaceous. Other examples of negative inversion due to late Cretaceous to early Tertiary compression are not found in the study area.

5.6 Quantification of Inversion in the Yorkshire, Sole Pit and East Midland Basins.

The period of Permian to Cretaceous subsidence and extension in the Yorkshire, Sole Pit and East Midland Basins was terminated by positive inversion due to lateral compression associated with major plate tectonic readjustments (figure 5.4). One can assess the affects that both lateral and vertical stresses have had on the basins by analysis of their structures initiated or reactivated during both subsidence and uplift (faults, folds, joints), and the present physical characteristics and geographical positioning of the sediments.

This study will firstly attempt to quantify the lateral and vertical deformation across the study area, using the widespread stratigraphic and borehole log data available. Having identified the components of this inversion, and analysed them with respect to theoretical models, an attempt is made to qualitatively assess the inversion and, in particular, isolate how it has been accommodated by the structures and sediments within the basins. Data used include published and

unpublished seismic data, geological maps and field studies. The basin inversion, basement uplift and associated structures are examined in the context of the local and regional stress regime.

5.6.1. Quantitative Analysis of Inversion.

In the study of basin formation one may quantify:-

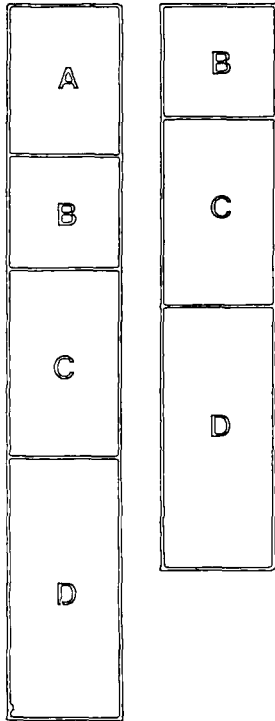
- A. Total subsidence of the basement, ie. subsidence including compacted or de-compacted sediments.
- B. Tectonic or driving subsidence of the basement, ie. subsidence that would have occurred had the basin not been infilled with sediments, which impart an additional load on the basement.
- C. Lithospheric extension or thinning, ie. theoretical models, assuming subsidence is caused by lithospheric extension, can predict the amount of extension or thinning within the lithosphere.

The need to explain the mechanisms of basin formation partly arose from the observation that the addition of a sedimentary load in a basin fails to account for the total subsidence observed. Thus, the force imparted by the sedimentary load on the lithosphere is insufficient to explain the total subsidence even if subsidence is seen to keep pace with sedimentation.

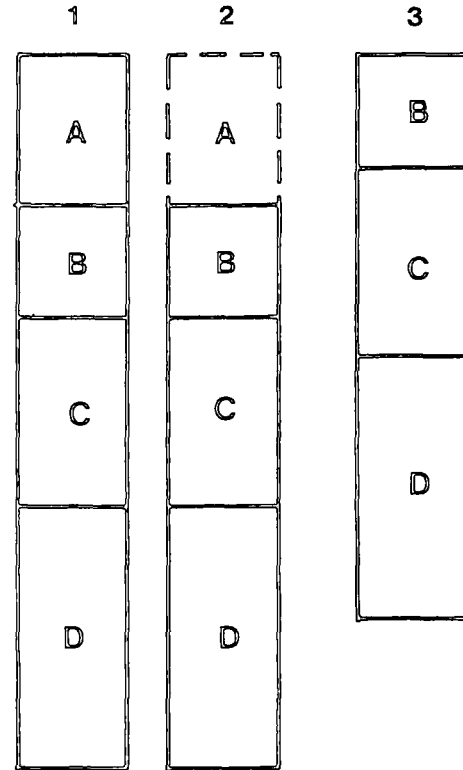
Conversely, the reverse is true for basin inversion. Removal of the sedimentary load is insufficient to account for all the uplift measured and also fails to fully explain the types of reactivation structures that are commonly mapped in inverted basins. Figure 5.9 illustrates the theoretical situation where we have the complete or maximum basin fill, A to D, and an uplift event which has elevated the basement by A, and is represented by present day basin fill B to D (figure 5.9A). Figures 5.9B and 5.9C explain two possible conclusions to be gained:-

TOTAL UPLIFT = A

A.

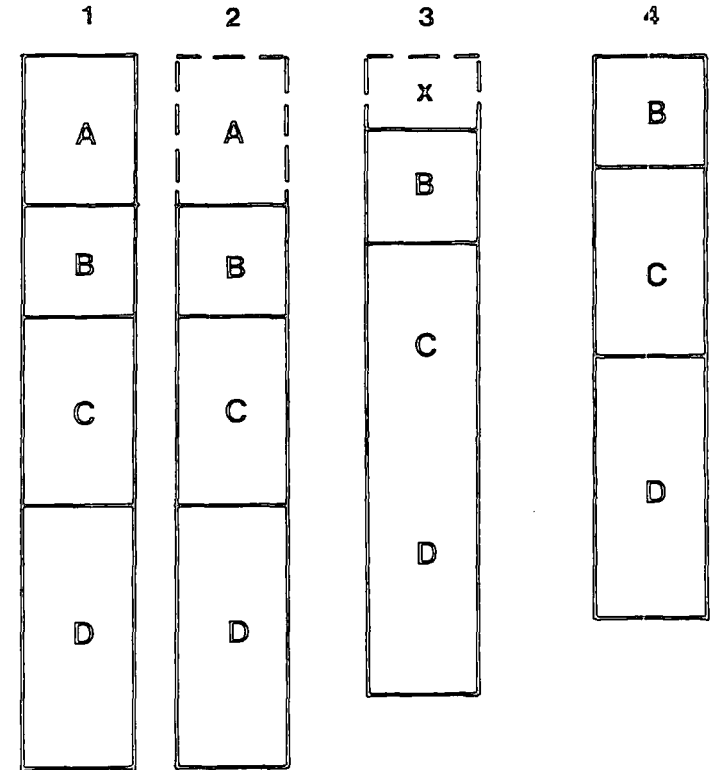


B.



REMOVE A
BASEMENT REBOUNDS
BY A

C.



REMOVE A
BASEMENT REBOUNDS
BY A-x

+ TECTONIC
UPLIFT (x)

= A (TOTAL UPLIFT)

Figure 5.9. Simplistic representation of the affects on the basement of removing a finite amount of sediment from a basin. Removal of the sedimentary load cannot account for the total uplift of the basement.

1. Removal of sedimentary pile A alone causes uplift of magnitude A due to unloading of the basement.
2. Removal of sedimentary pile A causes uplift of a magnitude less than the total uplift observed, ie. $A-x$. x represents the contribution from driving tectonic uplift which initiates the basin inversion.

The latter of these two is the mechanism by which inversion is found to occur in the study area. Uplift, once initiated will propagate or continue by removal of sedimentary load and by additional pulses of the driving tectonic force.

The most commonly used and readily explainable cause of inversion and uplift is, like subsidence, due to major reorganisation in the plate tectonic situation which impart and can change the polarity of the stress activity on the whole lithosphere. Thus, inversion and uplift are initiated by lithospheric compression and shortening.

This study addresses three major parameters that reflect the nature, timing, magnitude and geographical distribution of basin inversion:-

1. Total uplift/inversion of the basement.
2. Tectonic uplift/inversion of the basement, ie. basement uplift that would occur had no sediments been removed and unloaded.
3. Lithospheric shortening or thickening, ie. response to lateral compression of lithosphere.

5.6.2. Total Inversion/Uplift of Basement.

The total uplift or inversion of the basement is discussed in detail in Chapter 3. It represents the cumulative uplift that has occurred since the termination of subsidence, the components of which may include tectonic uplift, due to unloading

of sediments, diapiric uplift, flexural uplift or uplift by any other mechanism (see section 5.2.2.).

The method used here to calculate the total uplift and inversion of the basement involves identifying a depth or burial dependent physical parameter of sediments, such as porosity or interval transit time (see Chapter 3). These have been calculated using data from available sonic velocity logs. The nature of the physical parameter with respect to its present burial depth is assumed to reflect whether the sediment is at its maximum depth at present or whether it has been elevated from this position. The sediment is assumed to retain its maximum burial characteristics after uplift, particularly in areas where sediments have been buried to substantial depths and/or for significant geological time, eg. 65 million years.

A detailed discussion of the principles involved and results obtained from this analysis is held in Chapter 3. The regional uplift pattern (figures 5.10 and 3.32) is calculated from analysis of compaction trends for various lithologies, eg. shale, chalk, sandstone, and numerous lithologically defined formations of Carboniferous to Upper Cretaceous ages. Clearly, the physical parameters preserved in the sediments and utilised in this study mirror the expected inversion trends across the study area and allow the total uplift to be estimated. This not only provides valuable information as regards the nature and timing of inversion but also allows one to reconstruct the hypothetically complete sedimentary sequence or maximum subsidence prior to inversion. In turn this allows more accurate appraisal of the thermo-mechanical evolution of the area during basin formation (Chapter 4). Additionally, this data provides information for studying maximum burial depths of potential source rocks and assessing their history of subsidence and uplift which will greatly affect their maturity (Chapter 6).

As far as inversion is concerned, these data illustrate the significant basement uplift that has occurred, particularly in the Yorkshire and Sole Pit Basins, which

likewise may be termed the Yorkshire and Sole Pit Inversion Highs (Axes). Hence, the lateral stresses assumed to be responsible for initiating inversion and imparting compressive stress in the lithosphere have been, in part, transferred into vertical deformation of the basins and their sediments.

Reconstructing the pre-inversion structural and sedimentological configuration is achieved by computing the amount of sediment removed and analysing maximum tectonic subsidence and extension in the lithosphere. This has further uses, particularly when assessing the lateral and more detailed vertical deformation during, and as a consequence of, inversion of the Yorkshire, Sole Pit and East Midlands Basins.

The discussion below, makes a comparison of the present day crustal configuration with the postulated crustal configuration prior to inversion. This evaluates the effects that inversion and shortening have had on the lithosphere in the study area.

5.6.3. Tectonic Inversion/Uplift of the Basement.

As mentioned above (section 5.6.2.), the removal of a sedimentary load is found to be insufficient to account for total uplift observed and thus inversion is initiated or caused by some driving tectonic force. This will impart a component of uplift that would occur irrespective of other factors.

Tectonic uplift and inversion are the isostatic response to lithospheric shortening and compression (Chadwick, 1985a) and may be regarded as having two major components:-

1. Fault controlled inversion and uplift.
2. Thermal inversion and uplift.

Figure 5.5 simplifies the theoretical conditions of the lithosphere and the expected inversion and uplift episodes, 1 and 2, above. The tectonic inversion or uplift curves (trends) derived from the theoretical modelling are illustrated in figure 5.11. Initial rapid or instantaneous fault controlled uplift in response to compression and shortening is followed by gentle, regional thermal subsidence in response to thermal re-equilibration of the lithosphere after shortening. These can be compared to the curves derived for tectonic subsidence using McKenzie's (1978) model (Chapter 4, figure 4.8). However, one major difference exists between the actual or observed curves for uplift and those for subsidence:

Input into the backstripping program, which isolated the tectonic subsidence, includes a number of chronostratigraphic boundaries which are often lithostatigraphic boundaries as well. When combined with detailed stratigraphic thicknesses, information as to the rates and types of total and tectonic subsidence that have occurred since the onset of rifting result. The sediments themselves, thus identify the nature of the subsidence. In Chapter 4, these observations and results clearly show how the observed subsidence patterns can be adapted to a model for basin formation, and vice versa. This includes the recognition of syn- and post-rift subsidence and the occurrence of possible repeated tectonic extension pulses. When considering the reverse situation of basin destruction by inversion, the amount of sediment removed or total basement uplift can be quantified (figure 5.10). Once the sediment that was removed by the uplift is calculated, the contribution to the total uplift by unloading of this sediment column, can be quantified from density variations computed in the backstripping program. This isolates the driving tectonic uplift.

However, accurately predicting the path of tectonic uplift as in figure 5.11, and identifying the various components of the inversion event, proves very difficult for the following reasons:-

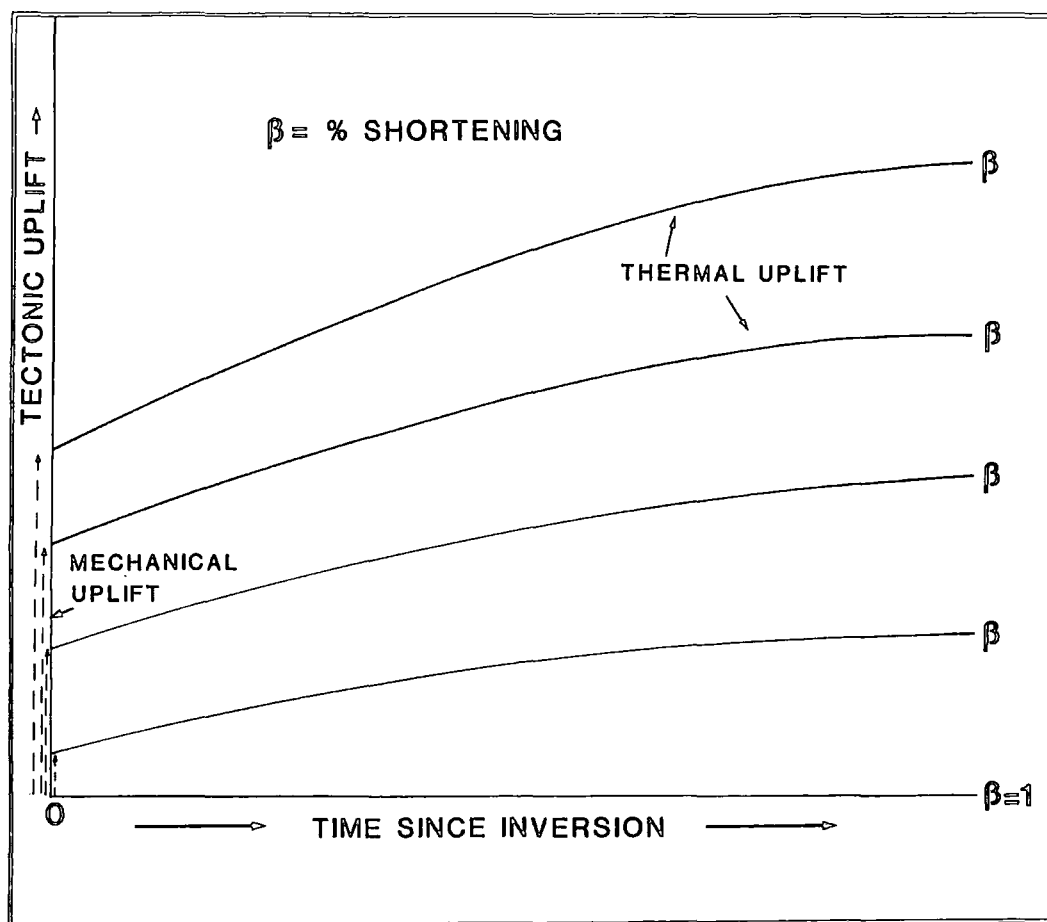
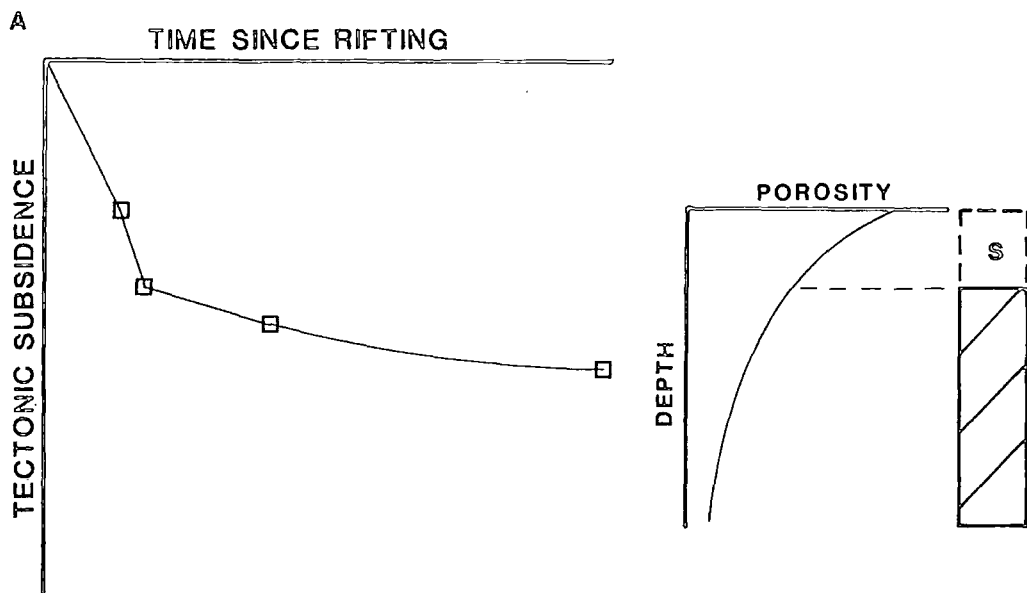


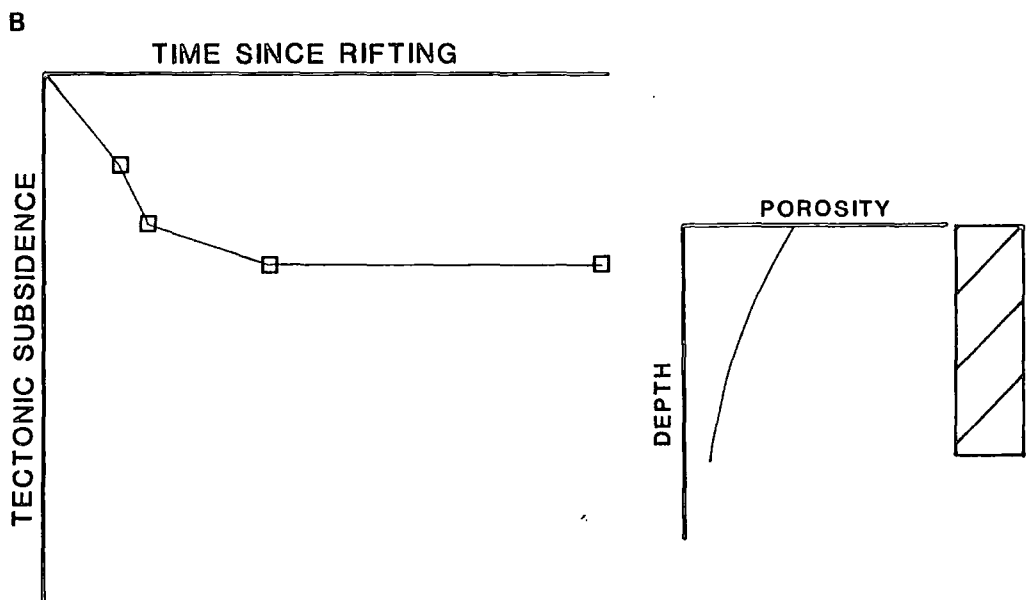
Figure 5.11. Components of tectonic inversion. Initial rapid, mechanical or fault controlled tectonic inversion is followed by more gentle, regional thermal inversion. Beta is lithospheric shortening.

It is not possible to model the accurate form of uplift and inversion in time if the total inversion or total basement uplift is composed of a number of cumulative events. This would be analogous to the path of subsidence being defined by a number of chronostratigraphic, sedimentological horizons. Some of the individual tectonic pulses may be recognised for example, by local structural deformation, but accurately quantifying each event in terms of basement uplift is not possible. The only criterion for inversion is a cumulative figure for basement uplift between two end points, the start and finish of the inversion event. This makes analysis of the detailed temporal fluctuations of the inversion difficult, which in turn would have, by definition, isolated the contributions of the mechanical and thermal components of inversion.

Figure 5.12.A, 5.12.B and 5.13 illustrate the method used to calculate tectonic uplift in this study. Emphasis has been placed on reconstructing the maximum basin fill and comparing it with the present post-inversion configuration for quantifying and qualifying components of both subsidence and inversion. These relationships are further used in the analysis of this particular part of uplift and inversion. Figures 5.12.A and 5.12.B represent hypothetical tectonic subsidence curves, compensated and uncompensated, for the amount of sediment that was removed during uplift. The difference between the two computed tectonic subsidence values, correspond to the effect of removing sedimentary column S, which is calculated from analysis of compaction trends (section 5.5.3. above and Chapter 3). The load of sedimentary column S on the basement, computed using density considerations from the part of the porosity curve that identifies with S (figure 5.12.A), is removed (figure 5.12.B) and the tectonic subsidence or uplift relative to figure 5.12.A. is computed for the remaining post-inversion sedimentary column. The latter retains its present porosity and density characteristics due to cohesive forces developed during burial and compaction. This is an important assumption used in this study and for computing the total basement uplift (section 5.6.2. and

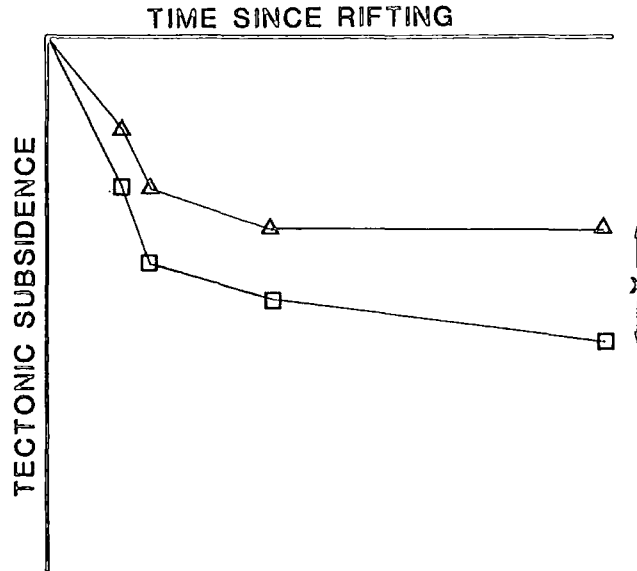


Maximum tectonic subsidence computed using reconstructed sedimentary sequence.



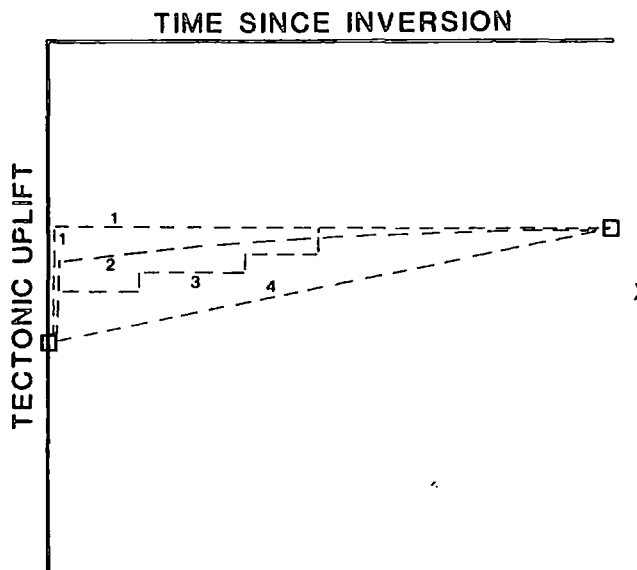
Effective tectonic subsidence computed after removal of sedimentary load.

Figure 5.12. Maximum tectonic subsidence compensated for uplift and removed overburden (A), compared with the observed tectonic subsidence, uncompensated for uplift. The difference in magnitude is the driving tectonic uplift initiating basin inversion (figure 5.13).



Tectonic uplift (x) computed using tectonic subsidence curves compensated and uncompensated for uplift/inversion.

Figure 5.13. The driving tectonic inversion or uplift is represented by difference in magnitude of the compensated and uncompensated tectonic subsidence curves. This represents the uplift after the load of sedimentary column S (figure 5.12) is removed.



Problems of identifying accurate form of tectonic uplift curve.

Figure 5.14. The accurate form of the tectonic inversion is difficult to model due to a lack of quantifiable and datable deformation events such as chronostratigraphic units during infilling of a subsiding sedimentary basin.

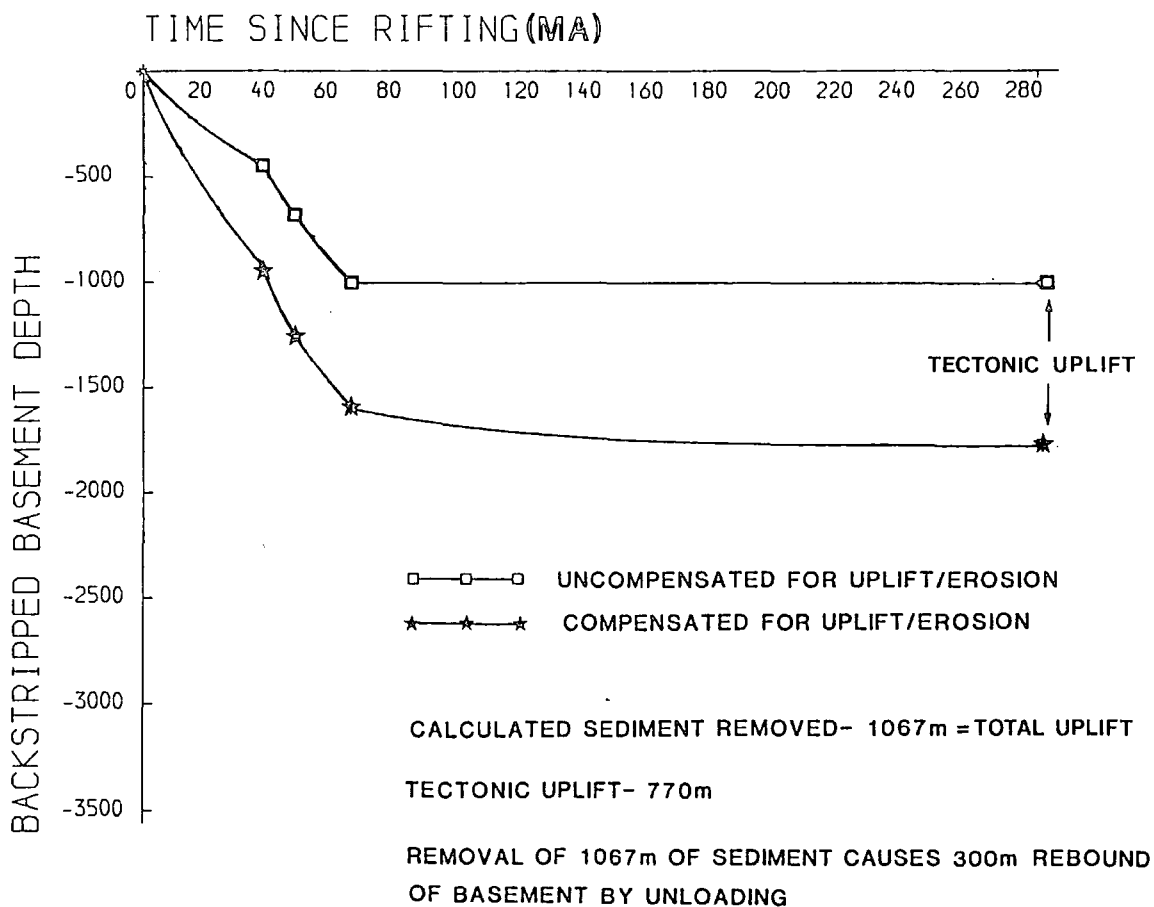
Chapter 3).

Figure 5.13 illustrates the difference between the two hypothetical curves and defines x the tectonic uplift. Value x corresponds to the contribution of tectonic uplift to the total observed basement uplift. That is, the resultant basement uplift after the uplift due to the unloading of sedimentary column S is removed. Thus, x defines the total tectonic uplift that has occurred since the onset of inversion. However the method by which it is calculated means that only the start and end points are identified (figure 5.14). The form that the tectonic uplift or inversion curve follows between these two end members may vary from:-

- a. One rapid, initial mechanical inversion episode and no thermal inversion (labelled 1 in figure 5.14), to:-
- b. One rapid, initial mechanical inversion followed by gentle, regional thermal uplift (labelled 2 in figure 5.14), to:-
- c. A number of mechanical inversion episodes (labelled 3 in figure 5.14), to:-
- d. One episode of amalgamated mechanical and thermal uplift in which neither component dominates.

Thus, one may not directly be able to separate the mechanical inversion from the thermal inversion using this method.

However, mechanical fault controlled inversion is recognised in the field by structural deformation and fault reactivation (section 5.7). This is expected to be confined to the hangingwalls of major reactivated faults and will in general not be recognised on the footwall side. Therefore, recognition of uplift (total) on the footwall of major mechanically inverted structures may reflect some component of gentle, regional, thermal uplift that will affect both footwall and hangingwall areas due to regional lithospheric thickening and shortening.



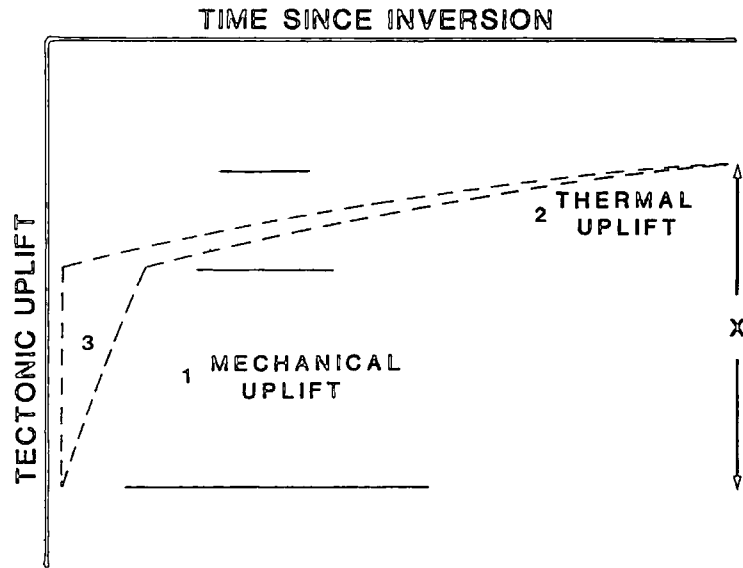
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Figure 5.15. Tectonic inversion computed for a location in the Sole Pit Basin.

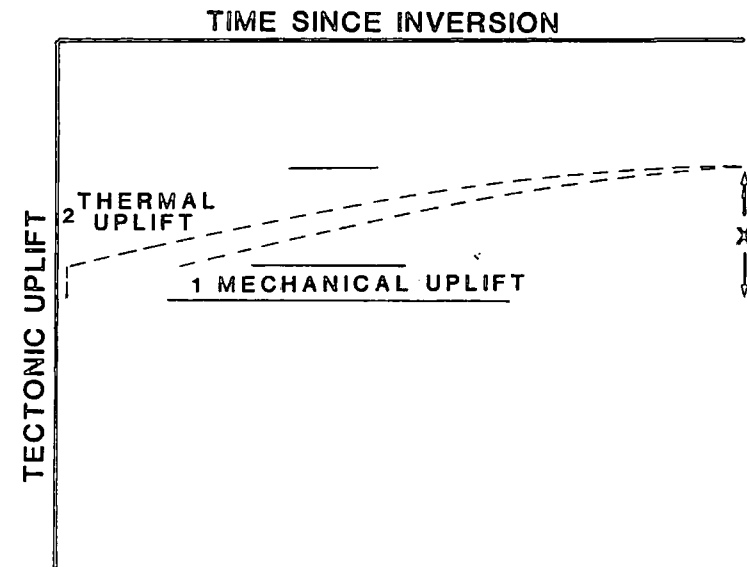
The procedure described above and in figures 5.12.A, 5.12.B and 5.13 was carried out on all boreholes in the study area to obtain a regional outline of the contribution of tectonic uplift to the total uplift (figure 5.10). This is illustrated in figure 5.15 for a borehole in the Sole Pit Basin, namely 48/30-4. From analysis of porosity and interval transit time trends for Triassic shales and sandstones, an estimated 1067 m or 3500 feet of sediment is calculated as having been removed during late Cretaceous-Tertiary inversion. This corresponds to the total uplift of the basement. However, removal of 1067 m of sediment causes approximately 300 m of basement rebound and uplift. Thus, approximately 770 m of the total uplift is contributed by the driving tectonic uplift. The results are summarized in a colour contoured map of tectonic uplift across the Yorkshire, Sole Pit and East Midland Basins (figure 5.16). These three distinct sedimentological provinces are immediately distinguishable by the variation in computed tectonic uplift. The more intense tectonic uplift is restricted to the Yorkshire and Sole Pit Basins, where values are of the order 500-1000 m. The margins of these two inverted areas are particularly well defined, the results showing a rapid increase from west to east across the diffuse north-west to south-east trending Dowsing Fault Zone which bounds the western margin of the Sole Pit Basin and inversion high. A relatively more gentle but still pronounced increase northwards across the southern margin of the Yorkshire Basin is observed, coinciding with the Vale of Pickering Fault Zone.

In the area of Flamborough Head, in the east of the Vale of Pickering Fault Zone, relatively high tectonic uplift values are observed (figure 5.16) particularly when compared with the East Midland Basin. Tectonic uplift of 200-300 m is computed. It will be shown below that this area coincides with a zone of complex fault reactivation, which although only apparent on a small scale, may have accommodated compression and inversion on a local and regional basis.

YORKSHIRE , SOLE PIT BASINS



EAST MIDLAND BASIN



1-DIFFERENTIAL MECHANICAL UPLIFT

2-THERMAL UPLIFT OF SIMILAR MAGNITUDE ACROSS ALL BASINS

3-TIMESCALE OF MECHANICAL UPLIFT INFLUENCED BY THERMAL COMPONENT OF UPLIFT

Figure 5.17. Postulated form of the tectonic inversion curves for the Yorkshire, Sole Pit and East Midland Basins.

The two major inversion highs and the Pennine Massif to the west enclose the little inverted East Midland Basin. Data for the latter display broadly spaced low values in the coastal, offshore and southern parts of the basin. The coastal and offshore areas represent the main un-inverted trough bordering the two major inversion axes and on the footwall of the major fault zones. The southern margin of the East Midland Basin and its associated low tectonic uplift values reflect the influence and negative inversion of the London Brabant Platform. Westwards, values increase as one approaches the onshore outcrop of older basinal sediments, and where uplift has therefore been calculated as being more intense. However, it is suggested here that this inversion does not represent true mechanical fault controlled inversion as few if any structures or reactivated structures are mappable. That is, uplift is apparently not accommodated or restricted by faults to the west. This uplift is suggested to represent the gentle, regional thermal uplift of the East Midland Basin in association with increasing flexural uplift westwards as one approaches the Pennine Massif (Karner et al, 1987; Hemingway, 1974).

As will be shown below, mechanical accommodation of the inversion and uplift by structural deformation and fault reactivation appears to be restricted to the two major inversion axes and their approximate basinal limits. The mechanical and thermal components of the tectonic uplift are difficult to isolate. However, the coincidence of intense tectonic uplift within zones of demonstrable mechanical deformation and inversion (Yorkshire and Sole Pit), combined with relatively minor tectonic uplift within a zone of mainly undeformed, unfaulted sediments is postulated to represent:-

- a. Accommodation within this particular area of initial fault controlled mechanical inversion and uplift on the hangingwalls of major pre-existing crustal discontinuities, followed by
- b. Gentle, regional thermal uplift of the whole area.

It is recognised that if inversion is mainly accommodated within faulted areas then one may expect greater contribution of thermal uplift in these areas than neighbouring areas due to local crustal shortening and depression of lithospheric isotherms. However, as in thermal subsidence, thermal inversion is a regional event, and is not influenced by previous major structural trends which may have isolated mechanical subsidence and/or mechanical uplift. Thermal uplift, like thermal subsidence will be regionally consistent in magnitude and thus, one should not expect large variations in its contribution to the tectonic or total uplift. Furthermore, if the involvement of the sub-crustal lithosphere is less than the upper crustal lithosphere, as may be expected by localised faulting, folding and thrust reactivation in the latter, mechanical inversion may be compartmentalised preferentially to the hangingwall basins where most deformation is witnessed. Then gentle, regional thermal inversion and uplift occurs in response to sub-crustal lithospheric shortening and thickening. As figure 5.5 explains, a number of locally inverting basins may occur in response to lateral compression, such as those in the Alpine Foreland (Ziegler, 1987). Their local effect on the regional lithospheric shortening is minimal and regional uplift of inverted and non-inverted areas occurs as the lithosphere re-equilibrates.

Data from the Yorkshire, Sole Pit and East Midland Basins support such a history of inversion. Removing tectonic uplift values from the Yorkshire and Sole Pit areas leaves a residual uplift which may be attributed to unloading of sediment. Tectonic uplift and total uplift in the East Midland Basin (figure 5.10 and 5.16) are low and therefore not dissimilar due to the small amount of sediment removed from the area. The East Midland Basin displays little if any evidence for mechanical inversion. The latter is postulated to have been initiated in the Upper Cretaceous and accommodated almost entirely within the Yorkshire and Sole Pit Basins. The East Midland Basin, largely unaffected by mechanical inversion due to a lack of preferentially orientated faults, remained relatively undisturbed on

the margins of the two inverting axes. The main tectonic pulse ceased in the early Tertiary (Walker and Cooper, in press), although the Northwest European area remains under relative compression to the present day (Greiner, 1975; Schmitt, 1981). This was followed by gentle, regional thermal uplift which is mirrored in the East Midland Basin tectonic and total uplift, but which is masked in the total tectonic uplift of the Yorkshire and Sole Pit inversion curves.

Thus, the history of inversion appears to imitate, in relative magnitudes and nature, the history of subsidence. During extension, the Yorkshire and Sole Pit Basins differentially subsided on the hangingwalls of major fault zones, whilst relatively gentle, unfaulted subsidence occurred in the East Midland Basin. The latter, from the form of the tectonic subsidence curves (Chapter 4), may partly reflect flexural subsidence westwards and southwards towards the Pennine Massif and London Brabant Platform. This is probably due to the regional distribution of the load imparted on the lithosphere by the Southern North Sea Basin and in particular, the Yorkshire and Sole Pit Basins which surround the East Midland Basin flexural wing. Relatively constant, gentle, thermal and flexural subsidence followed which transgressed, and was uninfluenced by, earlier basin boundaries. During inversion, the hangingwall Yorkshire and Sole Pit Basins were differentially uplifted utilising the same structures as those during extension and subsidence. Gentle uplift of the East Midland Basin is postulated to reflect a component of regional, thermal uplift that like regional thermal subsidence (Chapter 4) affected the whole study area.

Thus, the development of basins and succeeding inversion axes is directly controlled by the thermal and mechanical evolution of the lithosphere during extension and compression but in particular by the orientation and reactivation of pre-existing crustal and sub-crustal discontinuities. Significant tectonic uplift and inversion is recognised in the area. This does not preclude that one can or

will necessarily see accompanying or proportional amounts of vertical or reverse movement in structures within the basin. As figure 5.16 illustrates, the amounts of tectonic uplift are relatively constant across the inverted basins and hence the deformation is not entirely accommodated at, or by, any one location or structure. The total vertical deformation during inversion is the cumulative affect of a number of components, including mechanical and thermal inversion, which induce basement uplift.

The vertical deformation described above is a response to lateral compressive stress and lithospheric shortening. What evidence is there for lateral shortening during inversion of the Yorkshire, Sole Pit and East Midland Basins?

5.6.4. Lithospheric Shortening or Thickening.

Crustal and lithospheric shortening and thickening are difficult parameters to quantify accurately, particularly in partially destroyed basins where fault geometries reveal that despite the inversion, the basin system has retained a considerable component of its original extensional state, eg. Yorkshire Basin, Sole Pit Basin, East Midland Basin, Wessex Basin. Crustal and lithospheric shortening is a mechanism which undoubtedly occurs in response to wholesale lithospheric compression. It is represented at upper crustal levels by reverse, thrust and strike slip faulting plus folding indicating buckling and shortening, notably within younger sediments, eg. Yorkshire Basin anticline, Weald anticline, Channel Basin anticline (Lake, 1985).

Lateral compression is observed within the Yorkshire, Sole Pit and East Midland Basins as basement uplift, extensional fault reactivation, and folding. Thus, the reactivation in a reverse sense of crustal faults and the effective reduction in size or volume of the basins implies some form of crustal shortening (Ziegler, 1987). Lateral compression and shortening will be facilitated by discontinuities

which parallel or nearly parallel the stress direction and/or are weak enough to move, such as horizontal decollement horizons. Deep crustal sections, particularly of the Dowsing Fault Zone, suggest that faults in the basement form a complex en echelon system of small, vertical faults which do not directly link to structures in Zechstein and younger sediments. The latter appear to be of a more listric geometry (Van Hoorn, 1987). A similar situation appears to explain the Vale of Pickering Fault Zone with Zechstein and younger faults soling out in the Permian and Triassic and not apparently linking directly to, for example, the major Craven Fault System in the Carboniferous basement which lies on a similar trend to the west. This appears to be due to evaporite horizons failing to relay stress from basement to the cover and is a widespread occurrence in the Southern North Sea Basin (Jenyon, 1988). We seem to have an apparently ideal situation for accommodating lateral stress including near vertical basement faults orientated north-west to south-east and parallel to the compressive stress, eg. Dowsing Fault Zone, combined with weak horizontal decollement horizons in the upper crust, both of which can relay deformation and shortening (figure 5.6.A-E). The amount of shortening is proportional to the amount of inversion and uplift, particularly where lateral stress is opposed by structures orientated normal to the stress direction. Estimates of 2-3% shortening in the Wessex Basin of Southern England (Chadwick, 1985a) correspond with the small but structurally demonstrable amounts of vertical uplift and inversion. Compression has clearly reactivated major normal faults in the Wessex Basin, eg. Isle of Wight-Purbeck Fault, but has not caused much regional uplift or erosion, unlike inversion of the Yorkshire and Sole Pit Basins (figure 5.10). From deep seismic profiling in Southern England, this appears to be a contradiction, since the reactivated structures at the surface are found to link directly to major crustal and possibly sub-crustal detachments. Would one not expect more accommodation of lithospheric shortening where major lithospheric detachments occur?

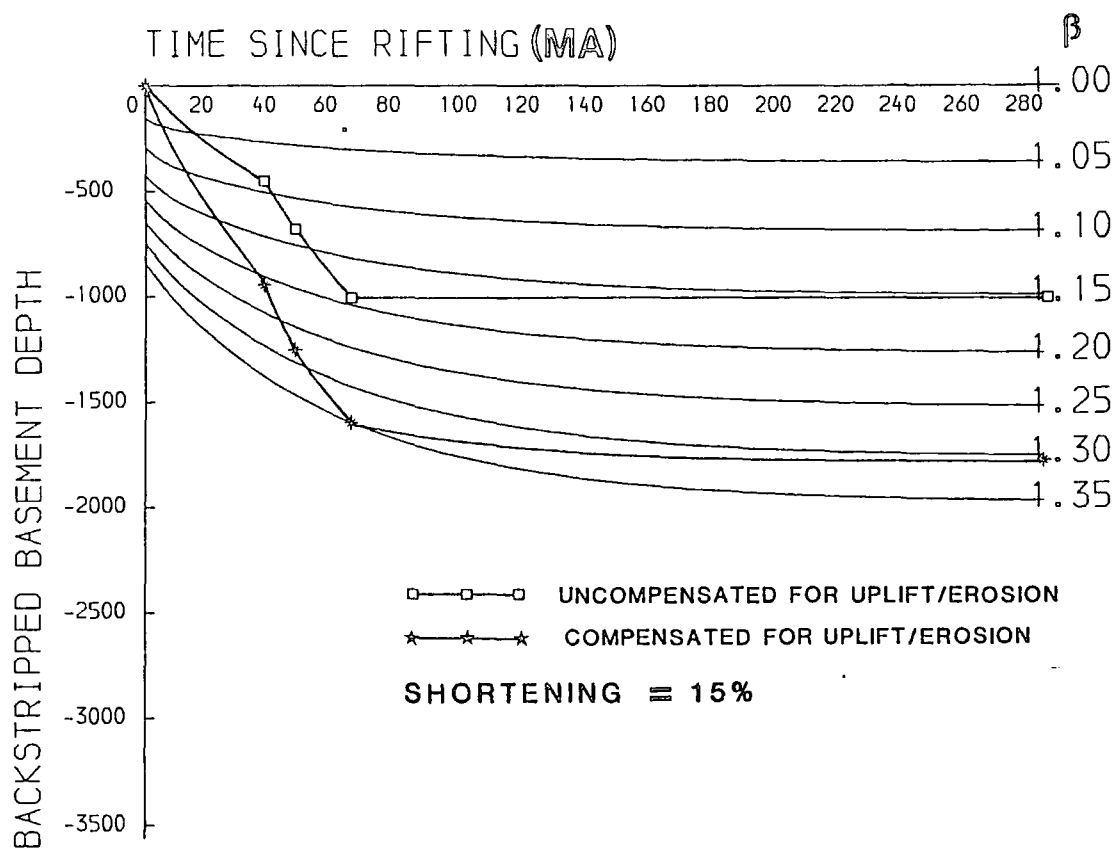
Structures on this scale are not known in the Yorkshire, Sole Pit and East Midland Basin areas due to the lack of deep seismic data and thus the detailed, deep crustal configuration cannot readily be used to explain the large differences in their response to, and accommodation of, lithospheric shortening.

Uplift in the Wessex Basin represents only approximately 6% of the maximum sedimentary thickness whereas the sediment calculated as being removed from the Yorkshire and Sole Pit Basins represents approximately 30% of the maximum sedimentary thickness. We may expect a proportional amount of shortening to accommodate removal of such a volume of sediment.

How can one make an attempt to isolate the representative shortening in an area that has suffered inversion? Accurate analysis of shortening from seismic sections is often fraught with complications due to problems associated with identifying every fault and its offset, bed thickening, recognition of decollement horizons, orientation of the section relative to the stress direction and identifying deep crustal deformation in basement. The latter is a point in case as Jenyon (1988) has recently identified numerous instances where comprehensive reactivation of faults in the basement are not relayed into basinal structures. Thus, shortening has occurred but may not be recognised, unless the study analyses all structural levels and dimensions.

Analysis of fault offsets tends to underestimate the real or expected amounts of shortening. This study attempts to predict the crustal and lithospheric shortening that would be expected in areas that display demonstrable and quantifiable inversion following extension and basin formation. Data derived from this study are compared to structural and seismic sections for correlation.

This thesis has utilised a comprehensive borehole coverage of the Yorkshire, Sole Pit and East Midland Basins and attained detailed regional analysis of the



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Figure 5.18. Calculation of lithospheric and crustal shortening from backstripped tectonic subsidence data.

components of subsidence and uplift. This same data base is used to compute the expected shortening in the study area that is represented by vertical uplift of the basement in figures 5.10 and 5.16. Basin analysis, using borehole data (Chapters 3 and 4) allows quantitative modelling of subsidence, extension and lithospheric thinning using the theoretical models of McKenzie (1978). In general, the observed tectonic subsidence curves for those boreholes found in the study area show good correlation with theoretically modelled curves. Similarly, the computed extension (β) for boreholes compensated and uncompensated for uplift, show close correlation with observed extension within the basins calculated from extensional fault offsets (figures 4.39 and 4.40). It is assumed that as the modelled and observed data correlate, the values for extension before and after inversion can be used to give a representative calculation of the shortening. That is, the difference between extension for present day, post-inversion situation and the reconstructed maximum extension prior to inversion is assumed to represent the theoretical amount of shortening necessary to invert the basement by the said amount (figure 5.10, total uplift and figure 5.16, tectonic uplift). This was executed on data from the Wessex Basin and the difference in β values corresponded to approximately 3% shortening, a similar magnitude to that computed from structural studies (Chadwick, 1985a).

Borehole 48/30-4 (figure 5.18), in the Sole Pit Basin is calculated as having undergone 3500 feet of basement uplift and associated sediment removal during inversion. Backstripped tectonic subsidence curves are illustrated and predict approximately 15% shortening at this particular locality. Lithospheric shortening may also be regarded as representing lithospheric thickening ($\frac{1}{\beta}$, where β = shortening). Figures 5.19 and 5.20 illustrate the regional maximum crustal extension in the study area for the pre-inversion and post-inversion crustal configurations respectively. The difference between β values in these two reflects the expected regional shortening in the area, computed from lithostratigraphic data within the

basins (figure 5.21).

From a comparison of figures 5.16 and 5.21, it can be seen that the magnitude of vertical deformation and uplift of the basement has theoretically been accommodated by a proportional amount of crustal and lithospheric shortening. The major inversion axes of the Yorkshire and Sole Pit Basins are defined by increased shortening in comparison to the non-inverted East Midland Basin. Shortening is calculated in the order of 5 - 15% in the Yorkshire Basin, 5 - 20% in the Sole Pit Basin and 0 - 5% in the East Midland Basin. The major faults and fault zones, eg. Vale of Pickering Fault Zone, Dowsing Fault Zone, do not correspond to the maximum shortening. This occurs uniformly in the central parts of the Yorkshire and Sole Pit Basins. However, they do correspond to the increase in shortening into the two above basins from the East Midland Basin. The faults in the post-Zechstein levels of these fault zones are listric in geometry and orientated normally and obliquely to the compressive stress. Such faults, by their geometry, will oppose significant shortening. Obliquely orientated faults may induce local folding and reverse faulting associated with transpression. Glennie and Boegner (1981), Van Hoorn (1987) and Jenyon (1988) have all revealed evidence for strike slip motion particularly along the Dowsing Fault Zone, orientated parallel or sub-parallel to the stress direction. These observations are mainly on fault offsets in basement and pre-Zechstein (Rotliegend) sediments. Regional lateral shortening, therefore, is accommodated by numerous, small strike slip offsets at depth. Shortening in younger sediments at higher levels attempts to be accommodated along extensional listric faults which sole out on Permian and Triassic evaporite horizons. The evaporites are distributed basin-wide in the Yorkshire and Sole Pit Basins and would be sufficiently weak to accommodate lateral movement in extension and compression. However, the portion of the listric fault which cuts vertically through the sediments will oppose shortening if orientated normal to the stress, eg. Vale of Pickering Fault Zone, Outer Silver Pit Fault, Butterknowle Fault, as

illustrated in figure 5.6.B1 and B2. Shortening in the evaporite within the basins is opposed at basin margins by listric faults. Stress may be backed up within the evaporite and transferred vertically into uplift at the basin centres. Figure 5.22 is a line drawing of a seismic section running north-south across the offshore continuation of the Vale of Pickering Fault Zone. The extensional nature of the faults is retained and it is evident that little shortening and uplift has occurred within this zone. This corresponds well with estimates of total uplift (figure 5.10), tectonic uplift (figure 5.16) and crustal shortening (figure 5.10). The latter is calculated to be approximately 5 - 10% in the offshore area of the Vale of Pickering Fault Zone. The major listric fault detaches into the Zechstein sequence, which is substantially thinned within the faulted area due to extension and salt evacuation. A north-south or north-west to south-east compressive stress could be facilitated along the horizontal detachment within the Zechstein sediments but this is opposed southwards by the major synthetic detachment and accompanying synthetic and antithetic faults. Stress is therefore transferred vertically to the area outside the region of mechanical faulting causing uplift and inversion of the basin centre. This corresponds to the high and much inverted central and northern parts of the Yorkshire Basin (figures 5.10 and 5.16). Thus, shortening within the Permian and younger sediments is mainly accommodated by vertical uplift and large scale folding and buckling due to the inability of the major extensional faults to significantly reactivate. Shortening can simply be measured by comparison of the present horizontal distance between two points and the pre-inversion distance measured along the folded strata. For the particular area shown in figure 5.22 this is computed to be of the order of 6 - 7% which once more correlates very well with theoretical shortening computed for this region in figure 5.22. These results have important consequences as to how inversion and shortening is accommodated elsewhere in the study area, particularly in the Sole Pit Basin.

The above research has shown how inversion can be modelled both quantita-

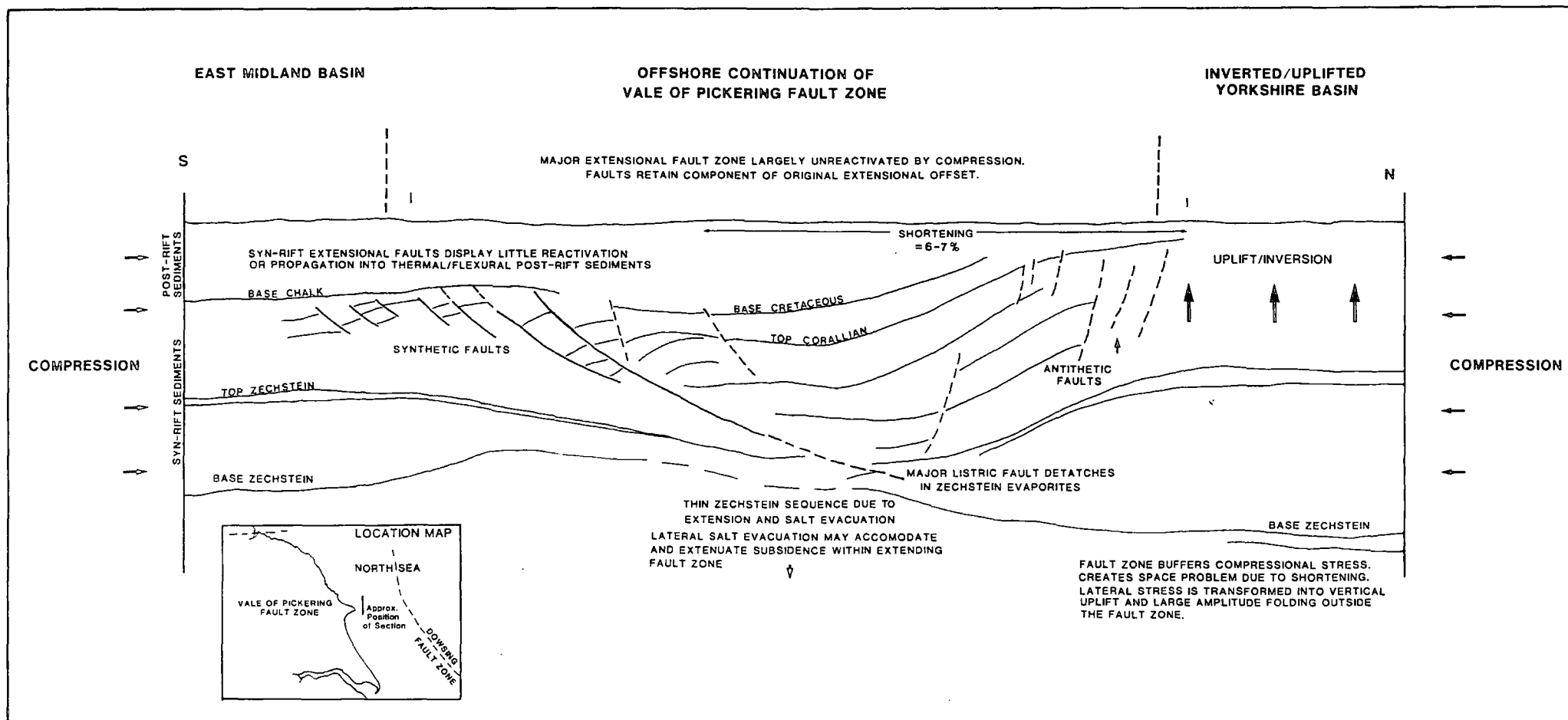


Figure 5.22. Seismic section (source-British Petroleum) across the southern margin of the Yorkshire Basin. Reactivation of pre-existing extensional faults is minimal and the main deformation is transferred into uplift of the basin centre. Compare the observed variation in accommodation of lithospheric compression in the basin with the modelled deformation (figures 5.10, 5.16 and 5.21) and field data (figures 5.24-5.31).

tively and qualitatively. The resultant data have indicated that both theoretical and observed components of inversion are compatible. Major trends in the Yorkshire, Sole Pit and East Midland Basins have also been determined. In the absence of a detailed knowledge of the deep structure in the area, deformation along high level crustal faults has been identified. High level horizontal detachments and basement structures that are suitably orientated and sufficiently weak to be re-activated have controlled and facilitated crustal shortening and basin inversion. Thus, it may be that lithospheric detachments such as those profiled beneath the Wessex Basin, involve significantly more work to reactivate than high level structures. This and the absence of weak decollement horizons such as evaporites in the Wessex Basin would explain the apparently anomalous nature and magnitudes of inversion witnessed between the former basin and the Yorkshire and Sole Pit Basins.

5.7 Stress System Operating During Basin Inversion.

The following discussion combines field and map data in an attempt to clarify the nature of the stress regime operating within the upper crust during inversion, and how, with particular reference to the Yorkshire Basin, it has been accommodated locally and regionally.

Inversion in the study area was initiated in the Upper Cretaceous and culminated in the Oligocene although it may not have been continuous during this time (Ziegler 1987). The main plate tectonic events and their combined influence on the orientation of stress within north-west Europe is illustrated in figure 5.4, and is probably approximately north-west to south-east. This parallels the major strike slip or wrench zones, eg. Dowsing Fault Zone, Pays de Bray Fault, Sticklepath Fault. Given the parallel orientation of these major fractures and the similar stress regimes to which they have been subject infers that they will respond in a similar manner.

Regional dextral wrench motion has been postulated as being operational during inversion of north-west European basins, including the Sole Pit Basin (Glennie and Boegner, 1981; Van Hoorn, 1987; Zeigler, 1987). Observation of fault orientation from seismic data provides the basis for this interpretation. However, clear-cut transcurrent or wrench motion is not easy to define, particularly along major strike slip zones where structures initiated during both extension and compression may overprint each other. This appears to be so for the Dowsing Fault Zone, where it is speculated that both dextral and sinistral wrench movements occurred during Upper Cretaceous to Tertiary inversion of the Sole Pit Basin (Glennie and Boegner *op.cit.*). Clearly the nature of the link between Pre-Permian and younger structures in the Sole Pit and Yorkshire Basins creates problems in interpretation unlike, for example, similarly orientated faults in the Wessex Basin. In the latter, the direct link between north-west to south-east wrench faults, eg. Pay de Bray Fault, and east-west listric faults, eg. Isle of Wight - Purbeck Fault, makes the identification of relative sinistral and dextral motion more easy.

Stress indicators such as faults, folds and joints, have been investigated to identify the local situation within the Yorkshire Basin. The results are compared to those from published data in the Sole Pit Basin in an attempt to link these two evolutionary similar basins to a common stress field.

Figure 5.23 outlines the general geology of the Yorkshire Basin. As described in the earlier sections of this chapter, substantial uplift and inversion has been restricted mainly to the central and northern parts of the basin, whilst in the south, the Vale of Pickering Fault Zone retains much of its extensional offset, created during extension and basin formation. A similar situation is recorded offshore (figure 5.22). Field and map evidence do not support the hypothesis that significant wrench motion has occurred along these faults. This is further supported by recent studies that infer that the fault zone is not the onshore continuation of

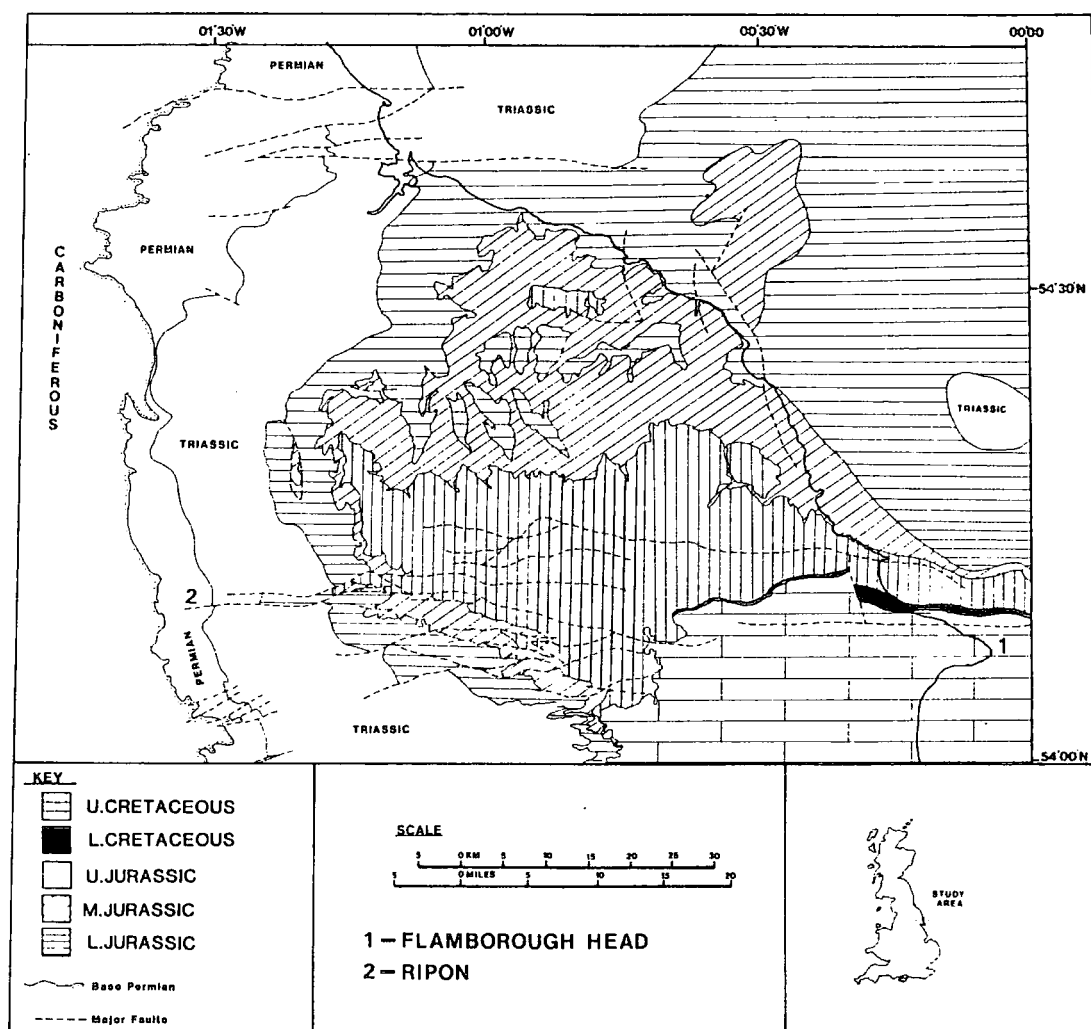


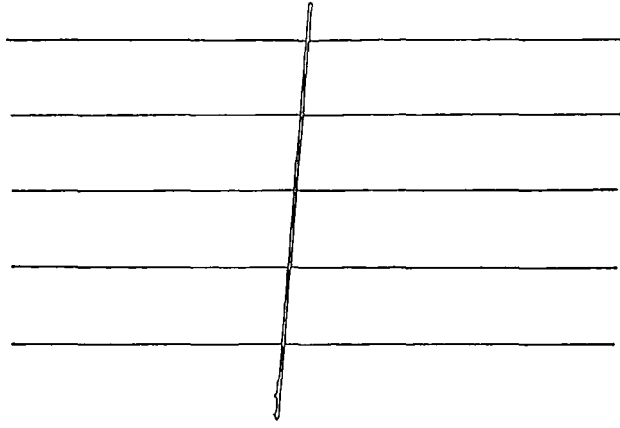
Figure 5.23. Geological map of the Yorkshire Basin. Faults have retained a significant component of their original extensional offset (figure 5.22). Location of field examples is given (1. and 2.)

the Dowsing Fault Zone. However, it does lie along the same trend as the Craven Fault Zone, a set of Carboniferous basin bounding faults along which wrench motion occurred in the Carboniferous (Arthurton, 1983). Figure 5.23 also illustrates the lack of propagation of these faults into Upper Cretaceous sediments, where they are mainly represented by very localised disruption such as the contortion zone and deformation seen in Selwicks Bay near Flamborough Head (Jeans, 1973; Neale, 1974; Kent, 1980a). The absence of Jurassic extensional faults propagating into the Cretaceous sediments is also evident offshore in figure 5.22. These zones display relatively intense deformation but they do not appear to cause any significant vertical offset of the chalk (Upper Cretaceous) strata. Nevertheless, the structures associated with this deformation event do reveal important information as to the nature and orientation of the stress acting during inversion.

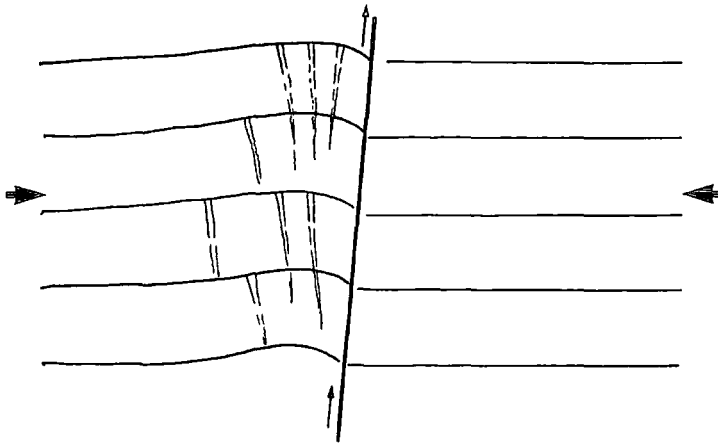
Figure 5.24 views the central part of Selwicks Bay, from the east looking west. Within the figure two specific localities are referenced. The scene also displays other interesting features including a number of low angle faults trending $E10-30^{\circ}S$, across which vertical offset is either indeterminate or slightly reversed, and tightly folded strata with axial trends parallel to the faults. Clear offsets of the faults are difficult to determine due to the lithological consistency of the chalk and often severe disruption in their vicinity (figure 5.24). A number of other local, small scale structures including folds, joints, veins, stylolites and slickensides reveal the cause and orientation of the deformation.

Locality 1 (figure 5.24) displays relatively tight, anticlinal folding within sediments on the hangingwall of a south dipping (facing), east - west striking fault (figure 5.25). Little vertical offset is apparent across the fault but generally the beds are structurally higher on the hangingwall due to the folding. Deformation increases in intensity towards the fault from the hangingwall side but no deformation is apparent on the footwall. The fold appears to represent a local

A.



B.



C.

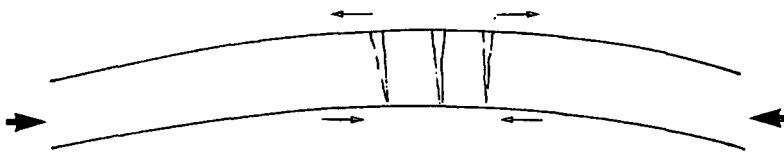


Figure 5.26. Interpretation of figure 5.25. High angle fault has acted as buffer to the deformation which is confined to the immediate hanging wall side. Slight reverse offset of the chalk, folding, fracturing and veining is interpreted to represent deformation under N-S oriented compression.

buckling of the sediments as the steep, south facing fault opposes lateral compression. Bedding perpendicular, calcite filled veins or cracks occur in the crests of the anticlines. The veins display a radiating pattern and an increase in width vertically (figure 5.25). This represents increased dilatency during compression and folding with localised extension restricted to the outer parts of the fold crests (figure 5.26).

Jointing and associated structures within Selwicks Bay and Flamborough Head also fall into a similar model of north - south orientated compression. Locality 2 in figure 5.24, is typical of a number of examples and is illustrated more closely in figures 5.27 and 5.28. A conjugate pair of joints (or faults) both striking at 353° (approximately perpendicular to the structures mentioned above), and dipping $63^{\circ}E$ and $53^{\circ}W$, are found in the north end of Selwicks Bay. Both joints display extensional offsets or downthrow of the chalk beds on their hangingwalls, indicating an east - west orientated extensional field. Fault gouge is present along both fractures. At first sight this infers a vertical compressional field, possibly due to the lithostatic pressure exerted by overlying sediments. Horizontal stylolites confirm this. However, both faults display good, horizontal north - south striking slickensides inferring a north - south compressive stress which has initiated some north - south, lateral, strike slip motion (figure 5.28). Figure 5.29 illustrates the occurrence of similar joint systems in the vicinity. These observations are summarized in figure 5.30 and are postulated to represent deformation within a north - south orientated compressive stress, due to weak reactivation of underlying major extensional basin faults. As suggested from figures 5.6, 5.22 and 5.23, older structures within the syn-rift sediments retain their extensional offset when inversion is relatively weak, whereas any reactivation or inversion of structures in post-rift unfaulted sediments causes reverse stratigraphic separation. The structures observed with the post-rift Upper Cretaceous chalk sediments (Chapter 4) of Flamborough Head, suggest a similar history of deformation.

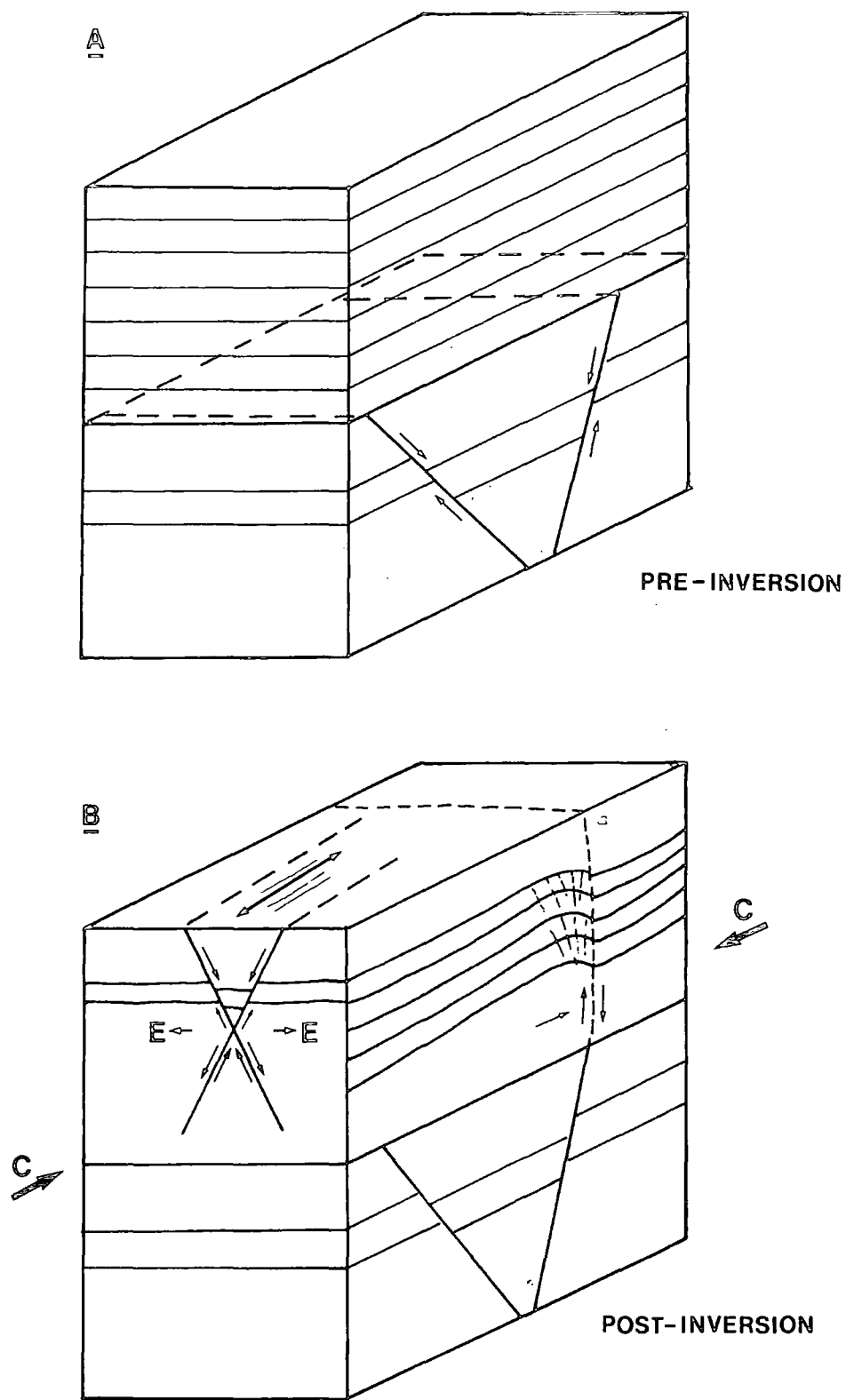


Figure 5.30. Block diagram of the integrated localised deformation on Flamborough Head.

Following, the Vale of Pickering Fault Zone westwards, few structures are known that represent reverse reactivation of the faults during inversion despite the regional uplift that has been computed for this area (figure 5.10 and 5.16). At the most westerly mapped extent where the two remaining faults die out in Permian and Triassic sediments (figure 5.23) Forbes (1958) recorded some interesting structures. At outcrop between the two faults, highly disturbed Permian evaporites and marls form a small zone of tightly folded and faulted strata. The folds are mainly tightly isoclinal or overturned anticlines and link to faults below (figure 5.31A). The fold axes are orientated east-west to northwest-southeast. Thrusting on the faults is apparent together with local thrusting and flow textures within the evaporites. These structures are suggested to represent local deformation in response to horizontal, approximately north-south orientated compression. Reverse reactivation of these faults has been discussed as minimal except in upper levels. However, if the evaporites acted as a decollement during faulting relaying stress laterally, then reactivation may cause deformation localised to these horizons. Figure 5.22, the seismic section of the coast at Flamborough Head, images the easterly extension of this same fault zone. The faults sole out in Permo-Triassic evaporites as above, and these sediments have suffered deformation, thinning and lateral flow during extension. Lateral flow and deformation under compression within the relatively weak evaporite horizons will produce small scale folding and thrusting as seen at outcrop (figure 5.31B). These structures are of too small a scale to be defined on a seismic section, but the mechanism is proposed to be the same.

Thus, evidence exists for the compressional reactivation of the Vale of Pickering faults at their lower and upper levels. Vertical motion along the faults is minimal and deformation is only recognised where previously unfaulted, unextended or relatively weak sediments occur.

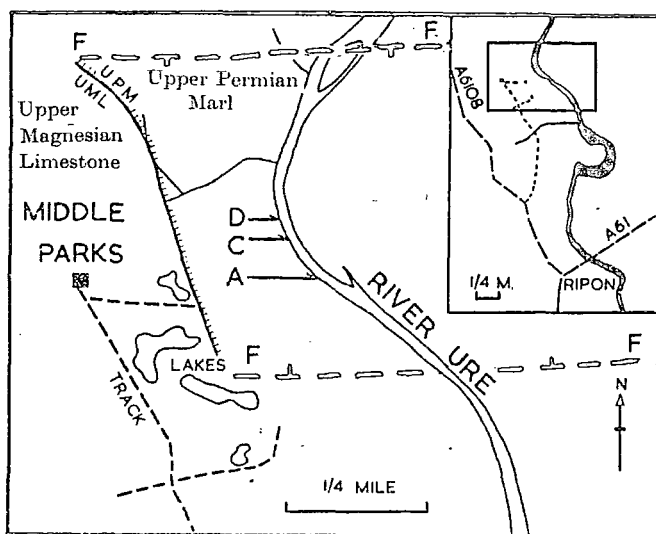
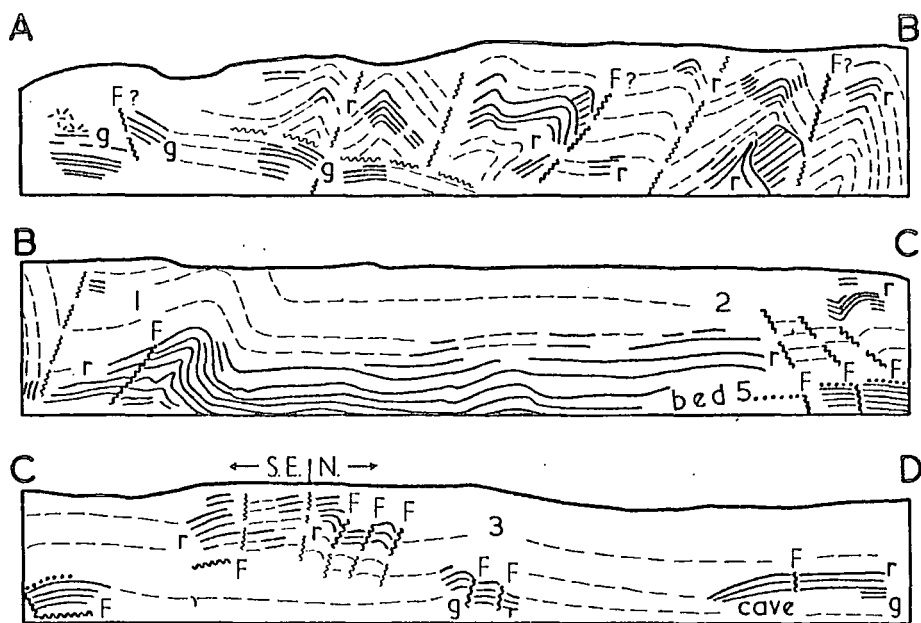


Figure 5.31A. Deformation in Permian sediments in the hangingwall of the Vale of Pickering



Reverse faulting, horizontal (decollement?) faulting, and tight isoclinal and overturned folding.

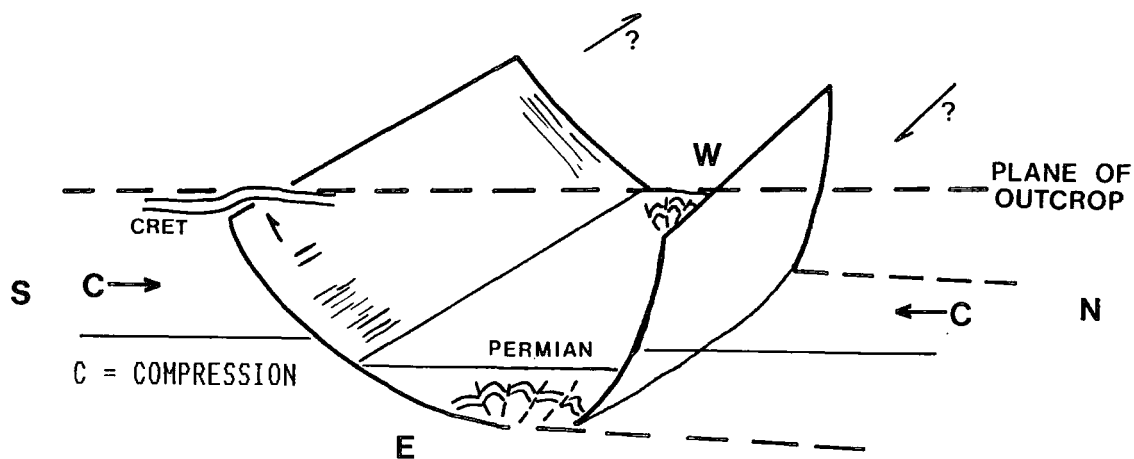


Figure 5.31B. Regional structural position of the deformation illustrated in figure 5.31A.

Faults in the north of the Yorkshire Basin are also still in an extended state (figure 5.23), although inversion appears to have been more intense at the northern margin as older sediments outcrop. Field evidence of these faults within Permian and younger sediments is scarce and therefore the structural relationships are difficult to appraise. Increased northerly dip of Lower Jurassic sediments at Redcar have been observed and may represent some deformation along the southernmost faults, but this cannot be verified. The Butterknowle Fault to the north was influential during Carboniferous basin formation and destruction (Smith and Francis, 1967). Extensional offsets in the Permian and younger sediments are significantly less than in the Carboniferous sediments, but they do exist, revealing some influence of the Butterknowle and associated faults during formation of the Permian to Upper Cretaceous Yorkshire Basin. Local east - west trending, fault-parallel folding in Permian and Triassic sediments (Smith and Francis op.cit.) is postulated to represent the structural response to Upper Cretaceous to Tertiary north-south orientated inversion.

Within the Yorkshire Basin, faulting is not a common occurrence, but a number of north - south orientated faults do occur. Some of these are postulated to display sinistral strike slip offset during inversion, eg. Peak Fault and Whitby Fault (Hemingway and Ridler, 1982). Additionally, remote sensing analysis of the central North Yorkshire Moors area has revealed a fracture pattern analogous to north-south orientated compression (figure 2.6).

Figure 5.32 combines all the above evidence into a regional picture of the Yorkshire Basin during inversion and compares it with deformation in the Sole Pit Basin. Inversion has clearly occurred in the Yorkshire and Sole Pit Basins and a number of definite structural observations reveal that the main compression was orientated approximately north - south. Inversion is restricted within east - west trending fault zones and their hangingwalls. Right lateral strike slip

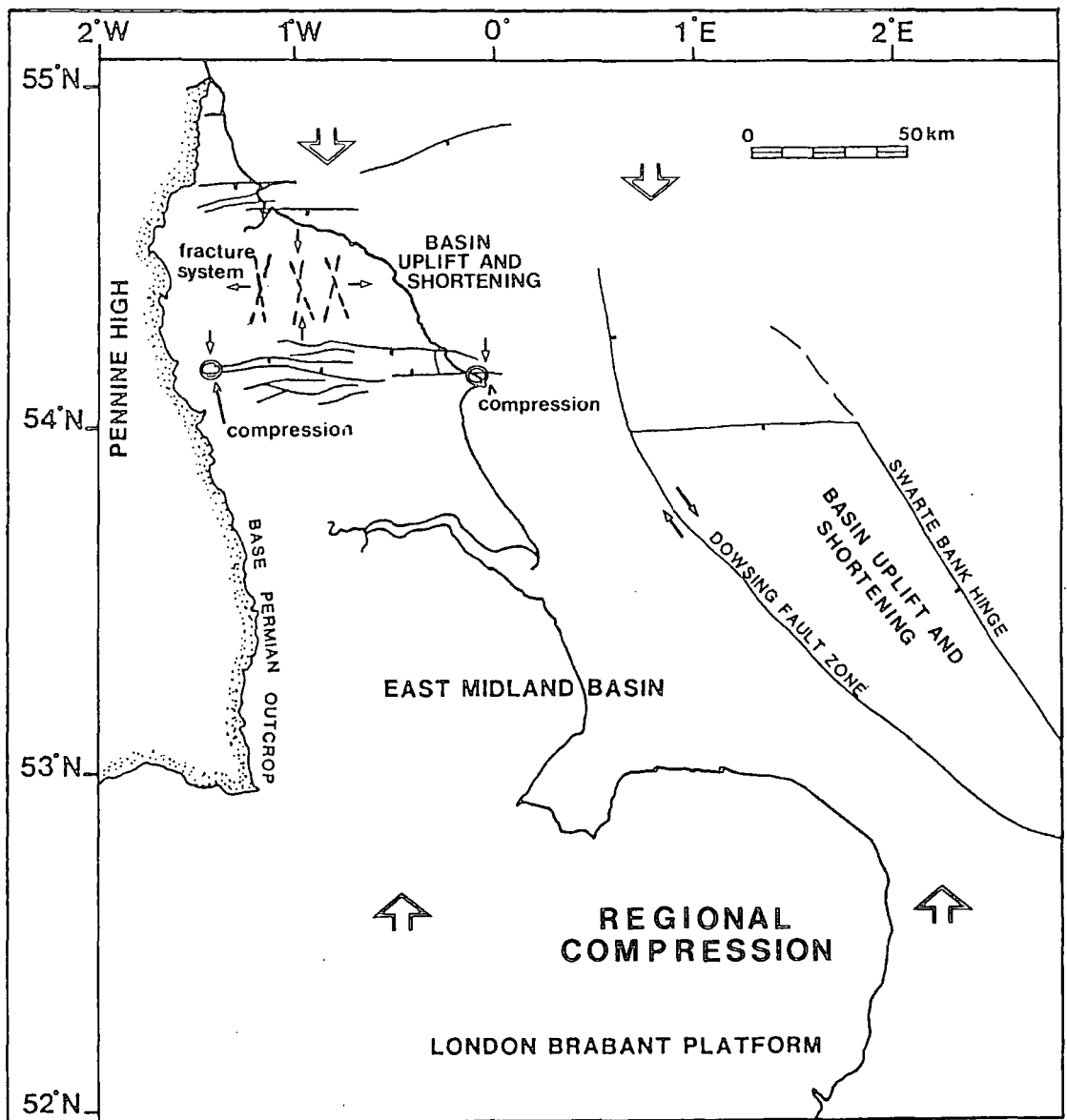


Figure 5.32. Stress system operating during positive basin inversion and observed local and regional structural deformation.

on the Dowsing Fault Zone does not appear to fit with sinistral movement along similarly orientated en echelon faults in the Yorkshire Basin. However, the sinistral transcurrent motion along the latter faults is by no means definite and recent work (Alexander, 1987) suggests that these faults were active and influenced sedimentation during the Middle Jurassic. It is thus postulated that the transcurrent motion, whether sinistral or dextral is relatively unimportant in the uplift and inversion of the Yorkshire Basin in particular, and that the influential factors have been a regional north-south orientated compression perpendicular to the major east-west trending faults.

5.8. Summary and Conclusions.

1. The Yorkshire, Sole Pit and East Midland Basins were controlled by major northwest - southeast and east - west faults during extension and basin formation.
2. These faults correspond to similar structures in the Carboniferous basement.
3. Major basin inversion (Laramide) was initiated by lithospheric compression due to plate tectonic readjustments in the late Cretaceous to early Tertiary.
4. Inversion was accommodated by the same structures that controlled basin development.
5. Total basement uplift, tectonic basement uplift and crustal shortening have been shown to be preferentially accommodated within the Yorkshire and Sole Pit Basins. This reflects the geometry and orientation of the pre-existing basinal and basement faults.
6. Local, brittle structural deformation including thrusting and reverse stratigraphic offset within post-rift sediments, occurs structurally above pre-existing extensional faults. This deformation represents subtle fault reactivation dur-

ing inversion.

7. The deformation at different structural levels of the Vale of Pickering Fault Zone has been witnessed by field, map and seismic data to be consistent with expected deformation along and above a high level, listric detachment fault. The fault zone has not preferentially accomodated inversion by reactivation but has acted as a buffer to the main deformation.
8. The techniques used to model inversion have revealed in detail both the regional and local response to large scale lithospheric compression. They provide an important tool for the understanding of the tectonics and evolution of the Yorkshire, Sole Pit and East Midland Basins.

CHAPTER 6

SUBSIDENCE, INVERSION AND HYDROCARBON SOURCE ROCK MATURATION

6.1 Introduction.

The potential for hydrocarbon occurrences in the study area was suggested by Kendall in 1921 (Kent, 1976), who identified a possible play between Carboniferous and Permian sediments in the Yorkshire Basin. Subsequently, exploration has increased (Falcon and Kent, 1960) up to the present day as this potential was realised. The Yorkshire, Sole Pit and East Midland Basins now form the basis of exploration in the U.K. sector of the Southern North Sea. Substantial gas deposits have, and are being developed, particularly in the Sole Pit Basin area, but also increasingly in the Yorkshire Basin. In the onshore East Midland Basin, accumulations of oil have been found in the Welton and Eakring areas. These two main types of hydrocarbon occurrence reflect the nature of the geological evolution of the respective basins and the types of source deposits that occur.

This study utilises the data, methods and results from the preceding Chapters of this thesis to analyse the history of subsidence and inversion and how they have affected the development of potential source rocks in the Yorkshire, Sole Pit and East Midland Basins. It is beyond the limits of this study to model the relationships in time of maturation, migration and trap formation.

6.2 Source Rocks.

Source rocks in the Yorkshire, Sole Pit and East Midland Basins are provided by the sediments from the Carboniferous and post-Carboniferous (Permian to Cretaceous) basinal developments which as discussed in Chapter 5 are superimposed. Thus, the Carboniferous source rocks have had a complex and long lived geolog-

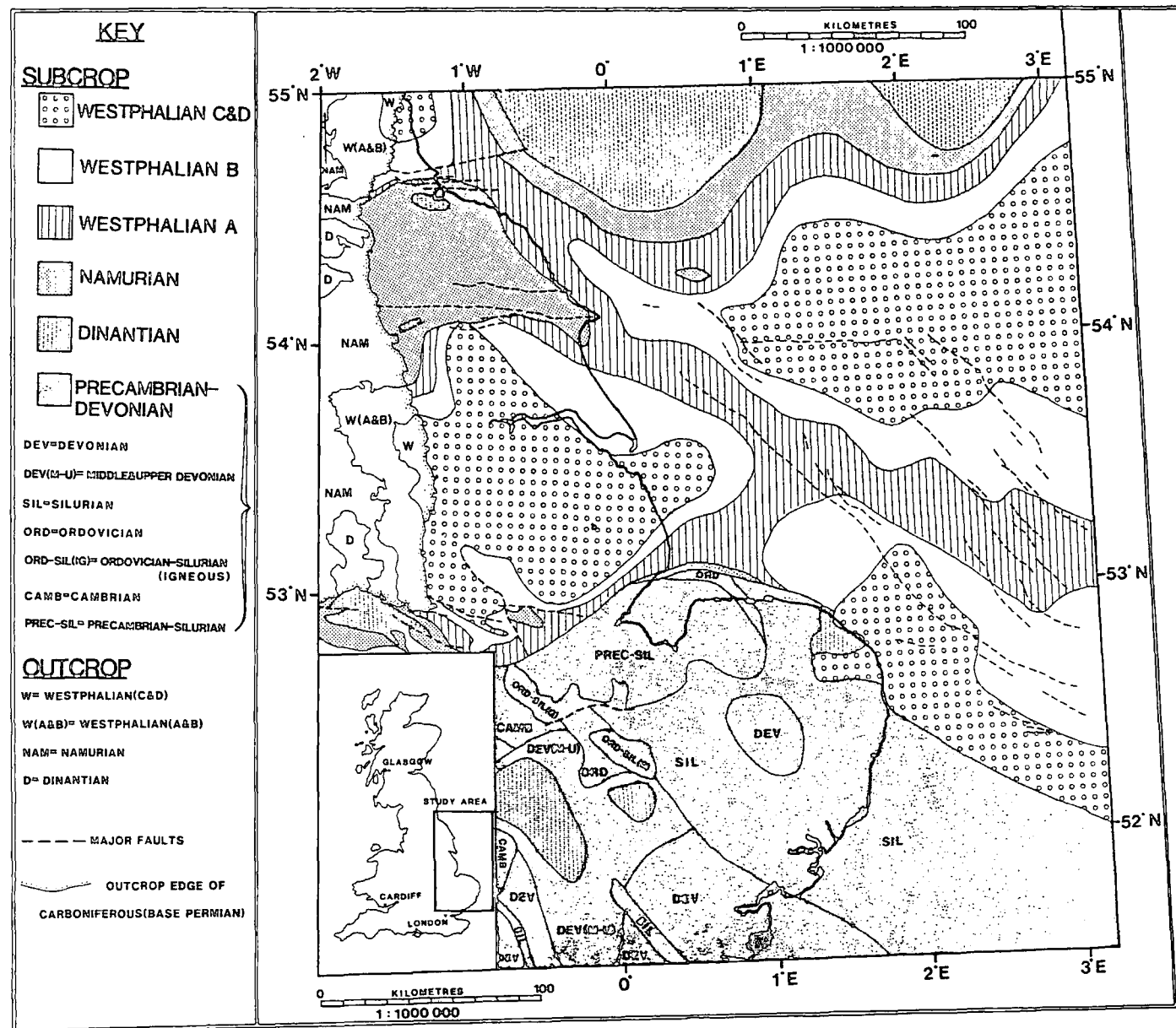


Figure 6.1. Outcrop and subcrop extent of Carboniferous (Dinantian to Westphalian) source rocks.

ical history, including two episodes of subsidence. This increases the chances of these sediments to be buried to maturity or to be subjected to sufficiently high temperature events. However, it also increases the chances of the sediments to be subjected to a destructive event, such as inversion and uplift. The effects of the Late Carboniferous (Variscan) inversion and the Late Cretaceous to Early Tertiary (Sub-Hercynian - Laramide, Ziegler, 1978) inversion on the source rocks will be discussed below.

The main source rocks are:-

1. Carboniferous

The most abundant source rock deposit in the Carboniferous is coal, a type III kerogen (Tissot, 1984). Extensive coals occur in the Westphalian, but also in smaller quantities in Namurian and Dinantian sediments. Despite the effects of Variscan inversion, Westphalian Coal Measures subcrop extensively across the study area (figure 6.1). In the Namurian of the Central Pennines and East Midland area, extensive organic, pelagic shales occur (Edale Shales- Anderton et al, 1979). Their occurrence appears to be restricted to the south of the Carboniferous Yorkshire Basin, in the Craven Basin (Ramsbottom, 1966). This may be important to the apparent preferential development of Carboniferous oil fields in the Welton and Eakring areas of the East Midland Basin. Because of the lack of available data for the Carboniferous sediments, the top of the Carboniferous has been used as a datum point in this study. Clearly the results will therefore not be a maximum for source rocks buried at depth in the Westphalian and Namurian sequences.

2. Lower Jurassic

The organic rich Toarcian (Upper Lias) Jet Rock provides a potential source rock. Data on the kerogen content throughout the Lower Jurassic marine shales is

not available. Therefore, the top of the Lower Jurassic is taken as a datum point.

3. Upper Jurassic

The Upper Jurassic Kimmeridge and Oxford Clays provide the youngest potential source rock horizons. The former, in particular is an important source for hydrocarbons throughout much of the North Sea. The top of the Kimmeridge Clay, where present, is taken as a datum point.

6.3 Reservoir Rocks.

Carboniferous deltaic sandstones, Permian sandstones and carbonates, Triassic sandstones and Middle Jurassic deltaic sandstones are all potential reservoir rocks in the study area. Permian sediments provide the main target in the study area (Department of Energy, published borehole information) but their development and that of the other potential reservoirs will not be discussed further.

6.4 Source Rock Maturation.

The evaluation of a source rock formation must take account of its history of subsidence and sedimentation (compacted or decompacted), its history of inversion or erosion, the geothermal gradient or gradients to which it has been subjected and its regional distribution.

Because of the two major periods of inversion which caused basement uplift and erosion (Chapters 3 and 5) some of the source rocks of Carboniferous and post-Carboniferous age have been removed. This is most pronounced over the Yorkshire and Sole Pit Basins where inversion was most severe. Figures 6.1, 6.2, 6.3 and 6.4 illustrate the present day outcrop and depth to subcrop of the Carboniferous (Westphalian and Namurian), Lower Jurassic and Upper Jurassic source rocks mentioned above (section 6.2). The effects and location of both inversion episodes can be seen. Despite these destructive events, substantial source

rocks are preserved in the study area.

In addition to the depth of burial of potential source rocks, the temperatures which they reach at these depths are also initially important in determining their state of maturity. The present day geothermal gradients across the United Kingdom and North Sea area are illustrated in figure 6.5. It is evident that the East Midland and Sole Pit Basins lie within an area of relatively high gradients compared to the Yorkshire Basin. Low gradients in the latter may reflect its inverted nature, whilst higher gradients in the similarly inverted Sole Pit Basin may reflect conduction by salt (Cornelius, 1975; Andrews-Speed et al, 1984). Higher gradients in the East Midland Basin may reflect the insulating effect of the younger, preserved sediments and retention of part of its basinal/subsiding thermal phase.

The present day geothermal gradient is unlikely to reflect the palaeogeothermal gradient. The palaeogeothermal gradient will have varied in time and will also vary in magnitude according to the type of basin formation (Waples, 1980; Cornelius, *op.cit*; Issler, 1984; Guidish et al, 1985; Price, 1983). Thus, the amount of lithospheric stretching will by inference reflect the contribution of heat during basin formation. It has been concluded (Chapter 4) that the form of the tectonic subsidence in the Yorkshire, Sole Pit and East Midland Basins correlates closely to the predicted model of uniform lithospheric stretching. This suggests the occurrence of a relatively high thermal anomaly during rifting which decayed in time due to thermal relaxation and subsidence. The importance of the basin formation model with respect to the lithospheric temperature structure has been recognised by Guidish et al *op.cit.*) and McKenzie (1978, 1981), but attempts to actually clarify or quantify these temperatures have not been made. In this study it is assumed that the palaeogeothermal gradient was higher than at present, particularly in the Yorkshire Basin.

The following sections compute the maximum depth of burial and subsidence

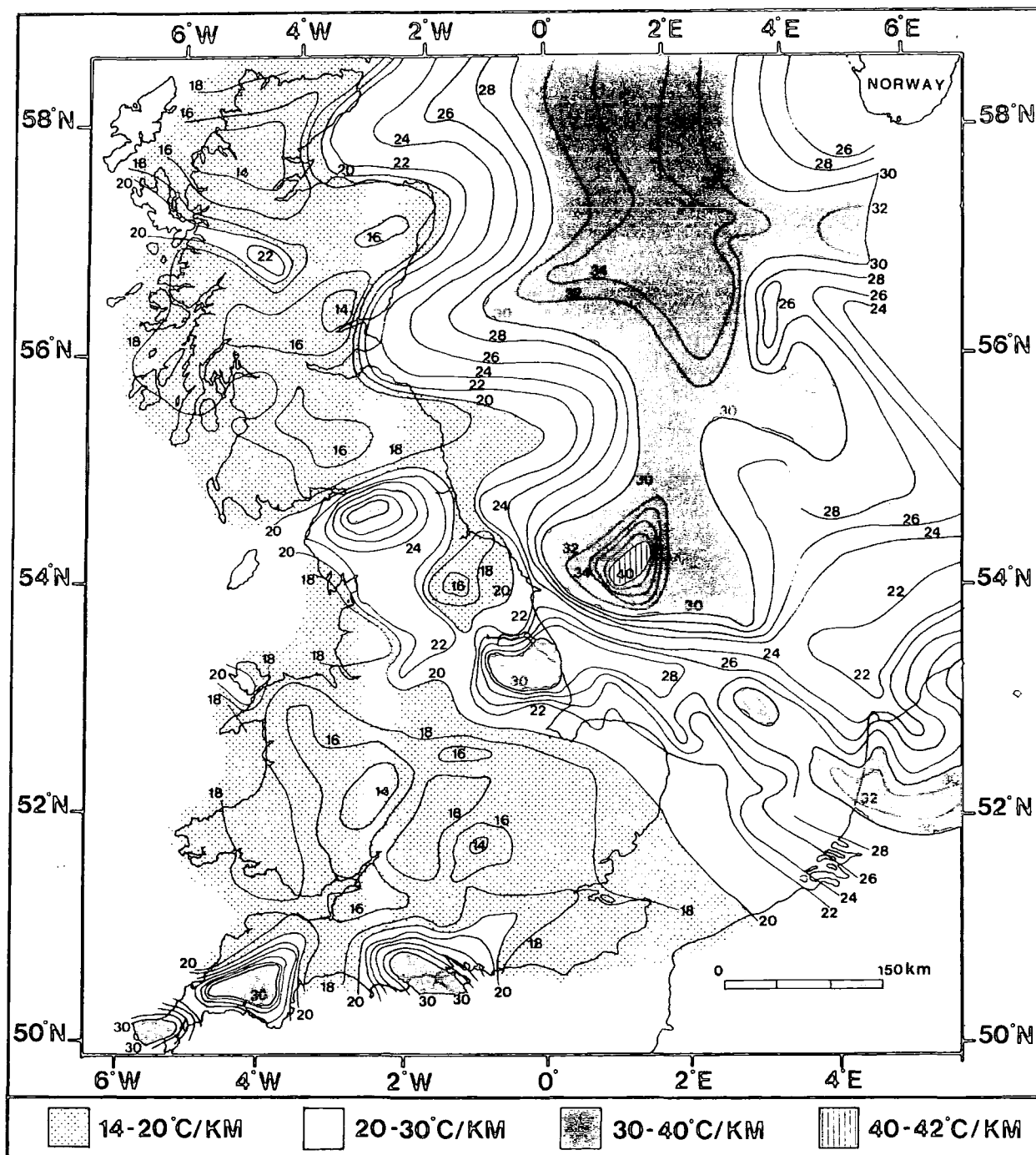


Figure 6.5. Present day geothermal gradient of the UK and North Sea area (from Downing and Gray, 1986; Harper, 1971).

history of the source rocks and investigate their degree of maturation accounting for both present and past geothermal gradients.

6.4.1. Maximum Burial Depth of Source Rocks.

In chapter 3 the amount of uplift and removed sediment has been estimated for the Yorkshire, Sole Pit and East Midland Basins (figure 3.33). Using this data, the maximum burial depth of the source rocks prior to inversion has been calculated. This allows a tentative reconstruction of the original extent of source rocks in the now inverted but previously differentially subsiding basins.

Figures 6.6, 6.7 and 6.8 correspond to the reconstructed maximum depths to the top of the Carboniferous, Lower Jurassic and Upper Jurassic respectively.

6.4.1A. Carboniferous.

The reconstructed depth to the top of the Carboniferous (figure 6.6) represents a minimum value for any source rock or horizon in the basins. Maximum values occur in the Sole Pit Basin which correspond to high reflectance values of 1 - 2.8 (Roberts, 1980; Cornford, 1986). The potential for hydrocarbon generation, particularly gas, from Carboniferous coals and/or shales is greatest in this region. Maximum values in the Yorkshire Basin correspond to approximately 3 - 3.5 km offshore and lie above the post-inversion extent of the coal bearing Westphalian sequence (figure 6.1). Values in the onshore Yorkshire Basin approach 2 - 3 km and lie above the main inverted part of the Carboniferous Basin. Westphalian sediments have been largely removed (figure 6.1), but clearly gas accumulations could occur due to their preservation offshore. Additionally, the Namurian sequence consists of coal bearing strata.

In the East Midland Basin values onshore are of the order of 1.5 to 2 km. Addition of the Westphalian sedimentary thickness and a reasonable palaeogeothermal

gradient of $35 - 40^{\circ} \text{ C/km}$ (oil generation = $60 - 150^{\circ} \text{ C}$) facilitates the necessary maturity of Na murian shales, as Pering (1973) suggested.

6.4.1B. Lower Jurassic.

The reconstructed depth to the top of the Lower Jurassic (figure 6.7) is assumed to represent the depth to the top of the organic rich Toarcian Jet Rock. Values as expected are at a maximum in the Sole Pit and Yorkshire Basins. However, the top of the Lower Jurassic is largely missing from the Sole Pit Basin and their source, reservoir (Middle Jurassic?) and trap may have been destroyed. Lower Jurassic sediments would have been immature to early mature at their maximum depth and time of burial. Similar values occur in the Yorkshire Basin area. Local occurrences of hydrocarbons confirm these results (oil in ammonite chambers - Staithes to Port Mulgrave - this study). However, as in the Sole Pit Basin, uplift and erosion have destroyed prospects particularly in the northern half of the basin.

In the East Midland Basin, present day depth of burial (figure 6.3) corresponds more closely to the reconstructed value (figure 6.7). The basin has suffered less inversion. However, the Lower Jurassic shales are not as organic rich as in the Yorkshire Basin and predicted maximum burial infers the sediments would be immature.

6.4.1C. Upper Jurassic.

Upper Jurassic source rocks include the organic rich shales of the Oxford and Kimmeridge Clay Formations, particularly the latter. The distribution of the Kimmeridge (and Oxford) Clay has been severely truncated by erosion (figure 6.4). Maximum burial depth in areas where it is preserved (figure 6.8) are of the order $0.5 - 1 \text{ km}$ and hence these potential source rocks would have been immature for oil generation. Locally higher values may have occurred in or on the flanks of

the Sole Pit Basin.

6.4.2. Time/Temperature Index (TTI) and Burial History of Source Rocks.

The maximum depth of burial to which a source rock has been buried is not the sole criteria for evaluating maturity. Organic material will mature as the temperature increases during burial (Waples, 1980). The integrated time/temperature and hence burial history determines the evolution of maturation. Burial or subsidence curves provide a direct means of recording the timing and magnitude of geological events. When combined with a geothermal gradient (either constant or variable in time) burial curves can map the path of a source rock through phases of hydrocarbon generation (figure 6.9).

Lopatin (1971) recognised the importance of both time and temperature during burial. He developed a quantitative method for assessing the maturation of a source horizon accounting for both temperature and time and also the change in the reaction kinetics of organic matter with temperature. Thus,

$$TTI = time \times r^n$$

The method assumes that reaction state, r , doubles every $10^{\circ}C$. Time is the duration the source horizon spends in each temperature increment and n varies with each temperature increment.

The TTI is a numerical scale on which the onset of oil generation = 15, end of oil generation = 160, end of wet gas generation = 1500 and end of dry gas generation = 65000. However, the fields for oil and gas generation may overlap considerably. Immature oil maturation may occur at lower values than 15, eg. 3 - 6 (Issler, 1984).

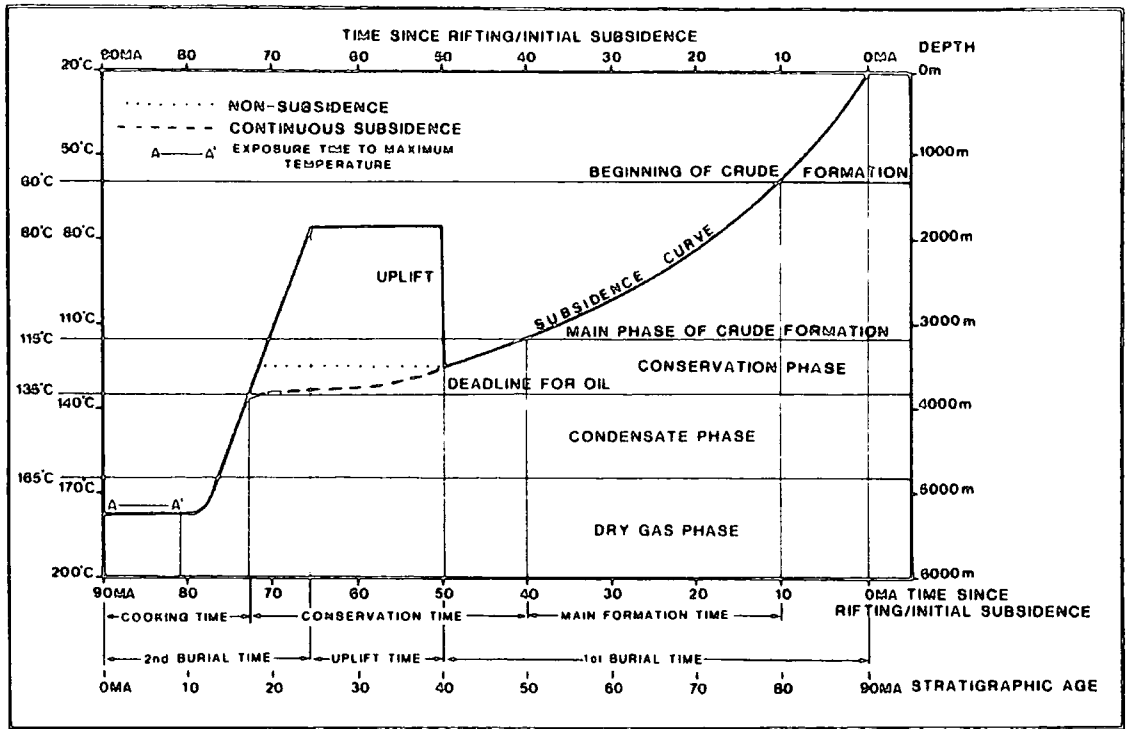


Figure 6.9. History of subsidence and thermal maturation of a hypothetical source rock (after Cornelius, 1975).

	TOP CARB.	TOP LIAS	TOP K.C.
48/25-1	184		
48/12-1	271	1.0	
41/25-1	71		
ROSEDALE	6.1	1.0	
MALTON	10	1.1	0.48
47/29A-1	3.4	0.65	0.28
47/8-A1	33.7	0.84	0.46
NETTLETON A	6.4	0.66	0.3
NETTLETON B	323	7.0	0.6

15 - ONSET OF OIL GENERATION. 160 - END OF OIL GENERATION.
1500 - WET GAS DEADLINE.

THESE MATURATION FIELDS MAY OVERLAP SUBSTANTIALLY

Table 6.1. Time-temperature indices of source rocks in the Yorkshire, Sole Pit and East Midland Basins using Lopatin's method(1971). Reconstructed subsidence curves displayed in figures 6.10, 6.11, 6.12, 6.13.

In Chapter 4 the basement, tectonic driving subsidence was calculated by backstripping. This technique sequentially decompacts the sediments through time. The data from this study (Chapter 4) has been used to produce burial curves accounting for decompaction in the Yorkshire, Sole Pit and East Midland Basins. Present day geothermal gradients have been used to produce a minimum estimate of maturation because of difficulties in accurately modelling the variation in the geothermal ^{gradient} during basin formation. As discussed (section 6.4) it is expected to have been higher through some or all of the subsidence history of the basins.

Figures 6.10, 6.11, 6.12 and 6.13 illustrate the decompacted burial curves of the top Carboniferous and where present top Lower Jurassic and Upper Jurassic horizons in the Yorkshire, Sole Pit and East Midland Basins. TTI maturity values for the above horizons are illustrated in Table 6.1.

6.4.2A. Carboniferous.

TTI values (Table 6.1) signify that applying the present day geothermal gradient (figure 6.5) to the reconstructed (pre-inversion) and decompacted burial curve for the Carboniferous in the Sole Pit Basin (figure 6.10) is sufficient for gas generation to have occurred prior to Late Cretaceous uplift. This uplift did not destroy source horizons but may have influenced subsequent migration and trap creation.

TTI values for the top Carboniferous in the onshore Yorkshire Basin are low, but increase offshore (figure 6.11 and Table 6.1). The present day geothermal gradient in the Yorkshire Basin is also significantly lower than the East Midland and Sole Pit Basins (figure 6.5). This is believed to be a remnant of uplift and inversion and not of subsidence during which geothermal gradients were higher. Imparting a ten to fifteen degrees per kilometre higher geothermal gradient pushes TTI values more closely towards the values observed in the Sole Pit Basin. It is unsure whether the Namurian sediments can act as a source in the Yorkshire Basin,

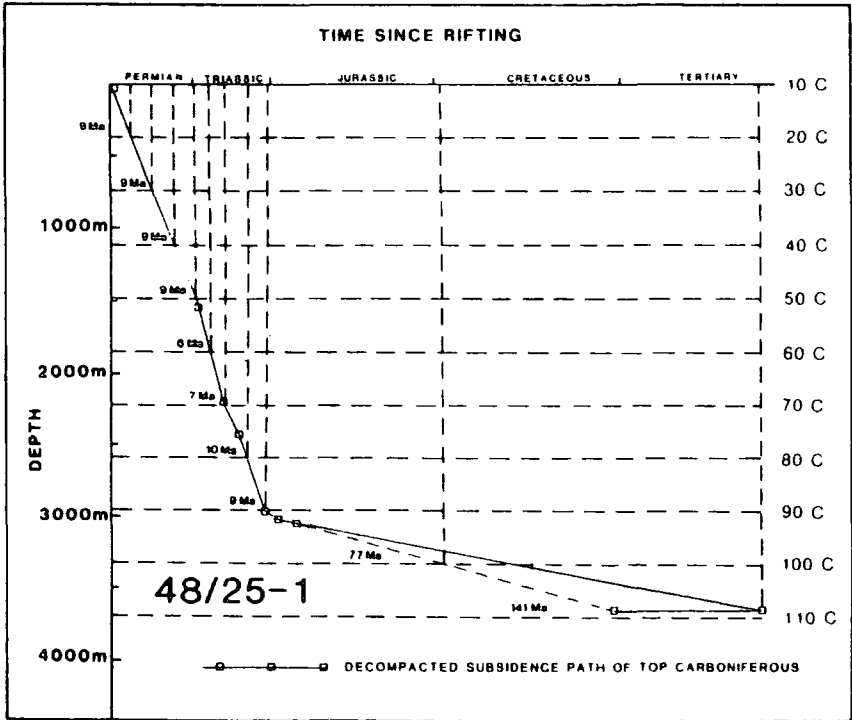
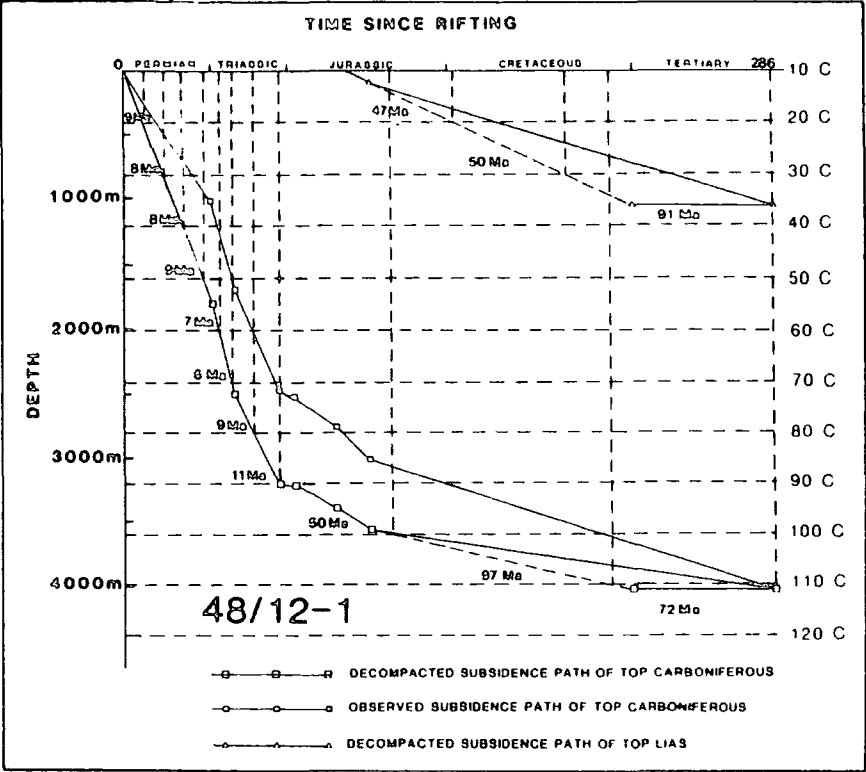


Figure 6.10. Reconstructed subsidence history of Carboniferous and Lower Jurassic (Lias) source rocks in the Sole Pit Basin. Present day geothermal gradient (figure 6.5). TTI results in Table 6.1.

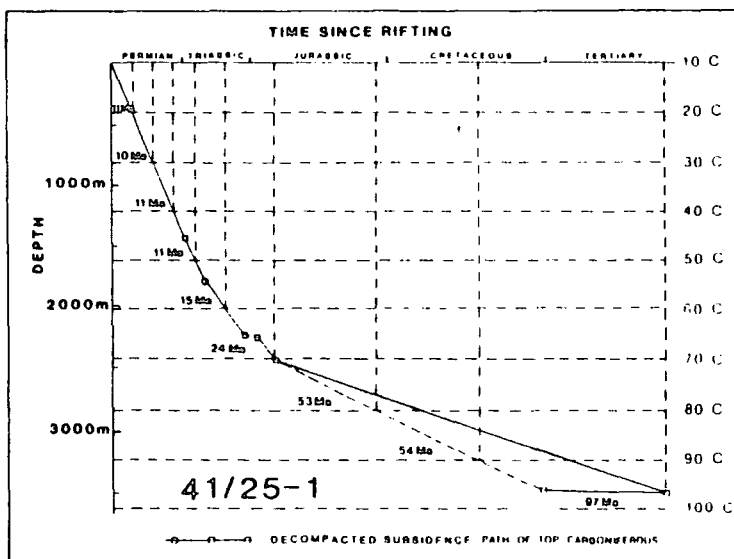
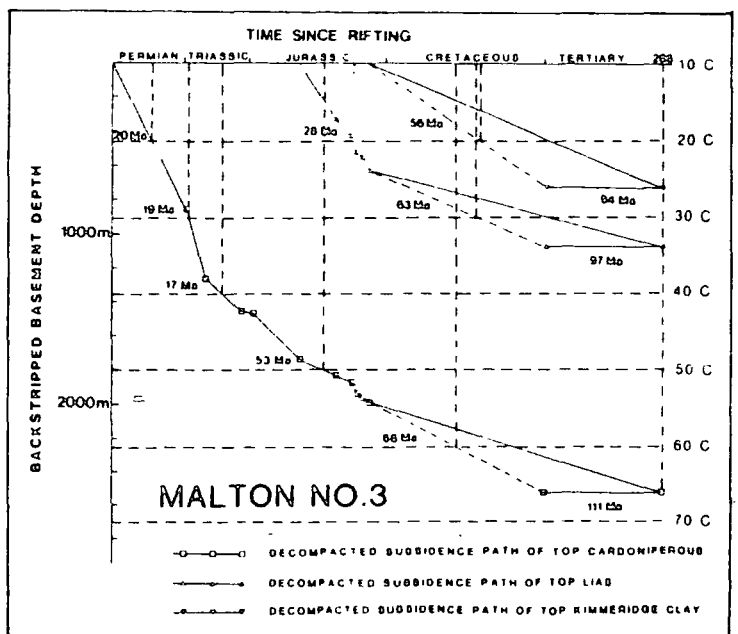
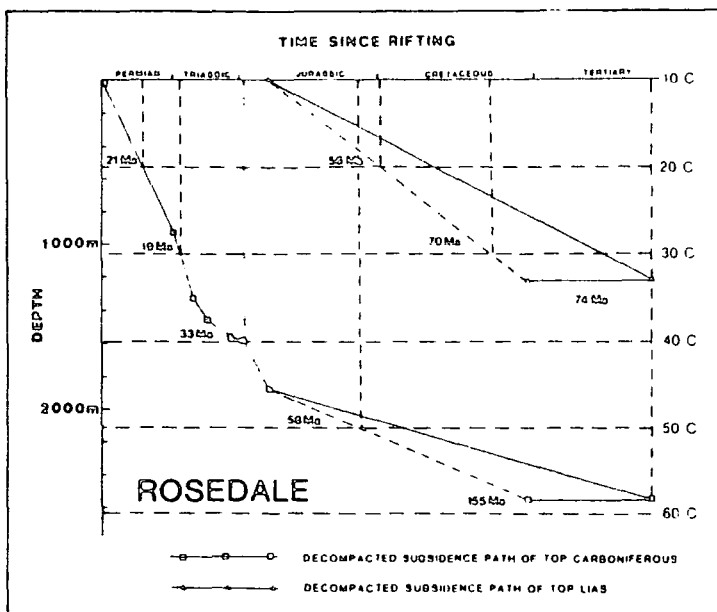


Figure 6.11. Reconstructed subsidence history of Carboniferous and Lower and Upper Jurassic source rocks in the Yorkshire Basin. Present day geothermal gradient (figure 6.5). TTI results in Table 6.1.

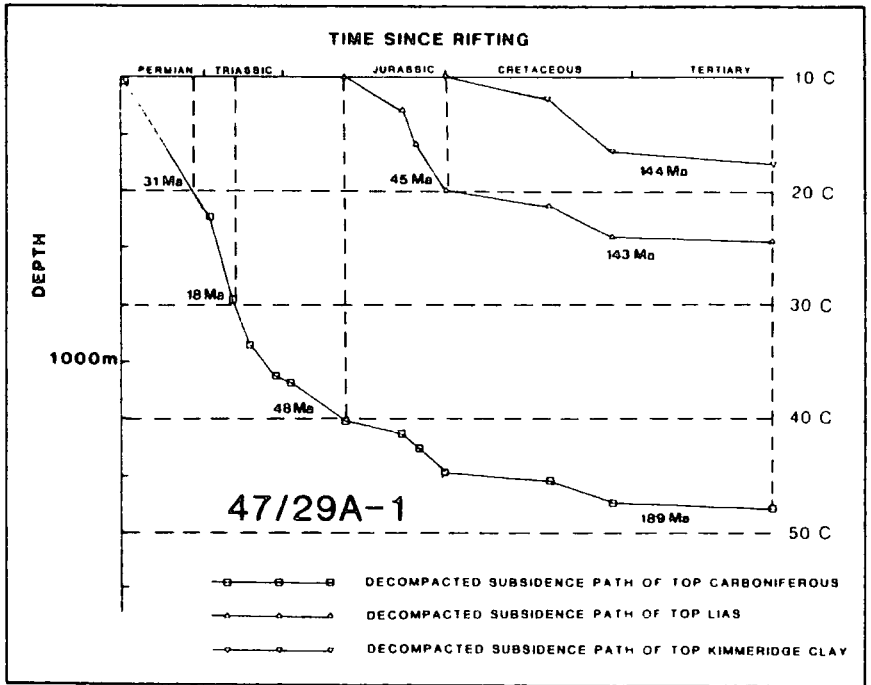
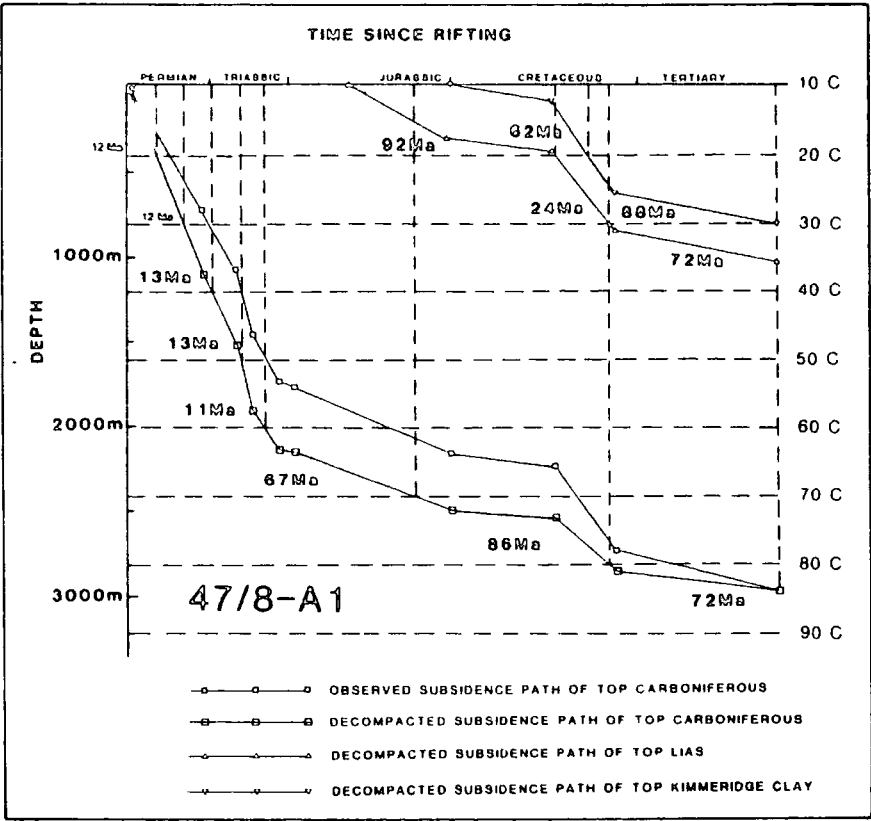


Figure 6.12. Reconstructed subsidence history of Carboniferous and Lower and Upper Jurassic source rocks in the East Midland Basin. Present day geothermal gradient (figure 6.5). TTI results in Table 6.1.

in the absence of Westphalian sediments. However, as borehole 41/25A-1 displays, gas generation may be more pronounced offshore where burial by Permian and younger sediments was greatest and also where Westphalian coal bearing deposits are preserved (figure 6.1). Migration could feasibly occur westwards and up dip into the margins of the Southern North Sea Basin.

TTI values for the top Carboniferous in the East Midland Basin are suggested to more closely represent the expected maturation level, as the present geothermal gradient (figure 6.5) is possibly more analogous to the palaeogeothermal gradient. Values approximate to those for oil generation. The source rocks are not expected to have been buried to sufficient depths or temperatures for gas generation. In the onshore East Midland Basin, where Namurian oil accumulations are found, values are immature at the top of the Carboniferous (Nettleton, 47/29A-1 - figure 6.12 and Table 6.1). Addition of the Westphalian sedimentary thickness increases the TTI values computed.

6.4.2B. Lower Jurassic.

TTI values in all three basins concerned are low and infer that the top of the Lower Jurassic was and is immature. However, a higher geothermal gradient is expected for the Yorkshire Basin. As in the case for Carboniferous gas generation (section 6.4.2A.), a higher geothermal gradient would give values within the region of oil generation and explain the occurrence of oil at this level in the basin.

6.4.2C. Upper Jurassic.

Where the Upper Jurassic Kimmeridge Clay is preserved, TTI values suggest that this source would not have been sufficiently mature for hydrocarbon generation (figures 6.10, 6.11, 6.12, 6.13 and Table 6.1). Increased geothermal gradients will not significantly alter this situation.

6.5 Summary and Conclusions.

From quantitative and qualitative studies of subsidence and inversion (Chapters 3,4 and 5) this chapter has investigated the hydrocarbon potential of the Yorkshire, Sole Pit and East Midland Basins. The results have highlighted the applicability of the methods employed, eg. reconstruction of maximum burial depth, burial curve analysis and time/temperature indices, to the evaluation of a basin and the source rock formation within it. They showed good correlation with the known geographical distribution and degree of maturation of hydrocarbon accumulations in the study area.

The most significant errors that could affect these studies are:-

1. A non-representative geothermal gradient. This may have been higher or lower than at present, and has probably varied in time.
2. The accuracy of the calculated amount of removed overburden.
3. The thickness of Carboniferous sediments has not been accounted for.
4. Carboniferous inversion has not been accounted for.
5. Applicability of the TTI method.
 - (a) The reaction rate of hydrocarbons may not be constant.
 - (b) As in most quantitative methods for calculating the degree of hydrocarbon maturation, eg. Vitrinite reflectance, the zones for the stages of oil and gas generation are imprecisely calibrated.
 - (c) The importance of time as an influential parameter for hydrocarbon generation. Price (1983) has suggested that burial depth and hence temperature, and not the time a source rock takes in specified thermal zones, are the most

important or dominant. This is not a widely held view and it is felt that time is important up to the moment where the sediment is no longer buried deeper and is thermally uplifted. Whether a source rock continues to cook and mature in a lower than maximum thermal regime is not clear. The results from the TTI method provide a useful comparison to the results for maximum burial depth. They appear to correlate well, which stresses the importance of both methods.

This study is intended to serve as a basis for other such appraisals of basinal areas that have suffered inversion and the problems that accompany it, eg. alteration of the temperature regime, removal of overburden. The results can be improved by a greater understanding and appreciation of the temperature history of the lithosphere during subsidence and basin formation.

CHAPTER 7

CONCLUSIONS

7.1. Objectives.

The main objectives of this study were:-

1. To utilize a multidisciplinary approach for analysis of the tectonic, structural and sedimentological evolution of the Yorkshire, Sole Pit and East Midland Basins.
2. To quantitatively and qualitatively model the observed development of the Yorkshire, Sole Pit and East Midland Basins with respect to theoretical models of basin formation.
3. To quantify and qualify positive basin inversion in the area.
4. To assess the problems associated with basin formation modelling in positively inverted areas.
5. To model the maturation potential of source rocks in the area accounting for the complex history of burial and uplift in the Yorkshire, Sole Pit and East Midland Basins.

7.2. Conclusions.

1. Satellite remote sensing has potential for regional tectonic correlation and large scale identification of texturally, possibly lithologically, distinct units in the relatively structurally simple post- Carboniferous basins of southern U.K.
2. The primary drawback to the use of satellite remote sensing in the study area is the extent of cover/drift sediments which suppress all categories of geological

expression in the subsurface. The lack of natural vegetation contrasts due to intense agricultural activity also suppresses geological information.

3. Satellite remote sensing provides a useful additional component for basin analysis studies in the Yorkshire Basin. Fracture patterns identified on Seasat SAR data may record deformation related to inversion and uplift of the Yorkshire Basin.
4. The potential of remote sensing techniques as a tool for frontier exploration in the Yorkshire, Wessex and Weald Basins is limited.
5. Sonic velocity records the compaction state of the sediments. This relationship can be used to determine whether sediments are presently at their maximum achieved burial depth.
6. Sonic velocities record that the Yorkshire and Sole Pit Basins have suffered significant uplift and sediment removal. These results have been taken from a multi-lithology study and their magnitude accords reasonably well with known stratigraphic thicknesses in the area.
7. The results suggest that the greater the uplift the greater is the variability in the uplift value computed for different lithologies and formations in the same borehole. This may reflect greater diagenetic influence on the apparent compaction (porosity) of the sediment and/or increased tectonic deformation of the sediments during differential subsidence and inversion.
8. Quantifying the amount of basement uplift and sediment removed has enabled reconstruction of the sedimentary thicknesses in the Yorkshire, Sole Pit and East Midland Basins. This in turn facilitates more accurate modelling of the nature of basin formation and the tectonic processes controlling it.
9. Modelling of the observed subsidence in the area suggests that basin forma-

tion conforms closely to the uniform lithospheric stretching model of McKenzie (1978), and that there is a significant component of thermal subsidence involved throughout its duration.

10. The onset of rifting is a synchronous and rapid basin wide event which infers thermal subsidence and significant sub-crustal lithospheric involvement.
11. The observed distribution of sediments accords well with the characteristic steer's head geometry for uniform lithospheric stretching.
12. Predicted extension factors for the uniform stretching model accord reasonably well with those observed from fault geometries.
13. The regional or background thermal subsidence is punctuated by a number of discrete or finite events related to renewed phases of mechanical, fault controlled subsidence.
14. The Upper Cretaceous coincides with a major eustatic sea-level rise. This exaggerates the effects of thermal subsidence due to a regional increase in load on a flexurally strengthening lithosphere. This is recorded by the tectonic subsidence curves.
15. Regional thermal/flexural subsidence was terminated in the Upper Cretaceous to Lower Tertiary by differential uplift or positive inversion of the basins in response to a change in regional stress from extension to compression.
16. Positive basin inversion was accommodated by the same structures which controlled basin formation.
17. Total basement uplift, tectonic uplift and crustal shortening have been shown to be preferentially accommodated within the Yorkshire and Sole Pit Basins. This reflects the importance of the geometry and orientation of pre-existing

basinal and basement faults during the subsequent deformation.

18. Local, brittle structural deformation including thrusting and reverse stratigraphic offsets occur adjacent to and above pre-existing extensional faults. This deformation represents subtle fault reactivation during inversion.
19. The techniques used to model positive basin inversion have revealed in detail the regional and local response to large scale lithospheric compression.
20. The study of basin formation and inversion has been used to model the maturation potential of source rocks in the area. The results show that the Carboniferous sediments have the greatest potential due to their greater burial and more widespread distribution. Lower and Upper Jurassic source rocks have in general not been buried to sufficient depths and have also suffered major uplift and erosion, specifically from areas where they achieved maximum burial, ie. the Yorkshire and Sole Pit Basins.
21. These results have revealed the importance of identifying and quantifying episodes of partial basin destruction. This must be compensated for in one's analysis of maturation potential, particularly in inverted basins.

The final conclusions of this multidisciplinary study of basin evolution suggest that the Southern North Sea Basin may have formed in response to uniform lithospheric stretching with a significant component of sub-crustal lithospheric involvement and thermal subsidence. This model differs from other models invoked for the formation of neighbouring basins, eg. Wessex Basin, which is thought to have developed mainly by upper crustal extension and block faulting with minor sub-crustal lithospheric involvement (Lake, 1985). The observed subsidence curves correlate well with the theoretically modelled curves for uniform lithospheric stretching in each of the Yorkshire, Sole Pit and East Midland Basins.

Subsidence, as in other post-Carboniferous basins in Northwest Europe, was terminated by a reversal in the regional stress which resulted in differential positive inversion and partial destruction of the Yorkshire, Sole Pit and East Midland Basins. This event was controlled by reactivation of earlier structures and its large magnitude may reflect the presence of weak high-level (3 - 4 km) crustal detachments, eg. Permo-Triassic salt horizons, above which most of the deformation would be concentrated.

This study has drawn important conclusions about the mechanisms controlling the history of the formation and partial destruction of the Yorkshire, Sole Pit and East Midland Basins.

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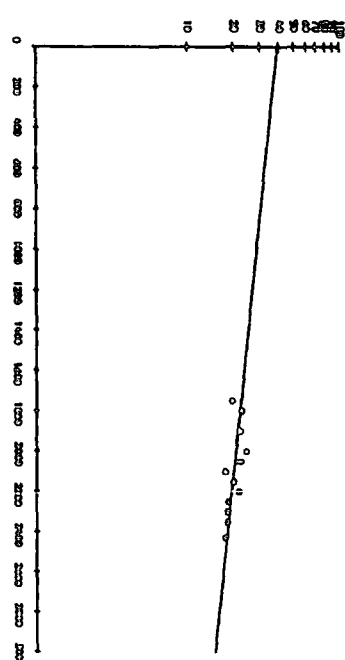
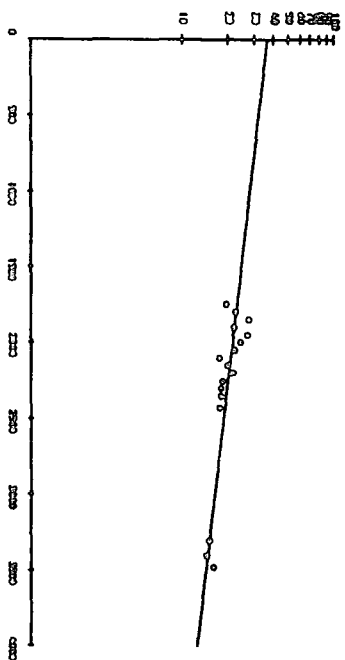
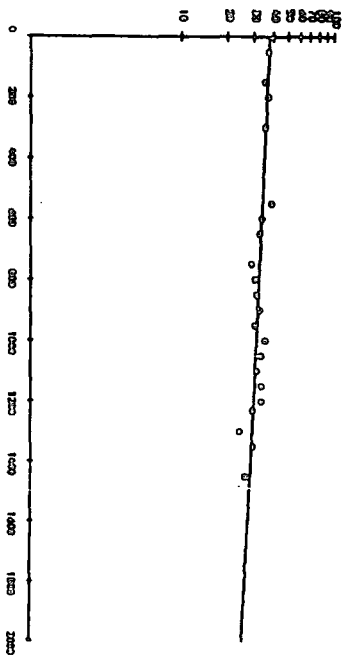
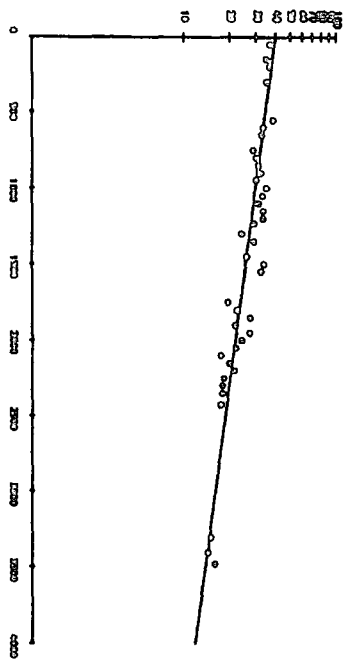
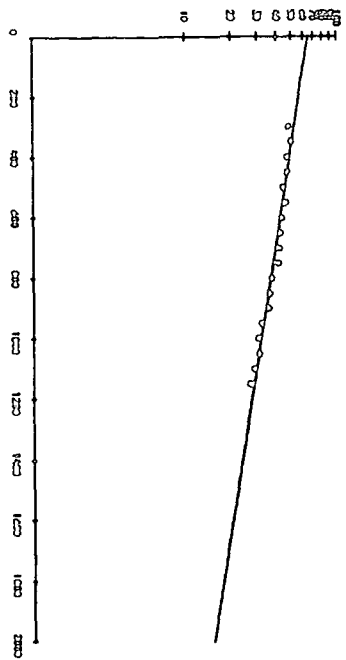
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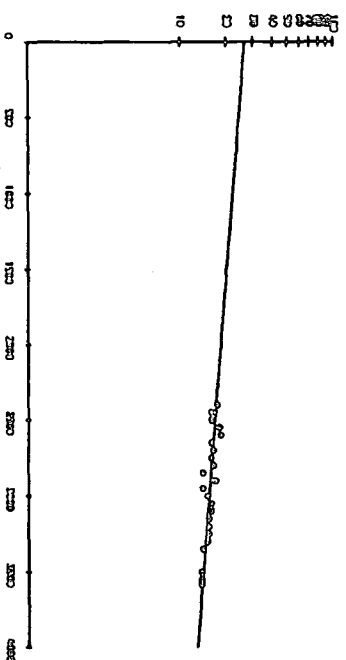
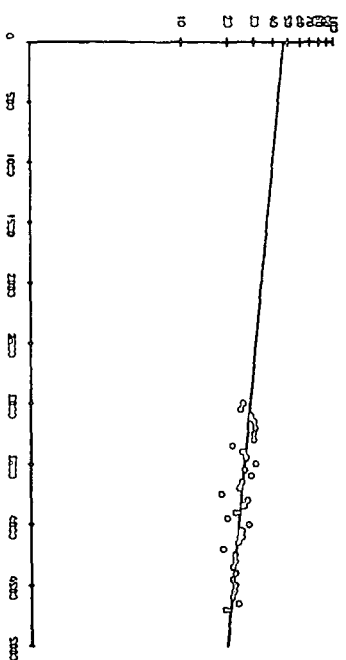
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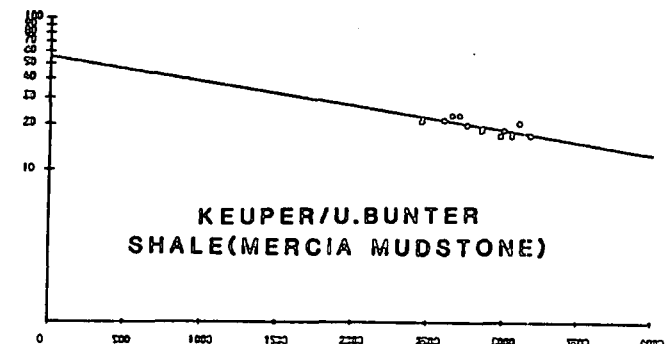
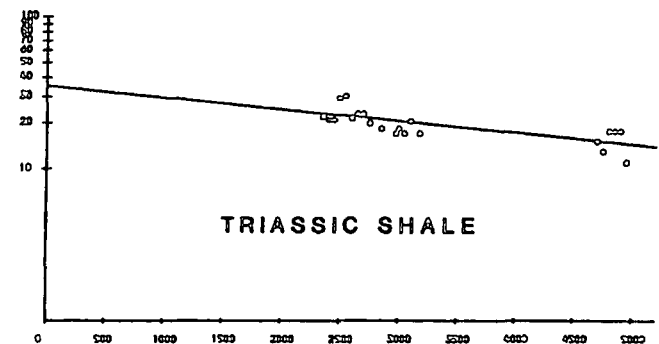
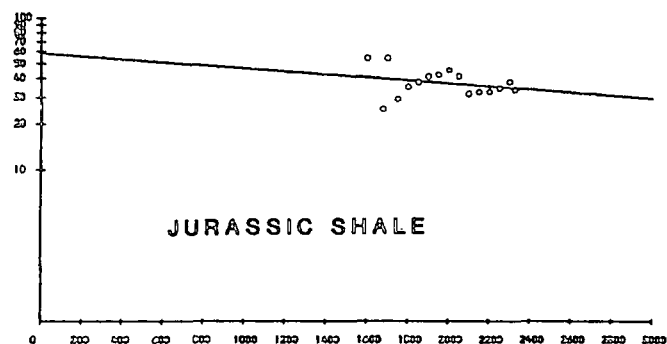
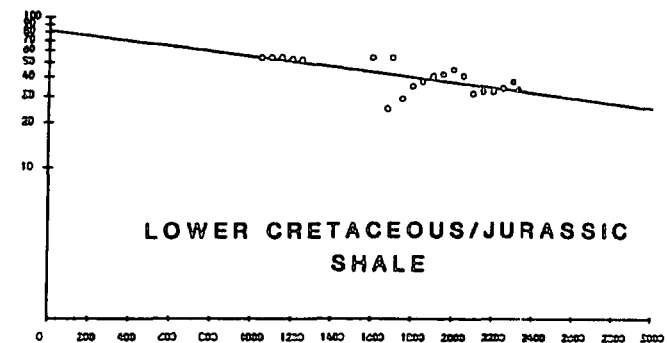
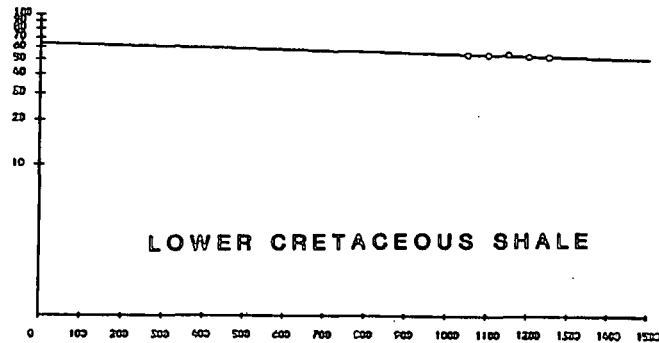
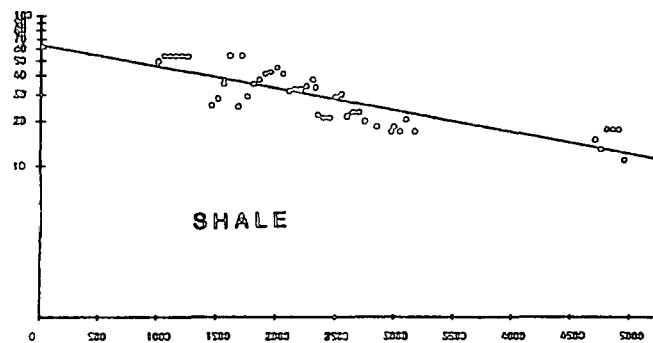
APPENDIX C3



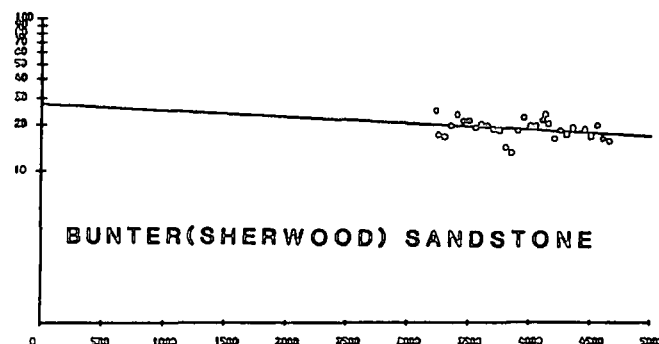
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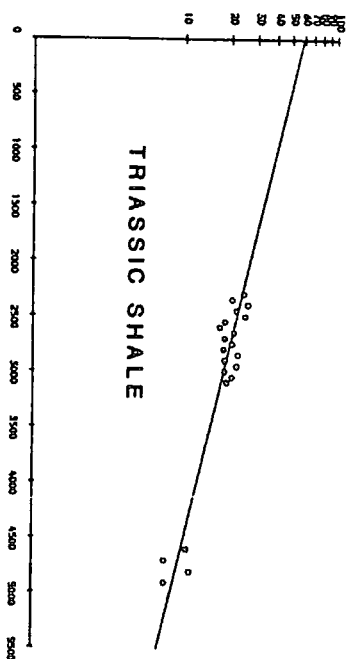
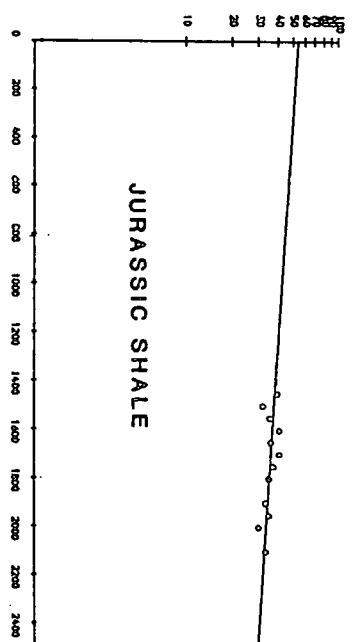
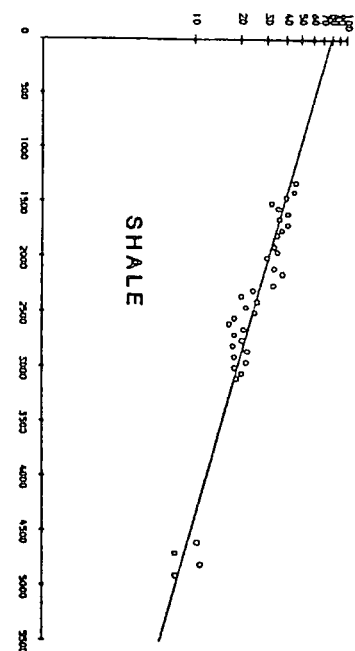
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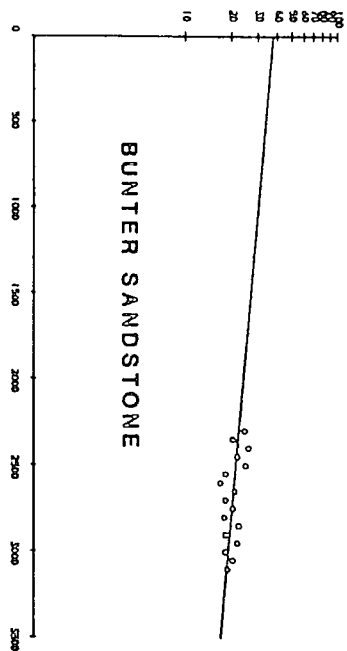
FORDON 2



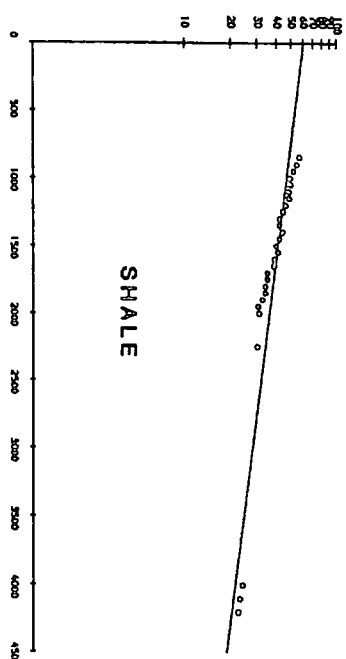
HUNMANBY



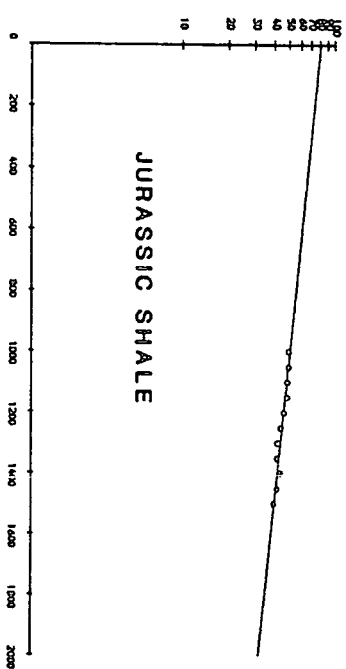
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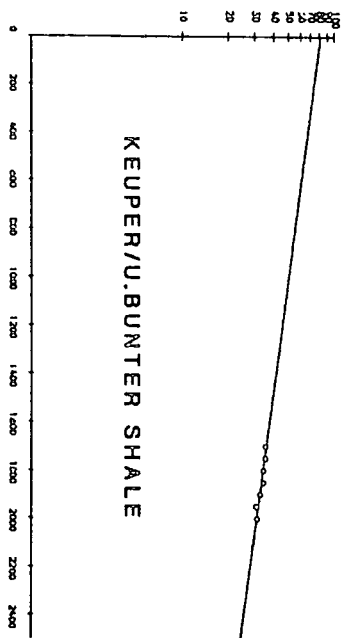
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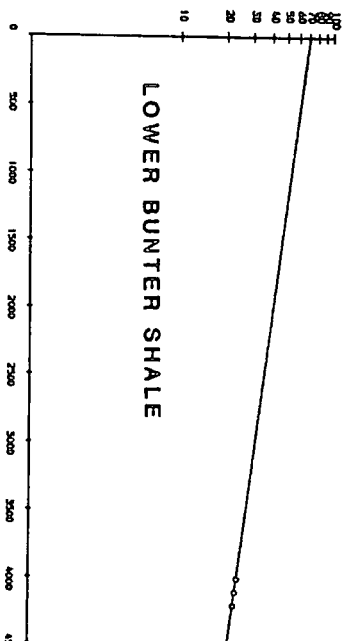
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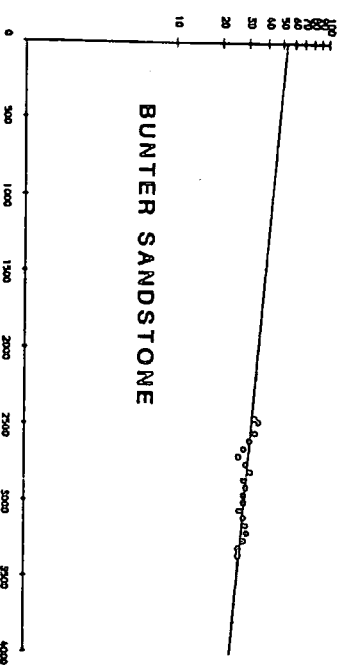
KEUPER/U.BUNTER SHALE



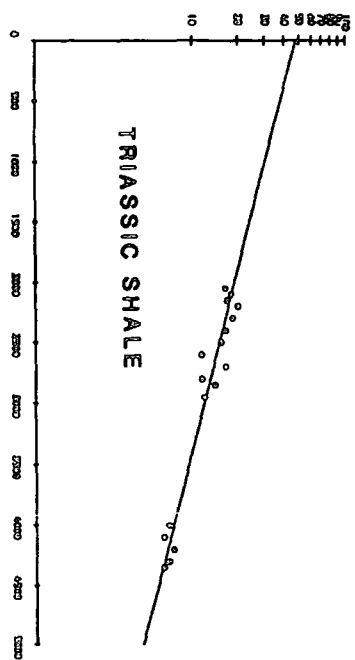
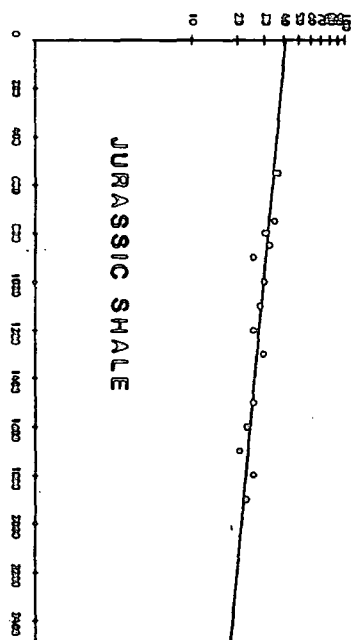
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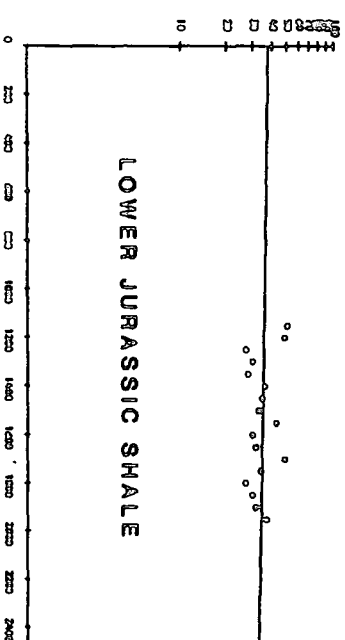
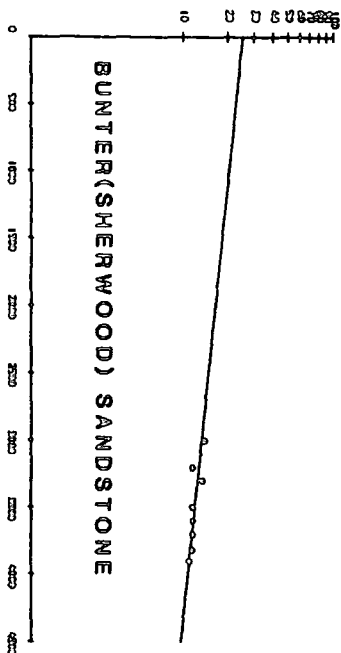
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LANGTOFT

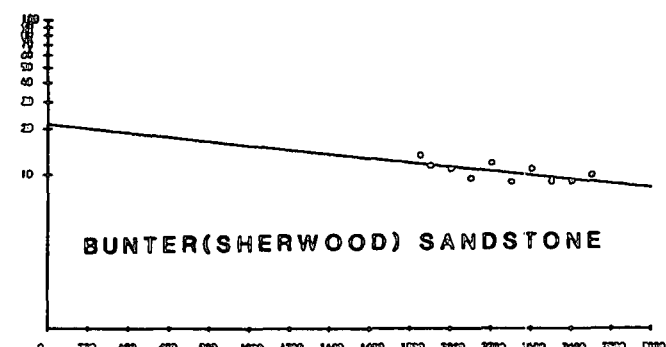
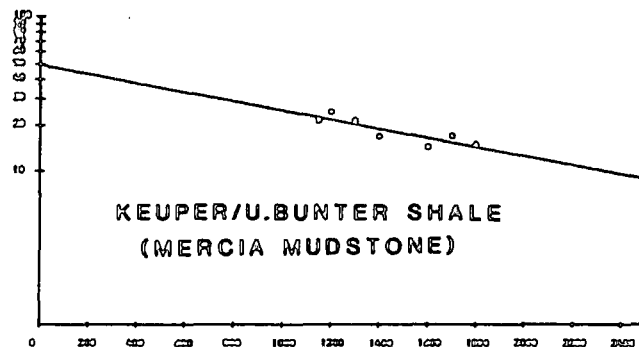
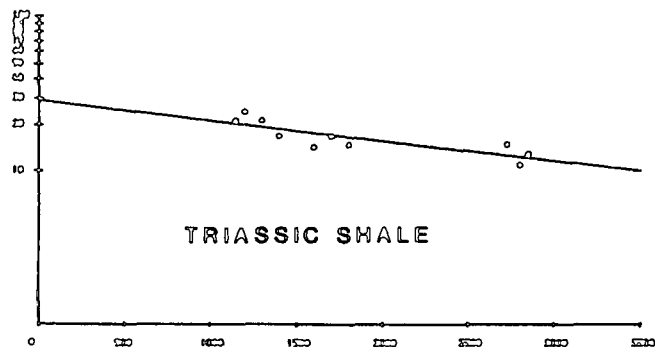
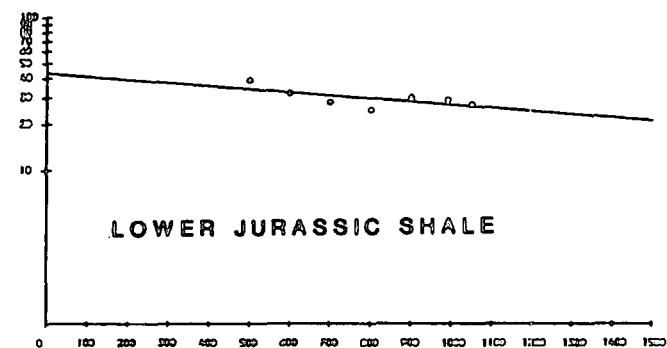
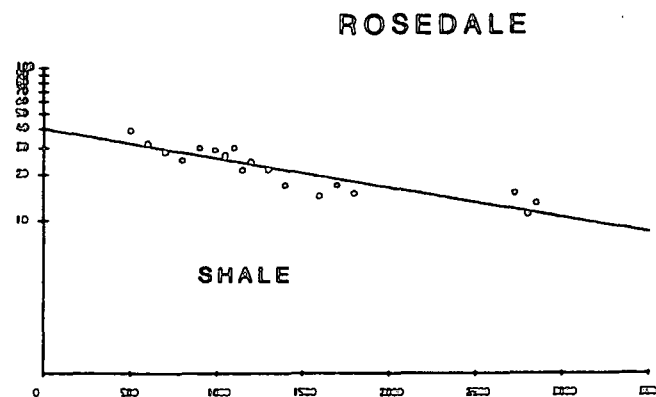
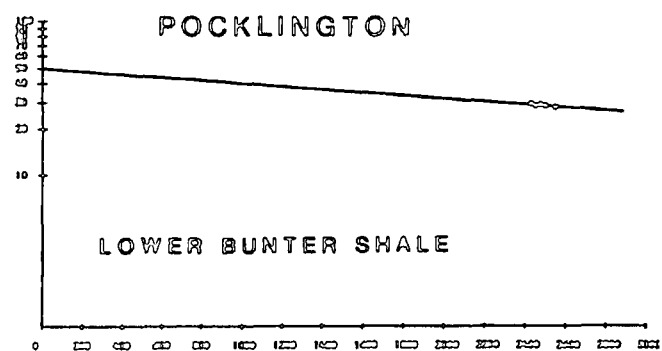
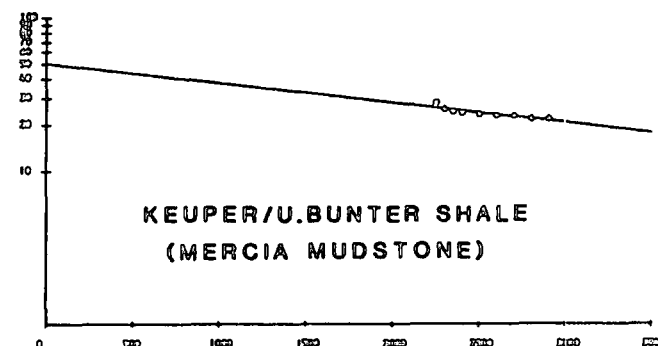
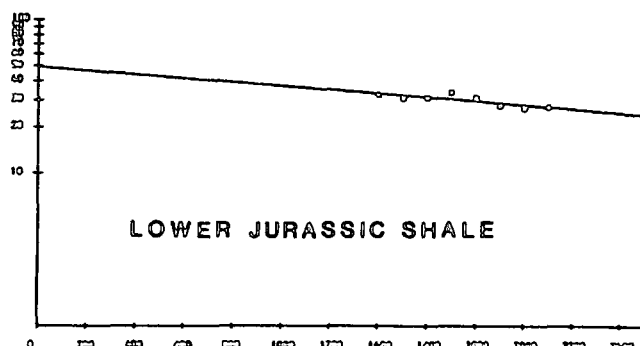
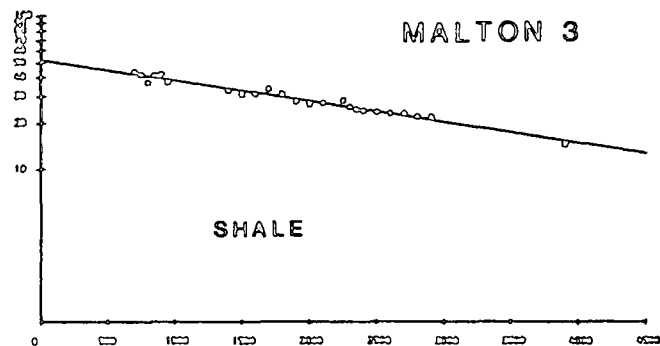


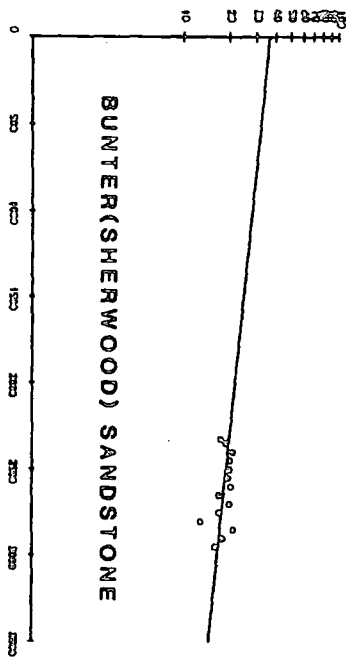
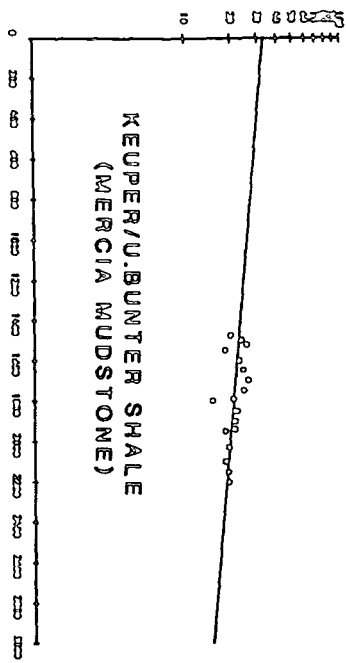
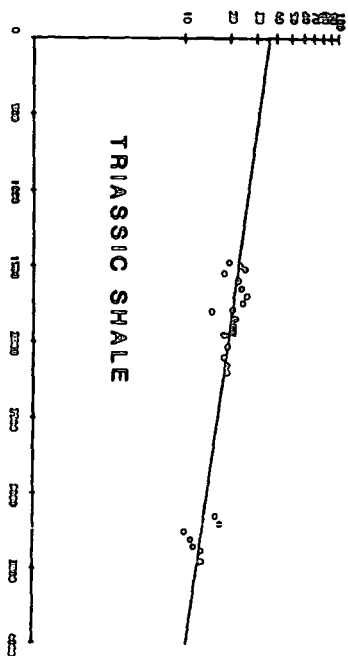
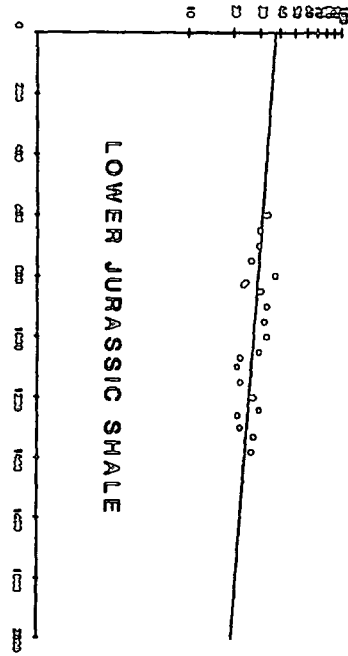
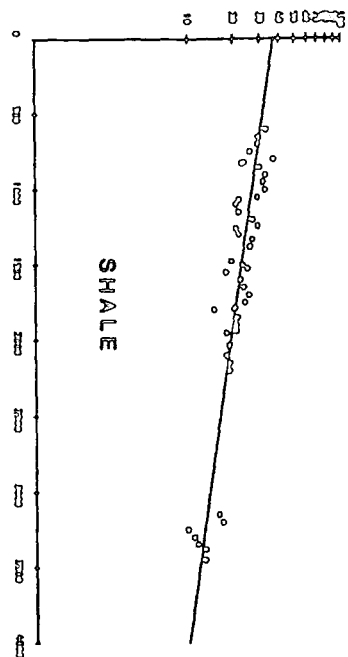
KEUPER/U BUNTER SHALE
(MERCIA MUDSTONE)



KEUPER/U. BUNTER SHALE
(MERCIA MUDSTONE)

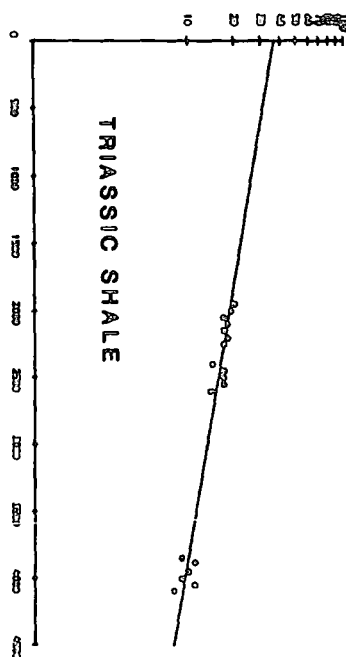
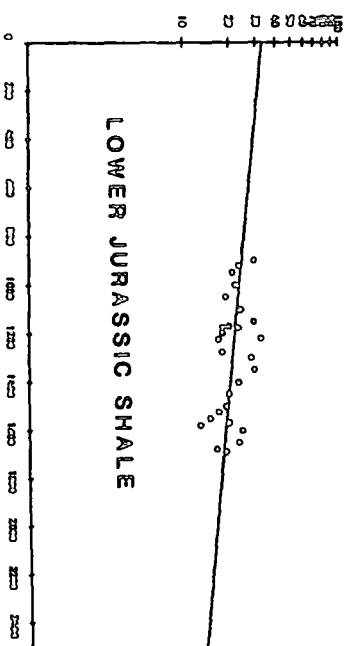
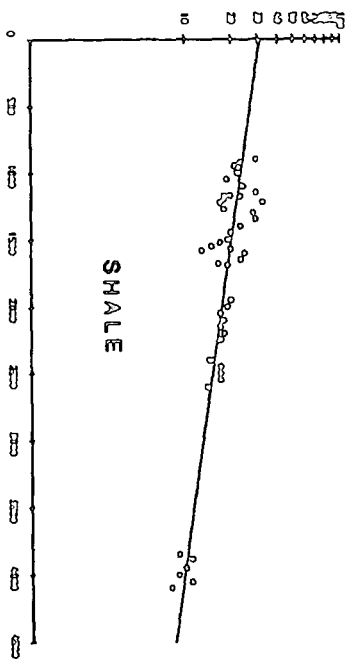
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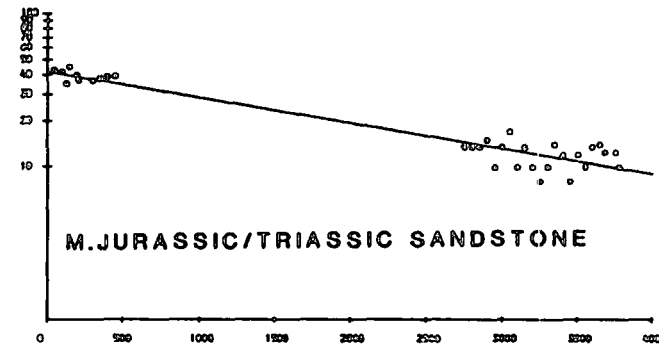
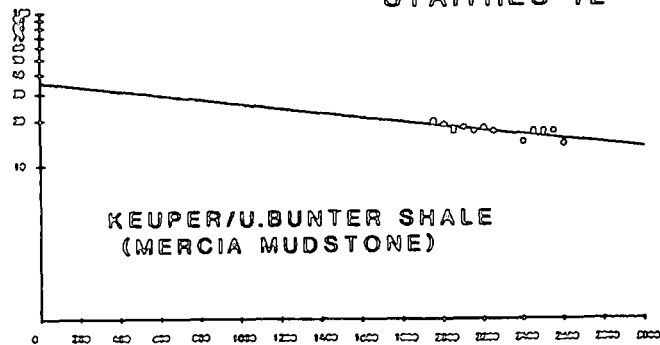


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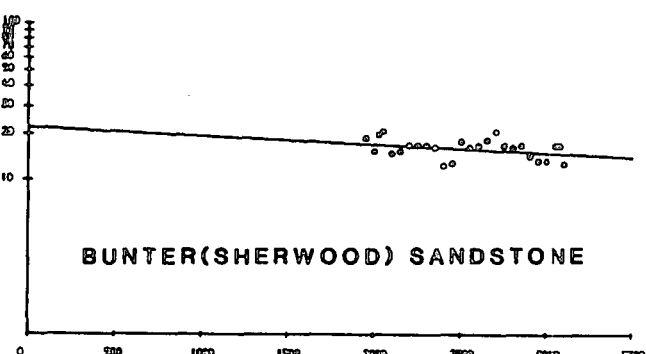
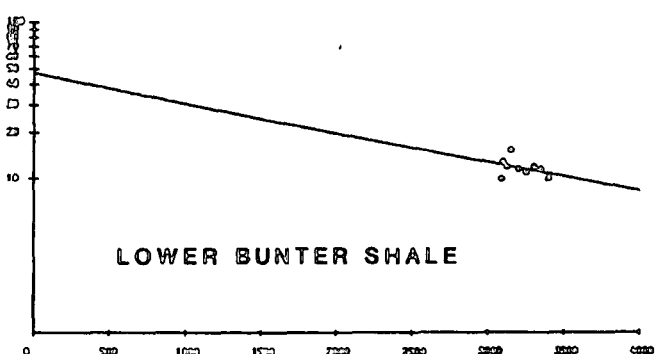
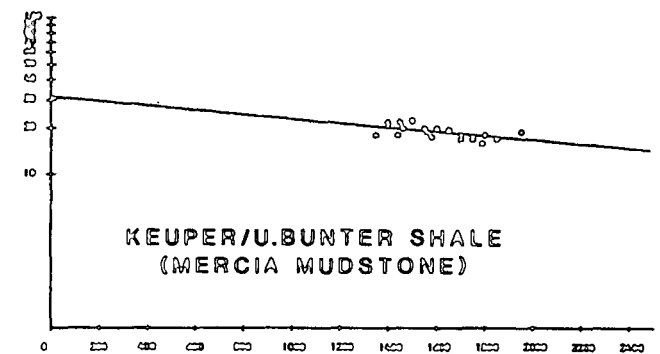
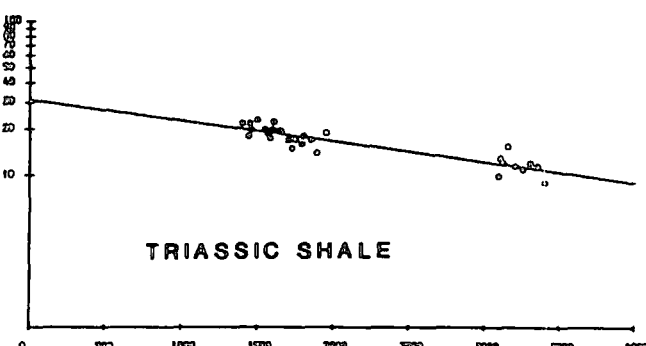
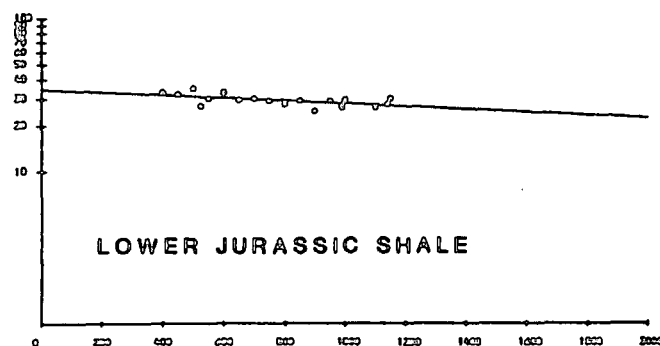
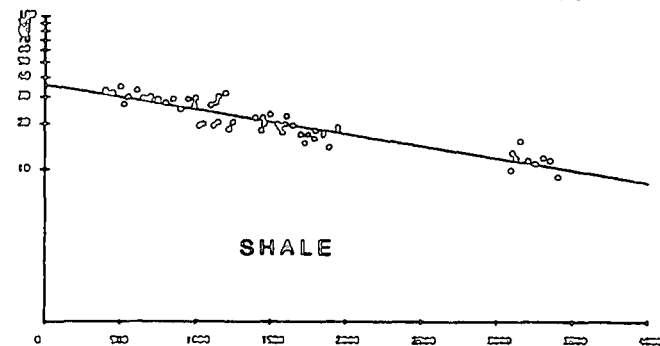
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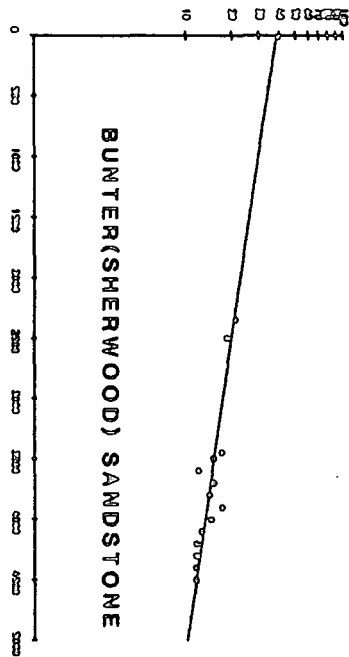
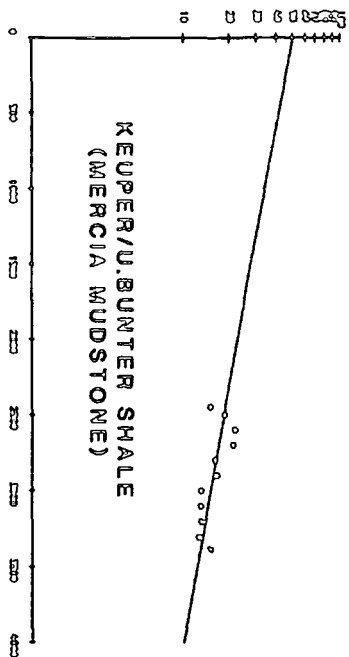
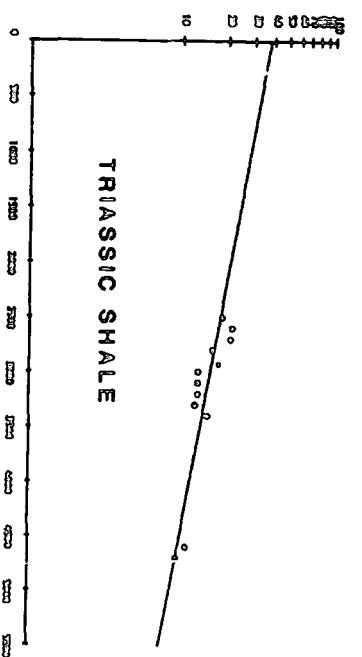
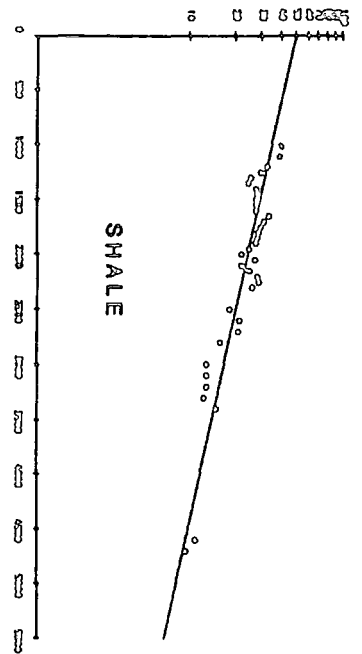


STAITHES 12



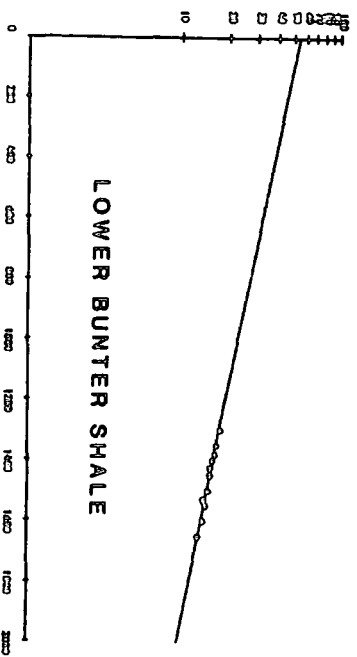
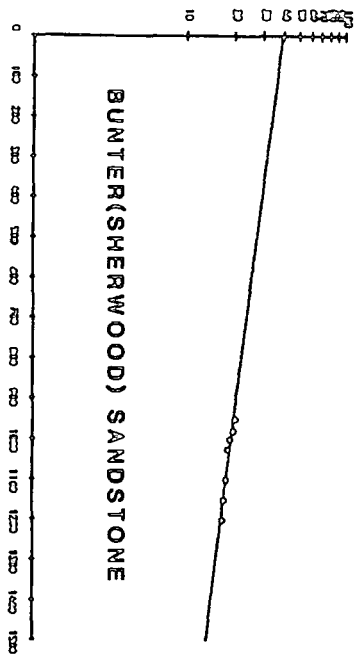
STAITHES 20

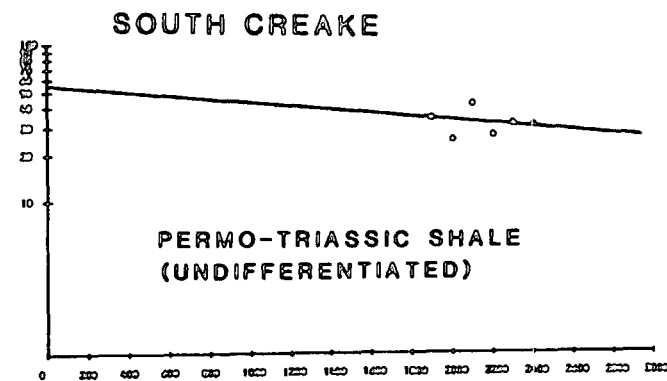
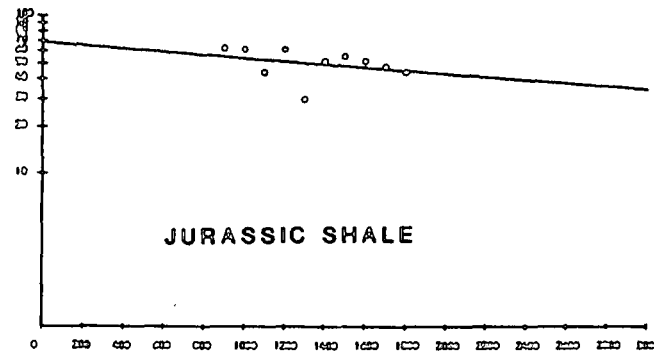
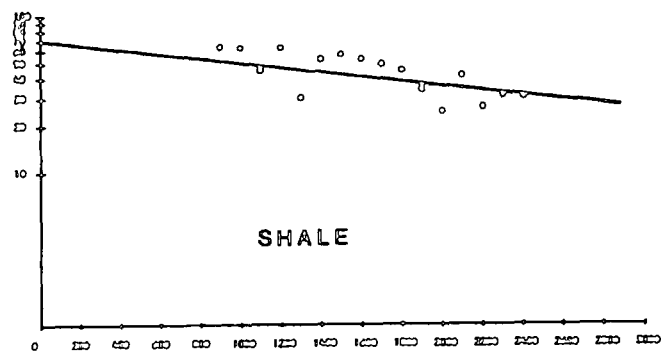
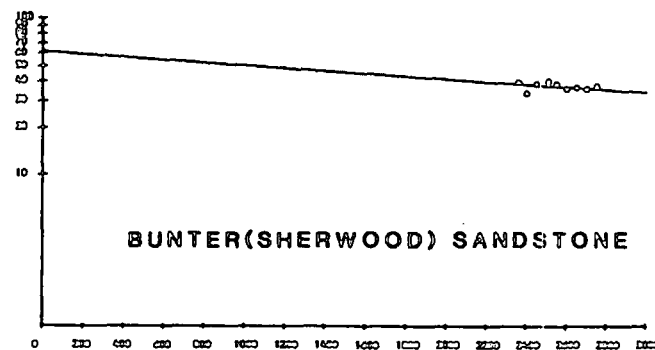
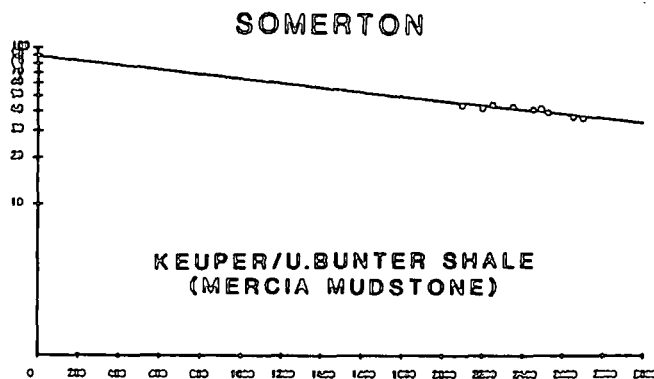
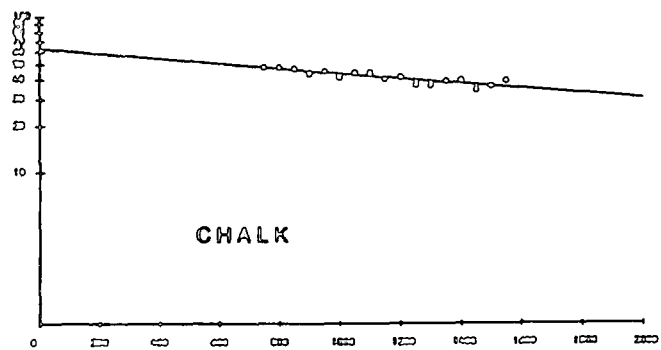
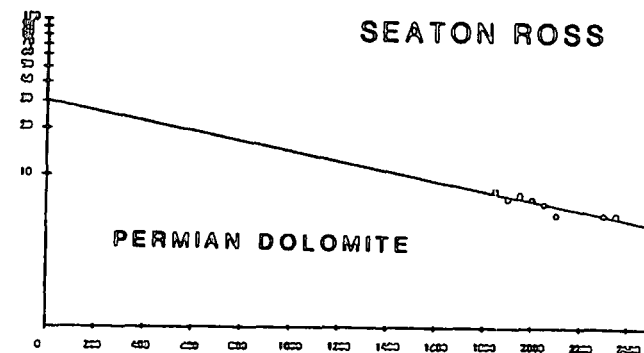
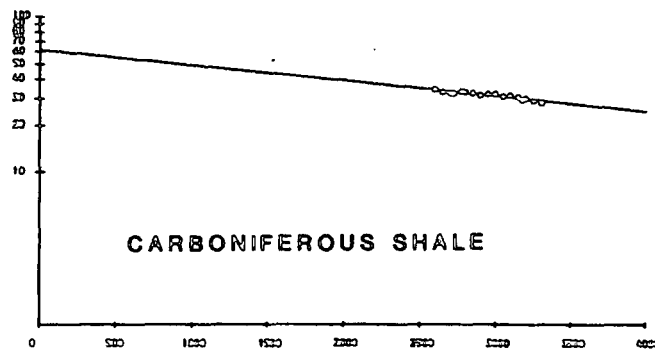
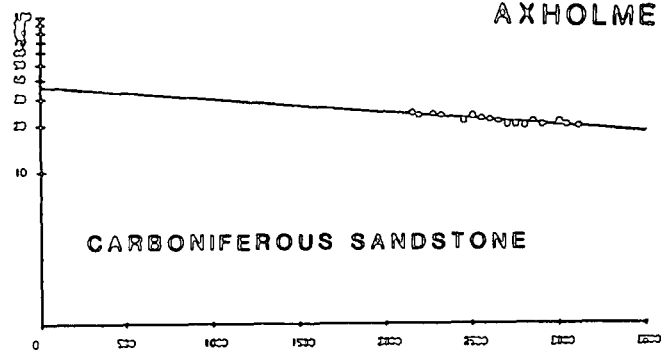


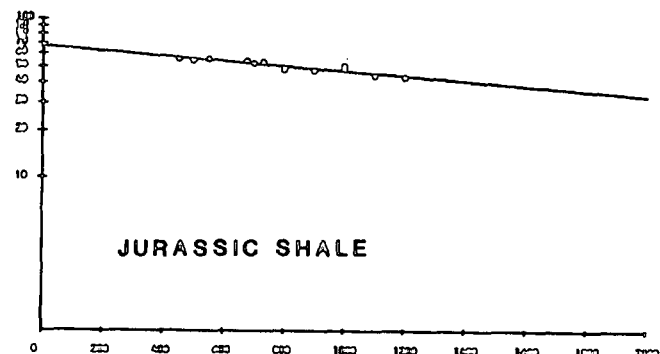
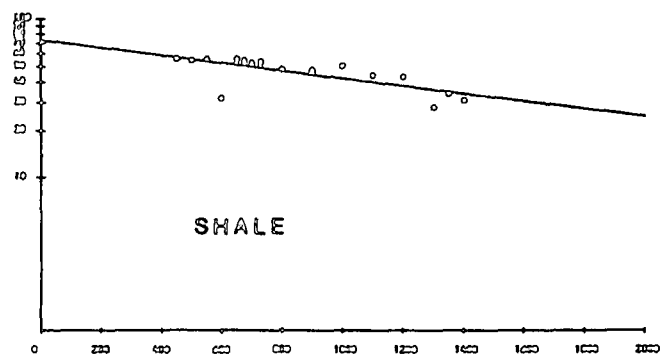
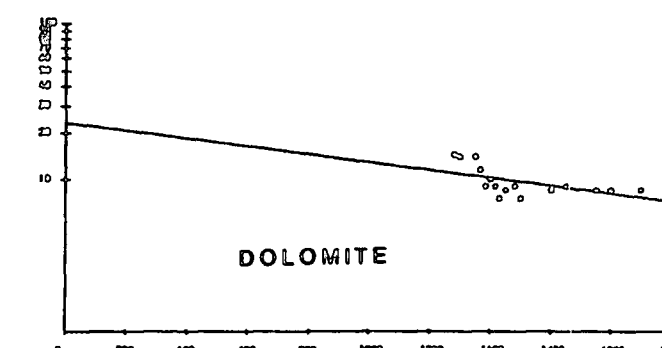
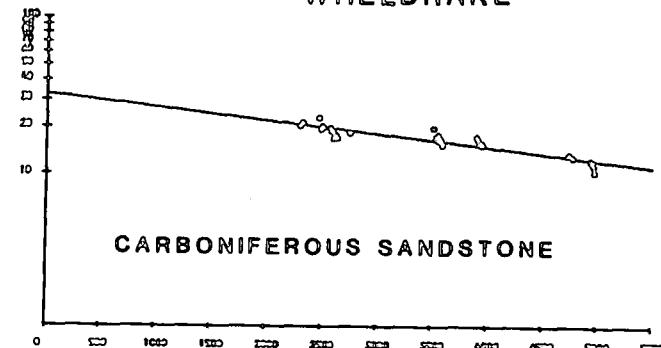
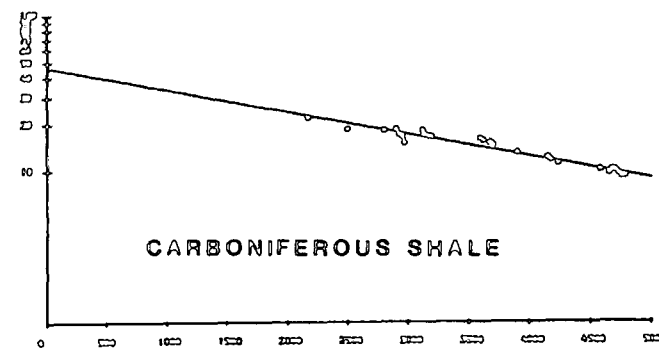
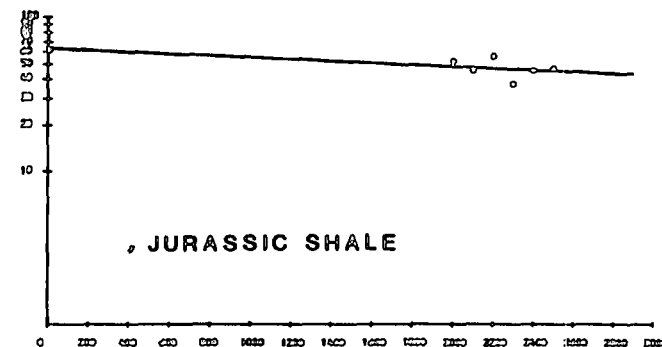
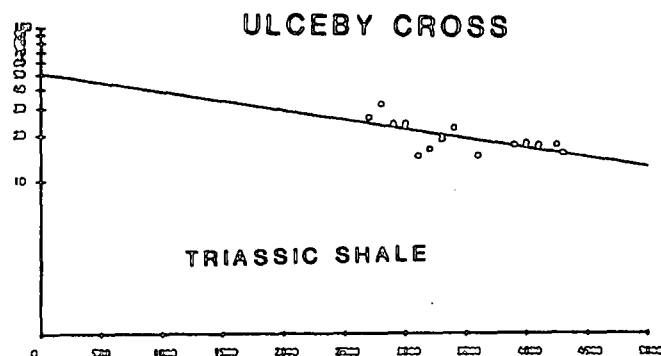
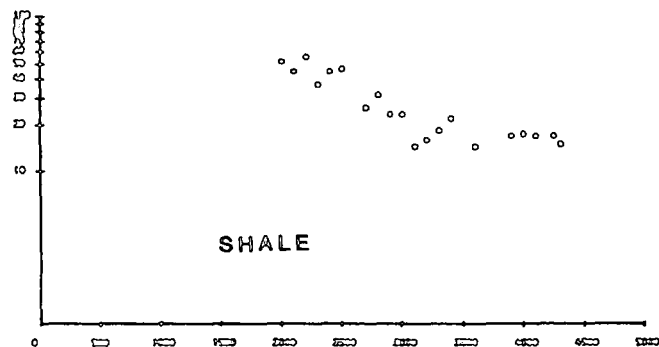


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HARLSEY

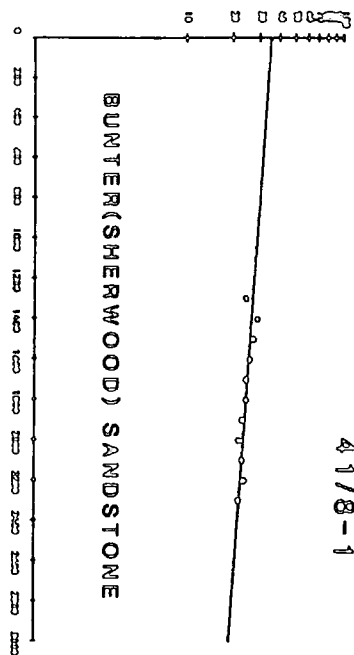




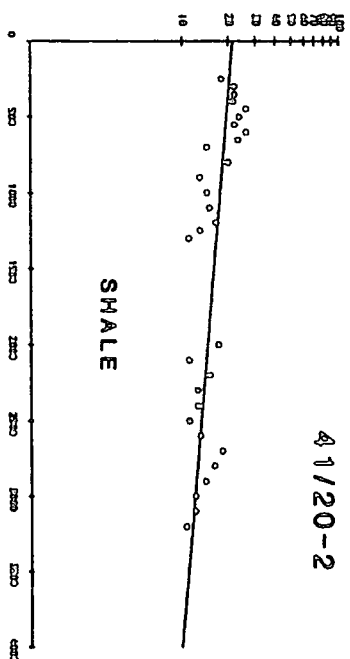


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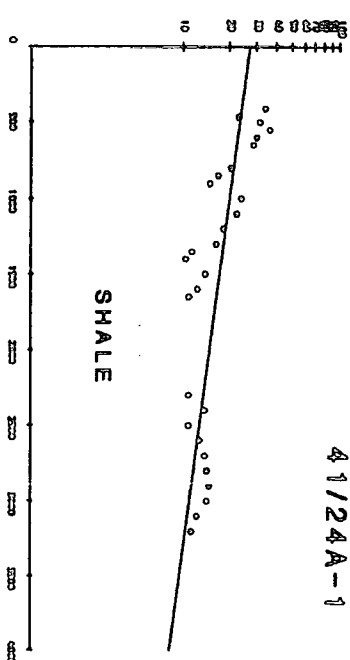
41/8-1



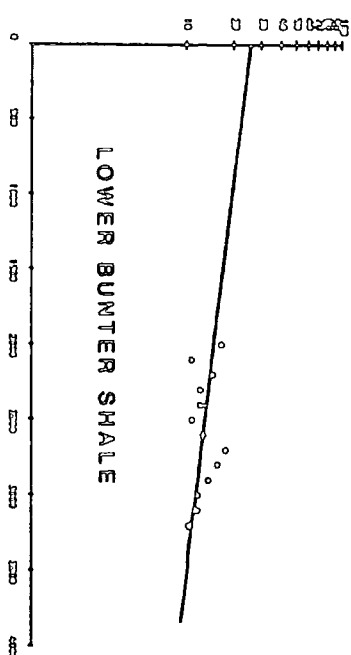
41/20-2



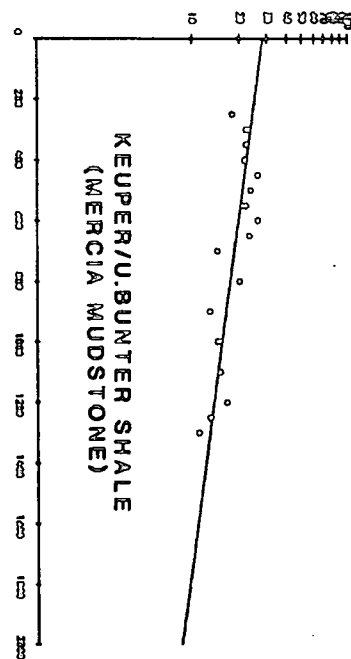
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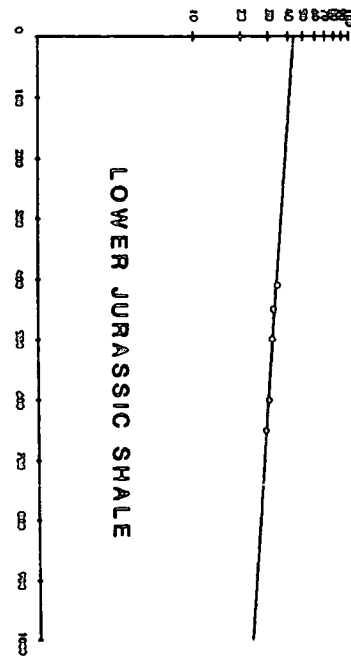
LOWER BUNTER SHALE



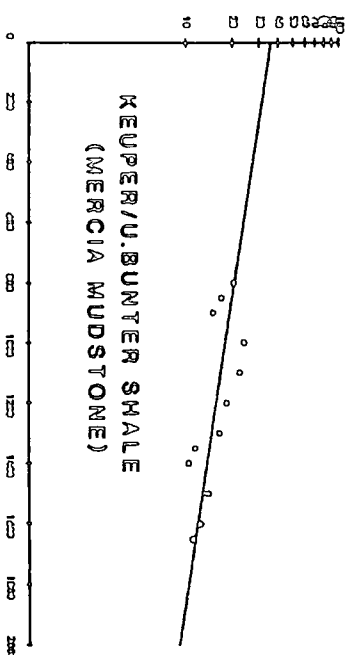
KEUPER/U.BUNTER SHALE
(MERCIA MUDSTONE)



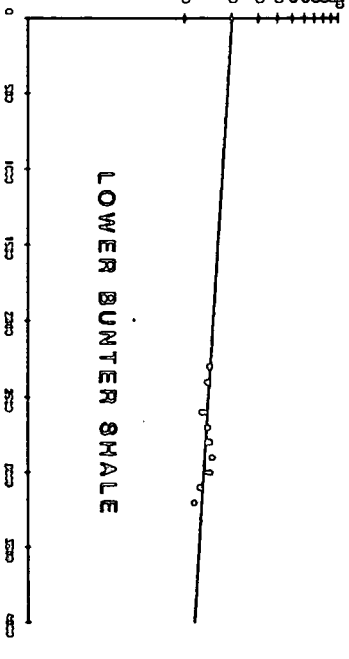
LOWER JURASSIC SHALE



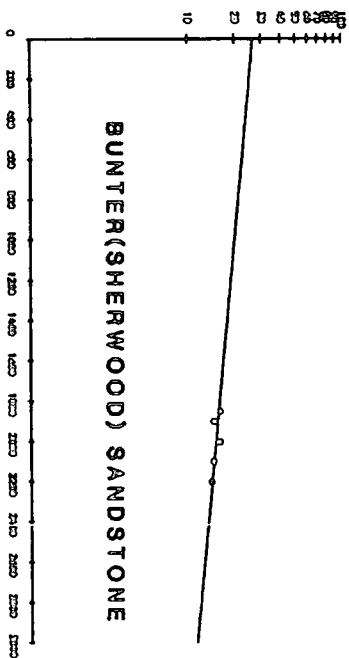
KEUPER/U.BUNTER SHALE
(MERCIA MUDSTONE)

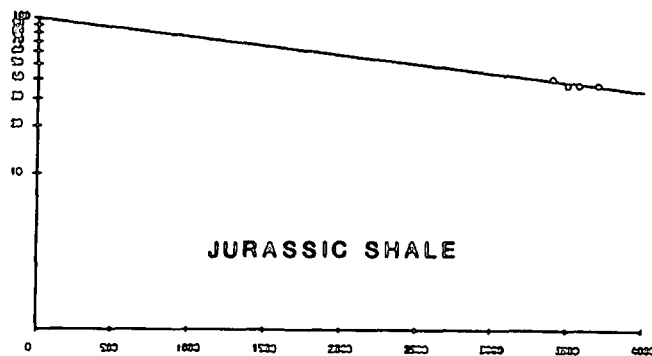
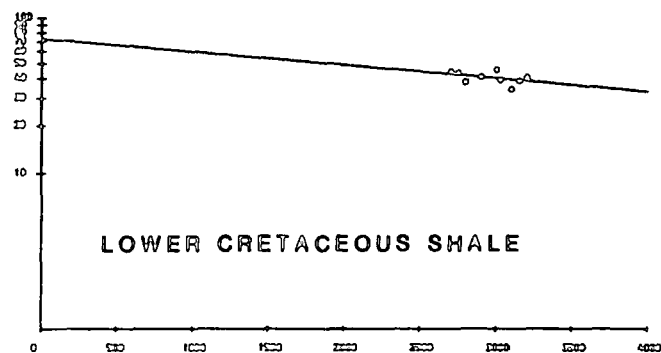
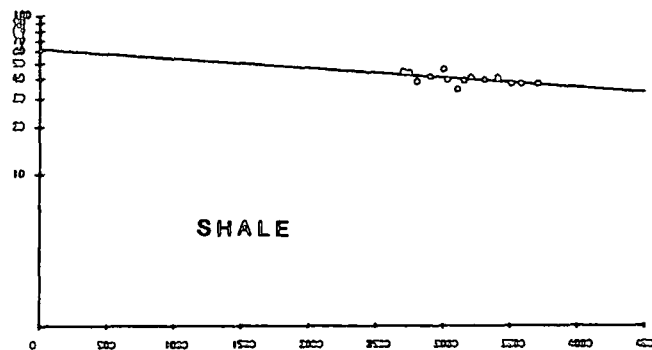
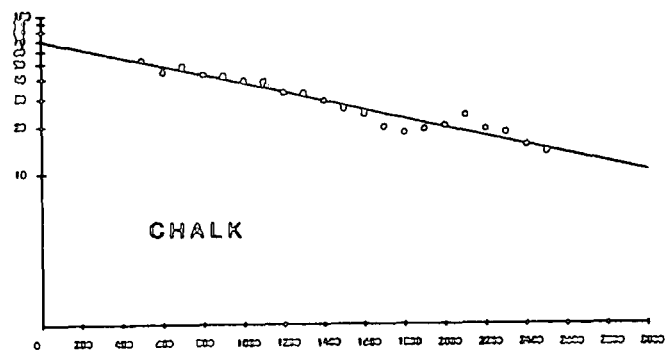
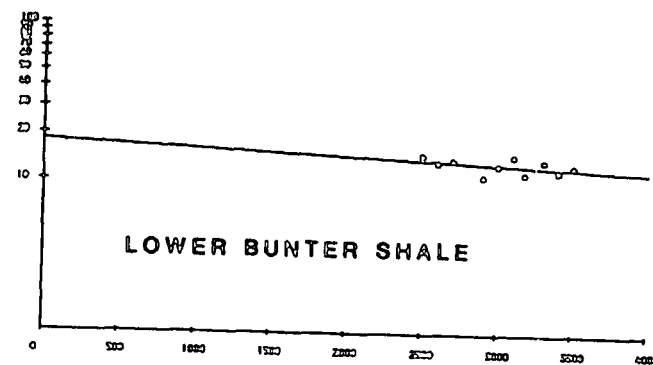
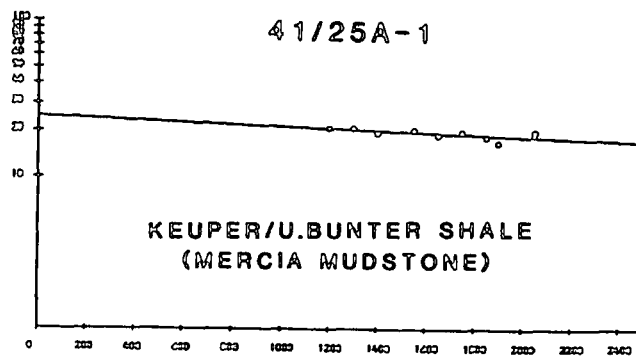
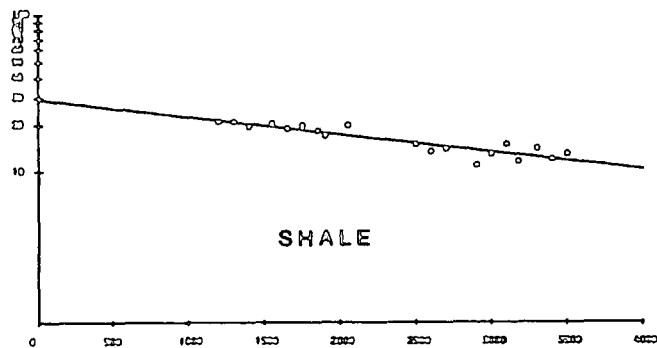


LOWER BUNTER SHALE

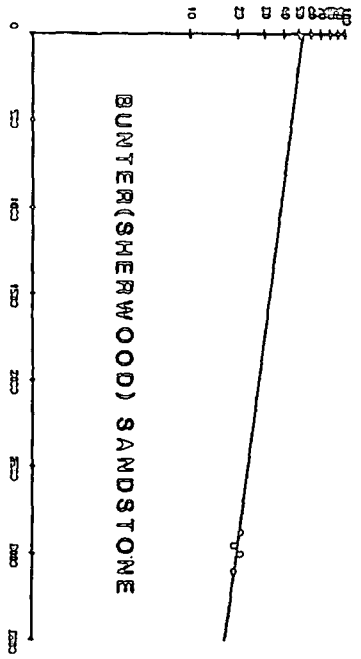
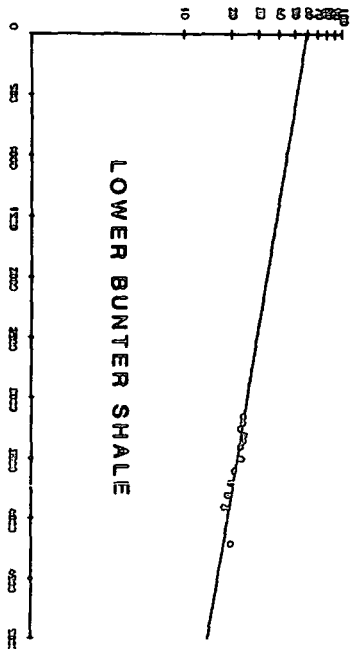
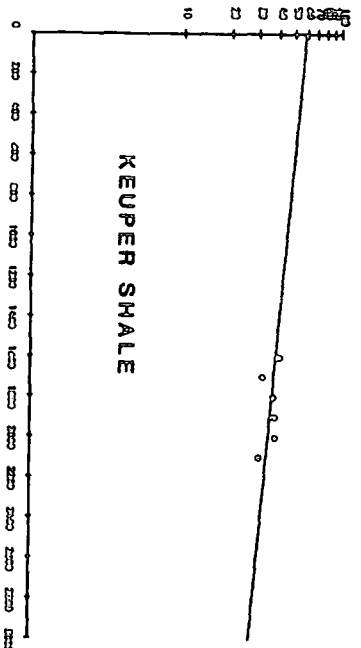
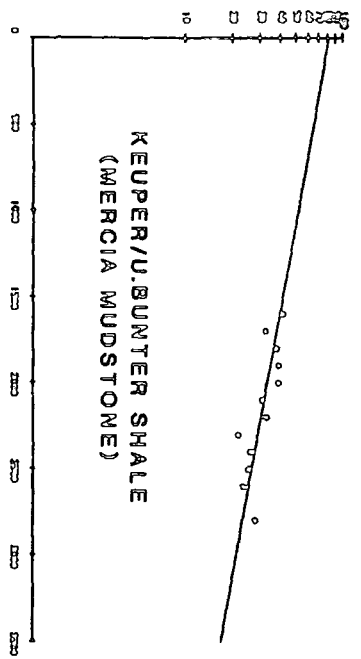
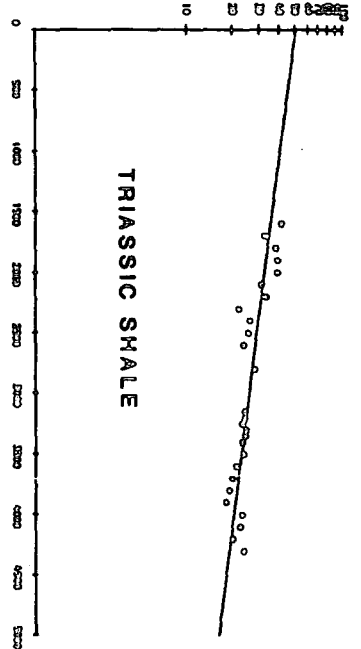
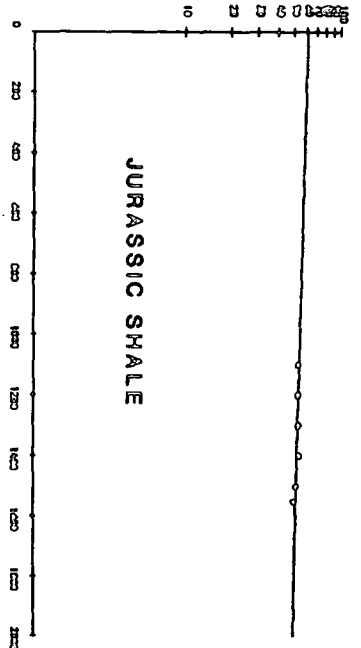
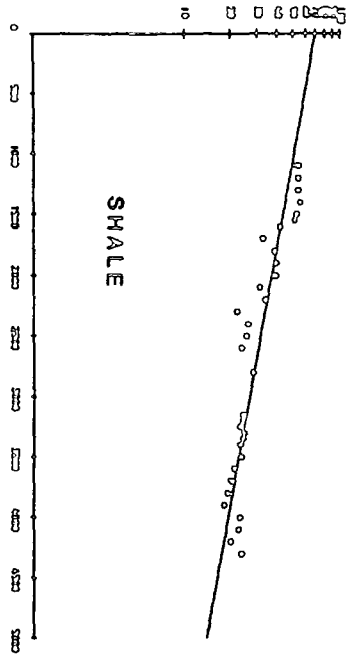


BUNTER(SHERWOOD) SANDSTONE



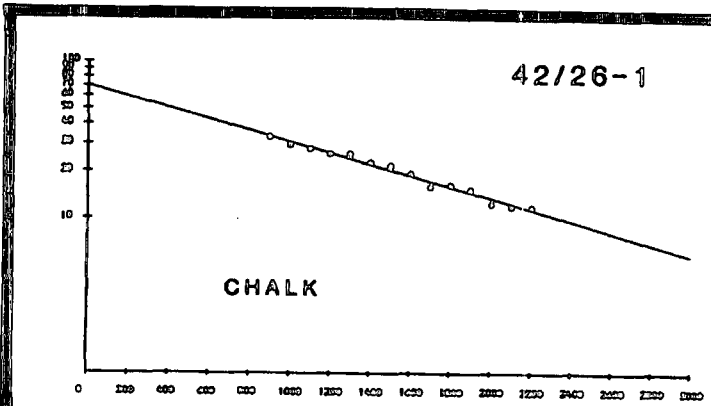
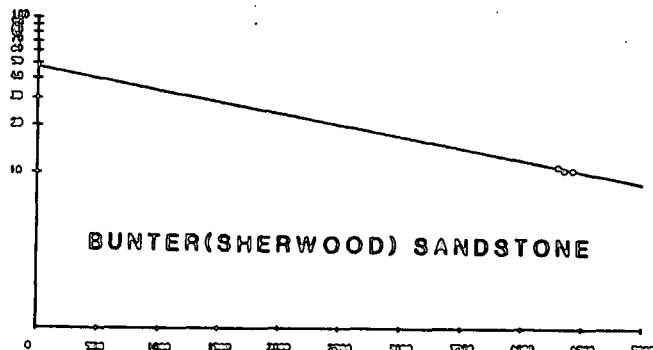
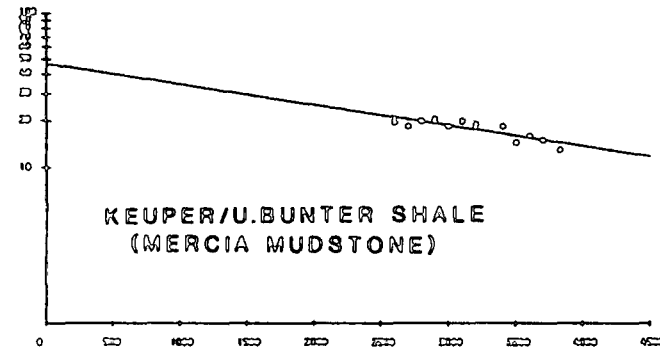
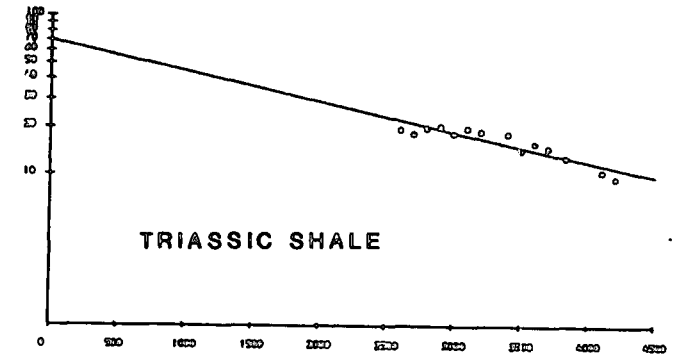
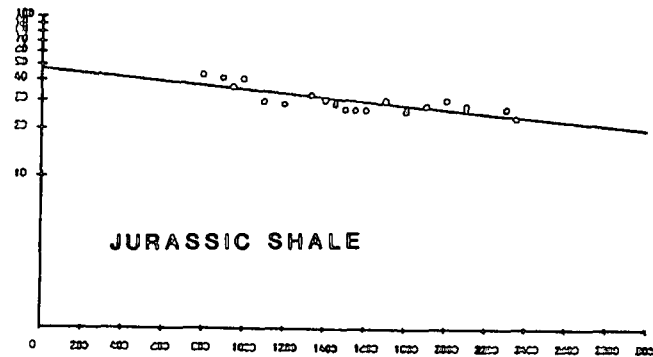
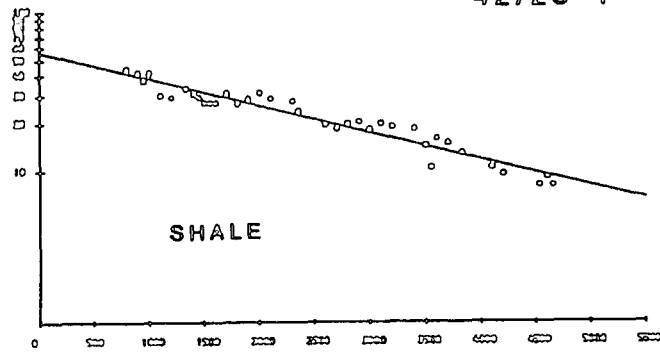


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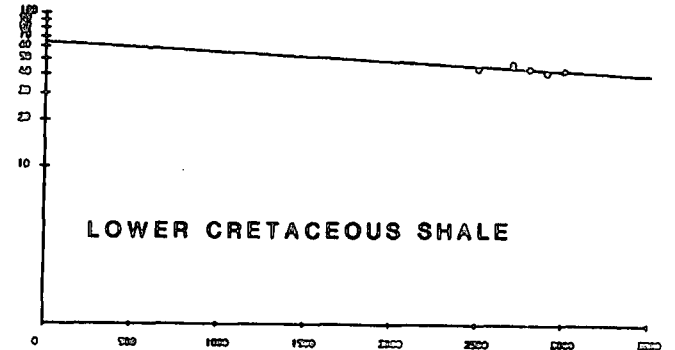
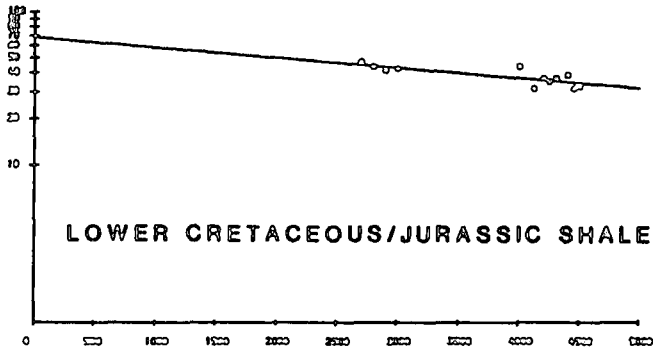
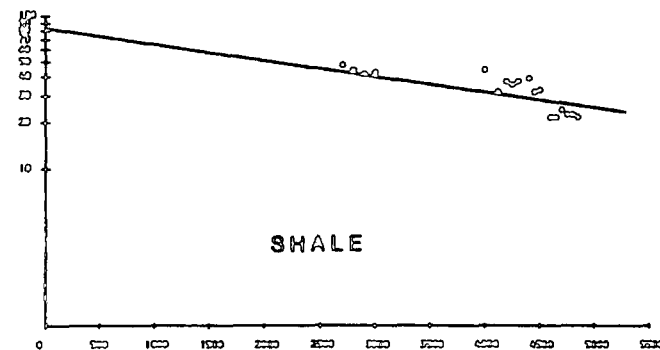


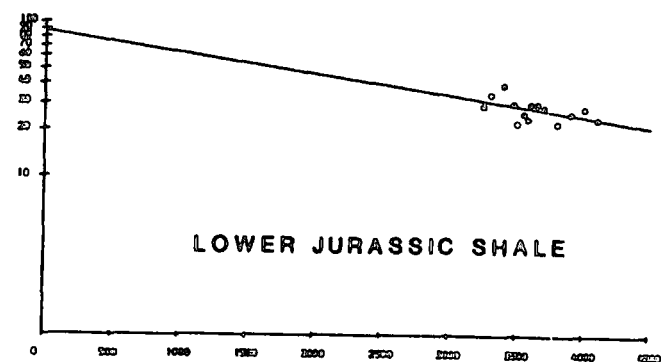
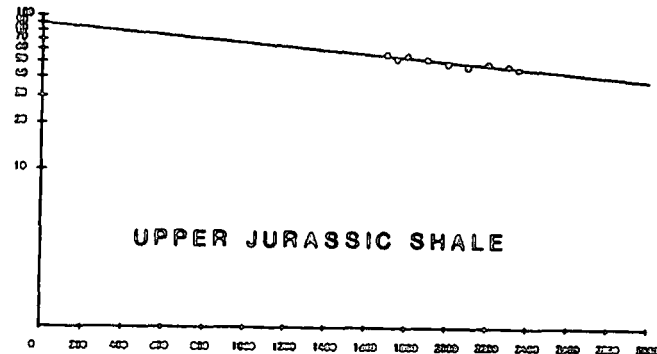
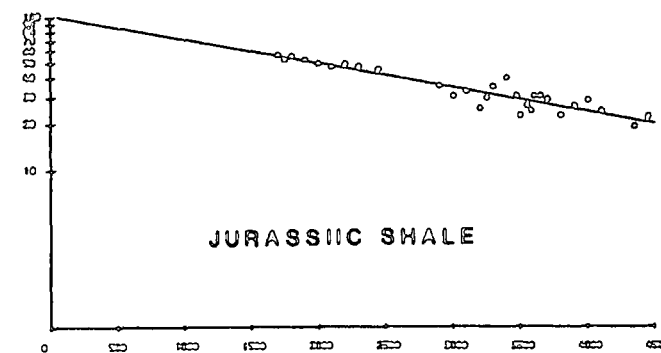
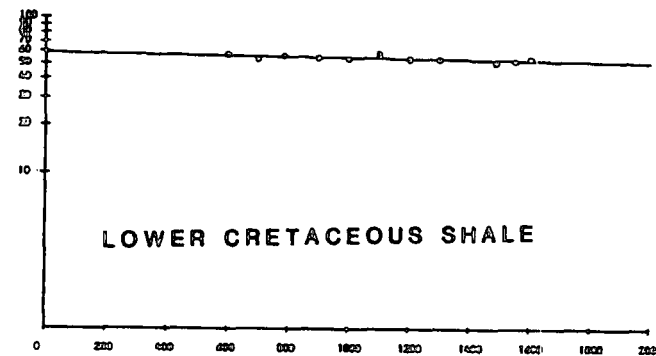
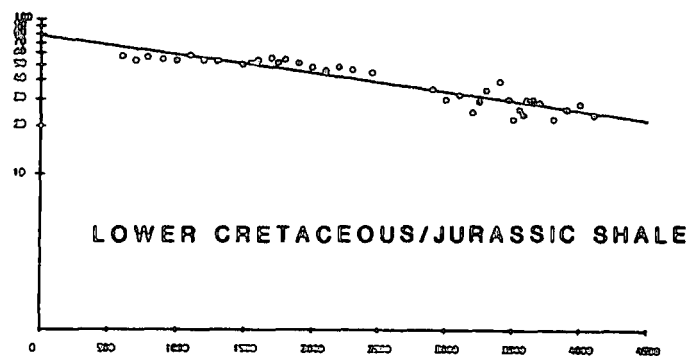
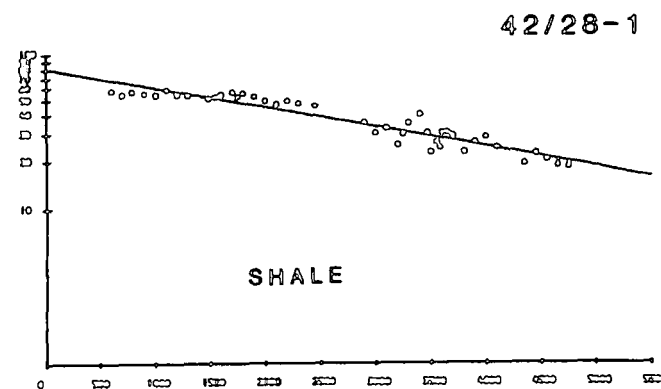
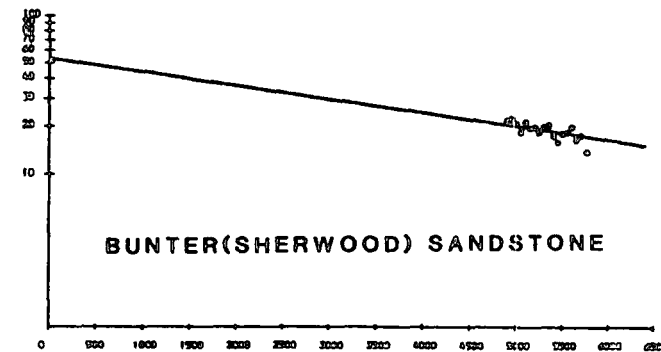
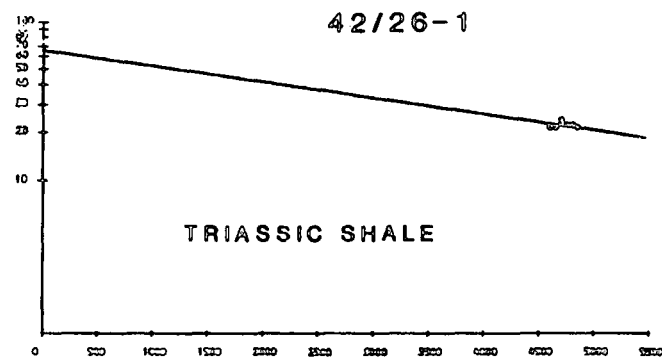
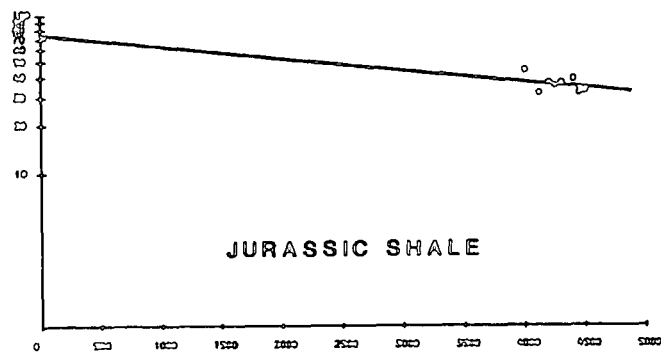
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42/23-1

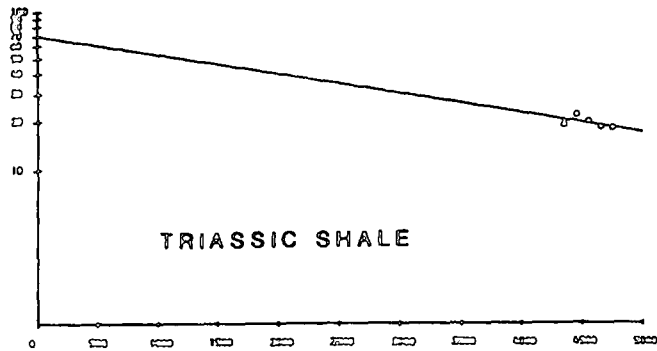


42/26-1

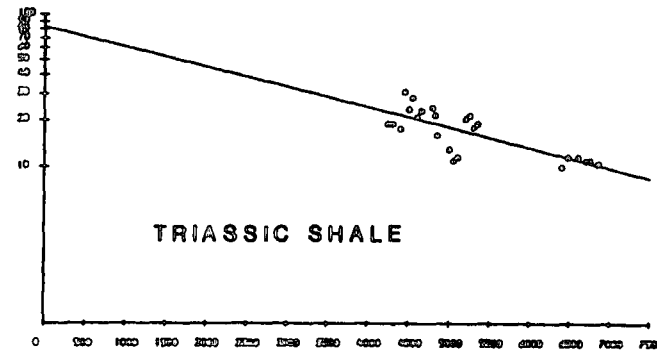
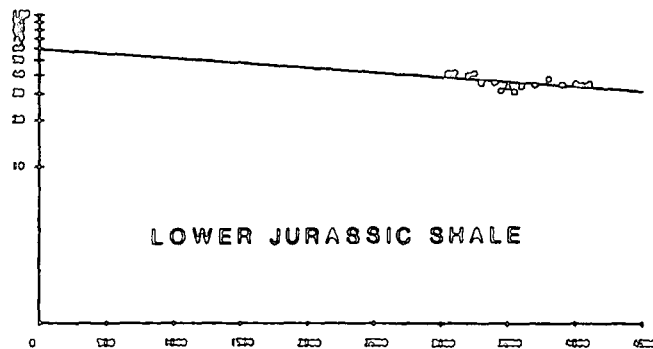
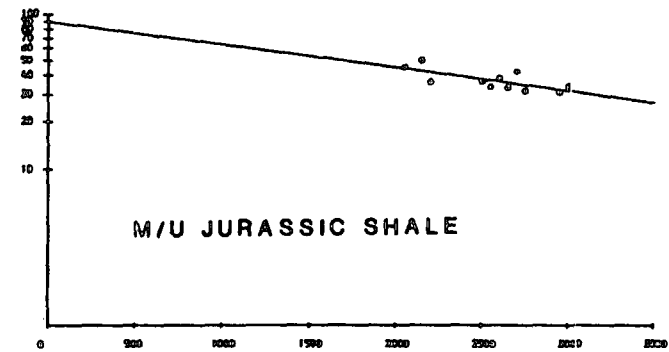
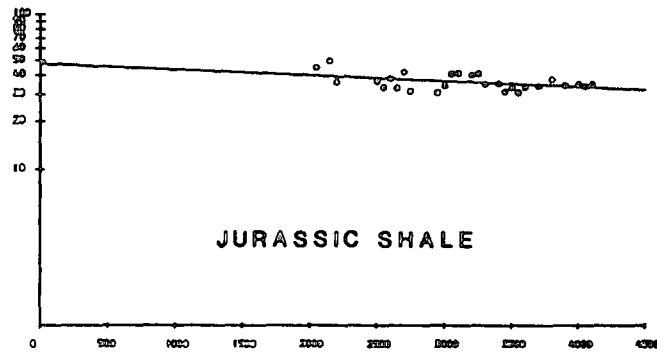
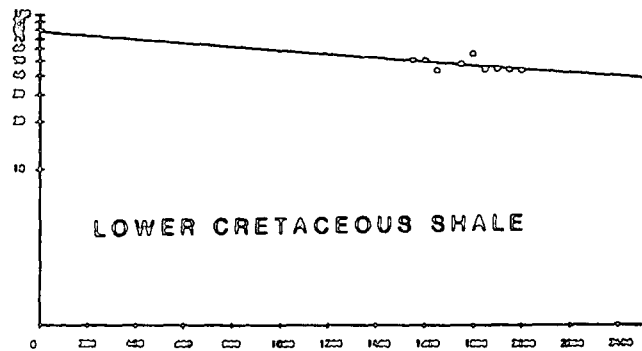
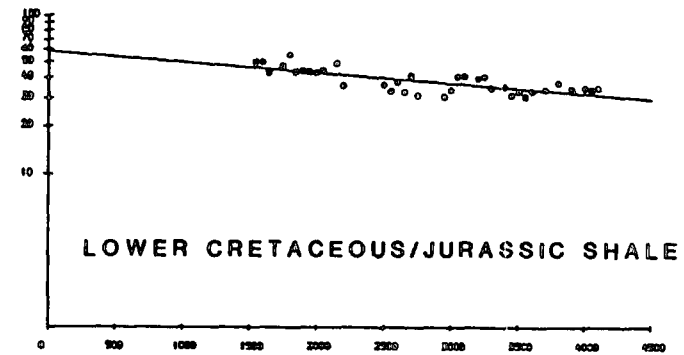
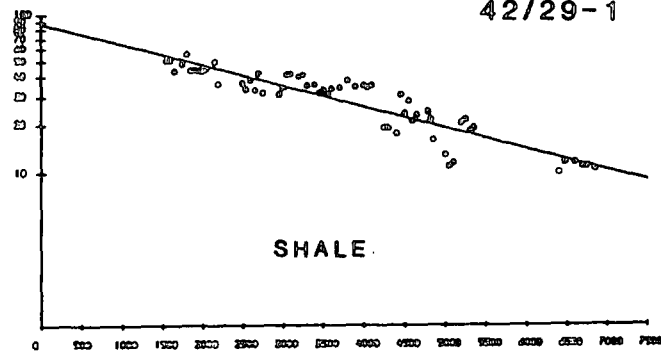




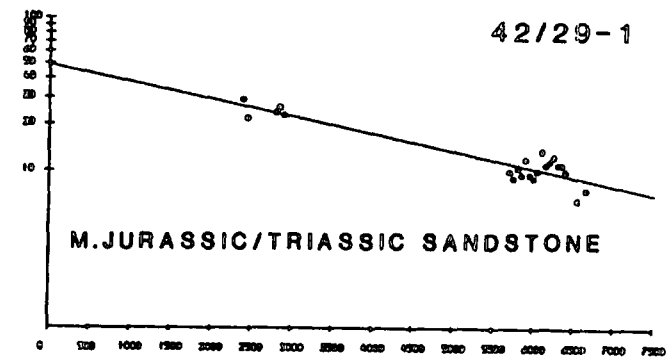
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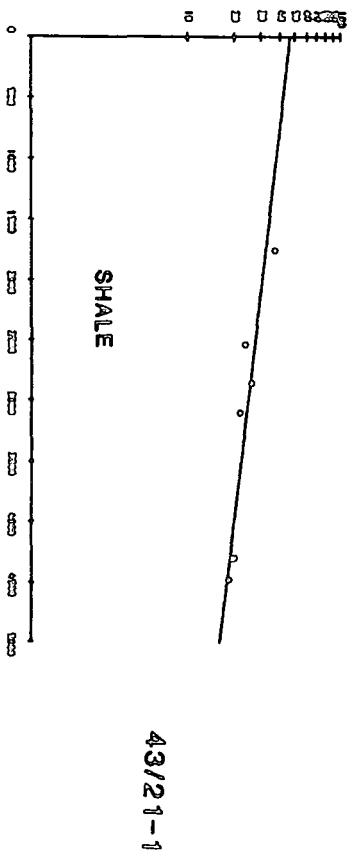
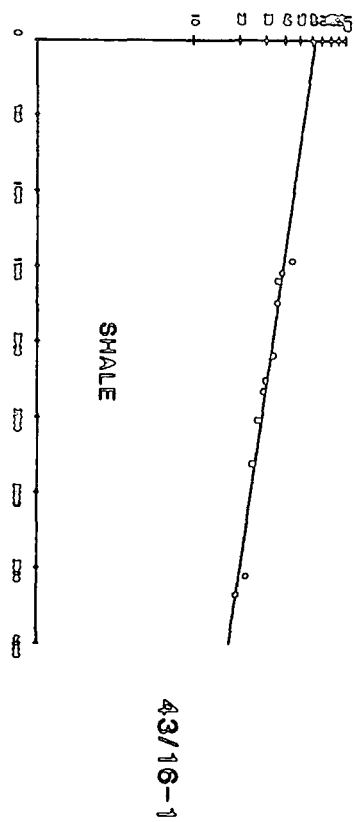
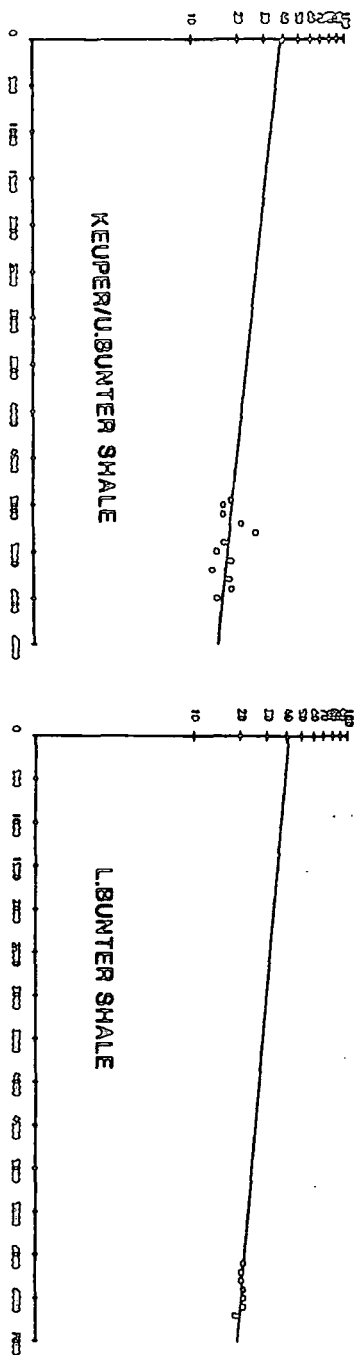
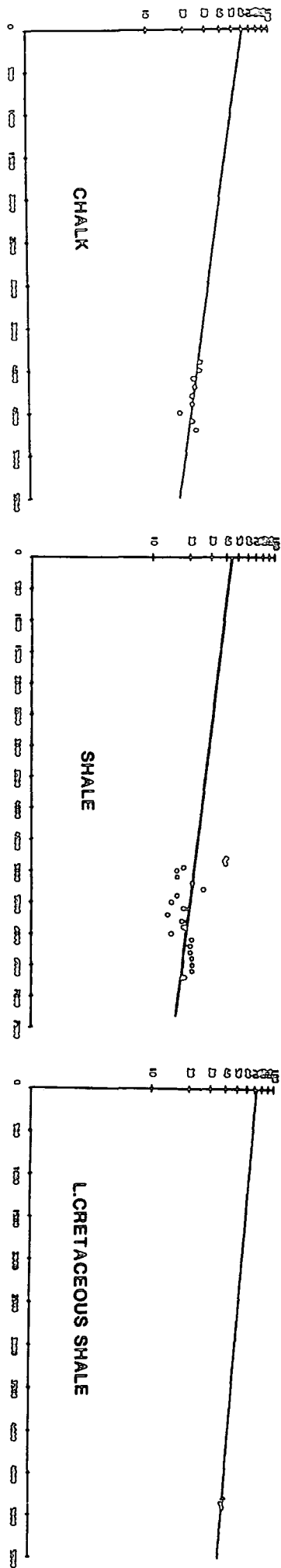


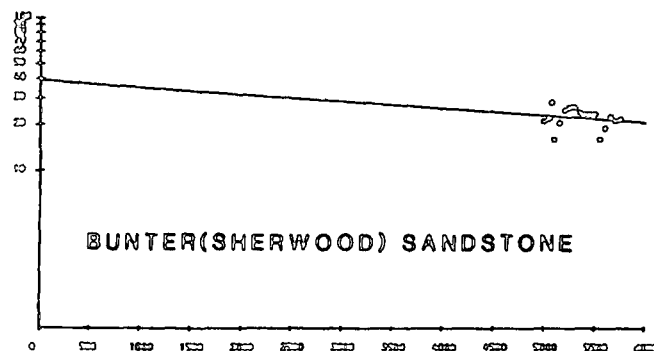
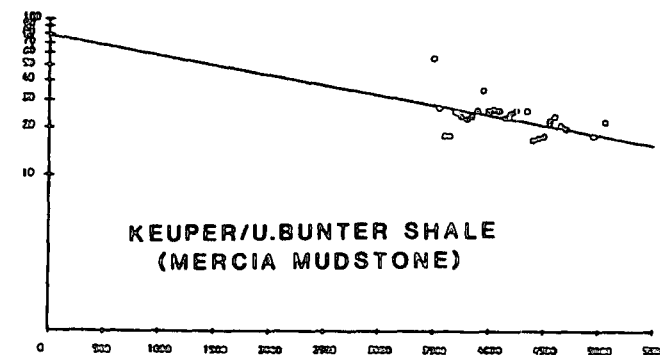
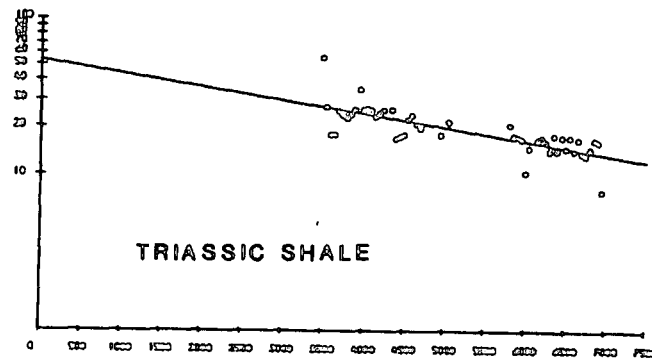
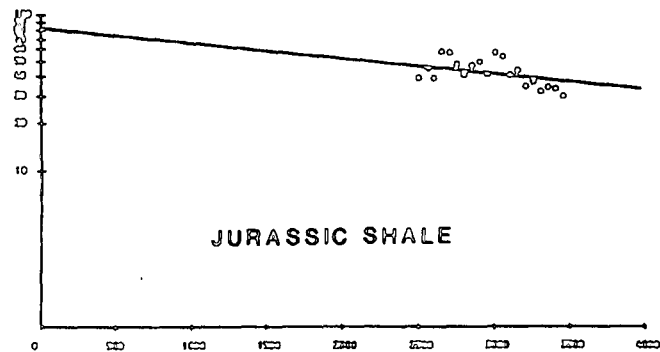
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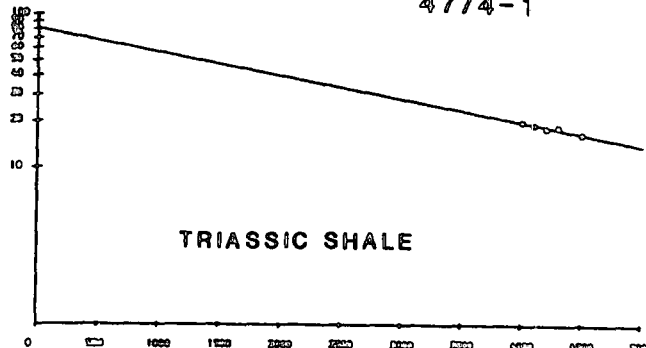
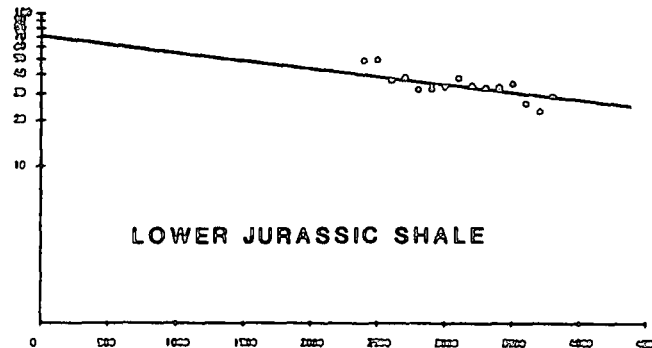
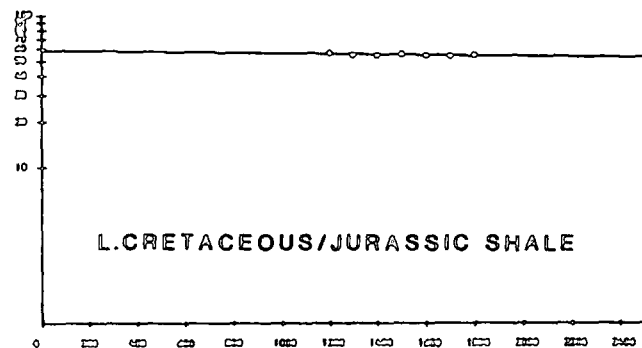
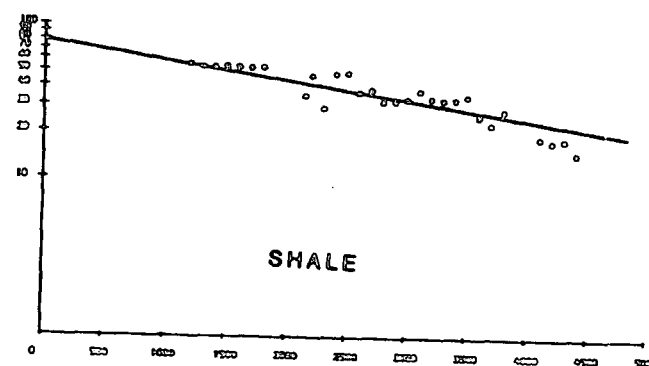
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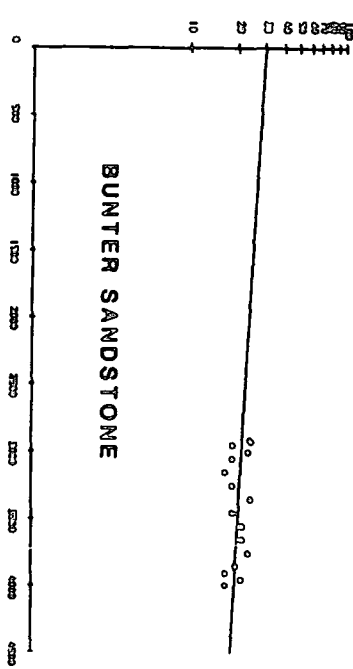
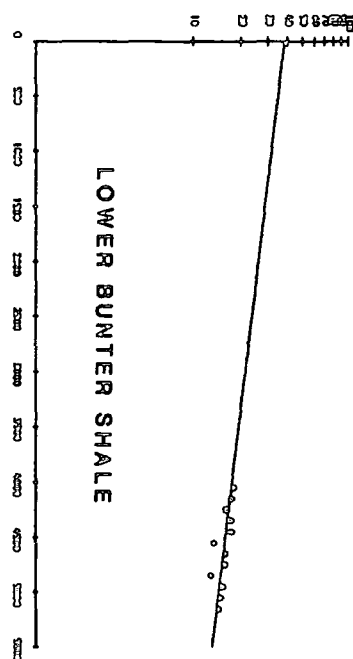
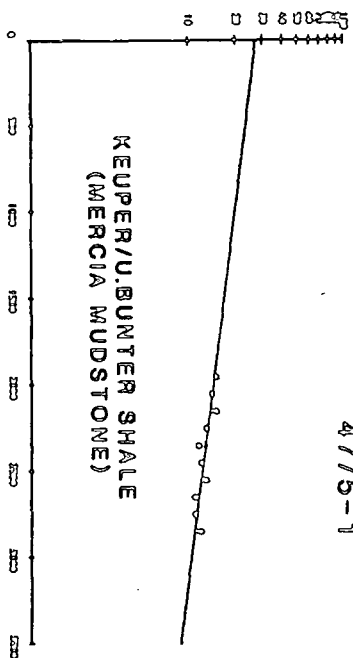


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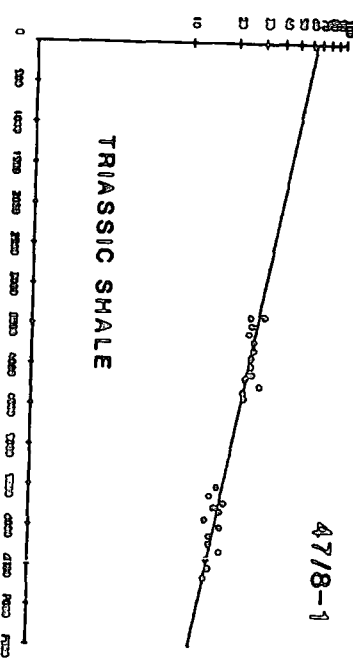
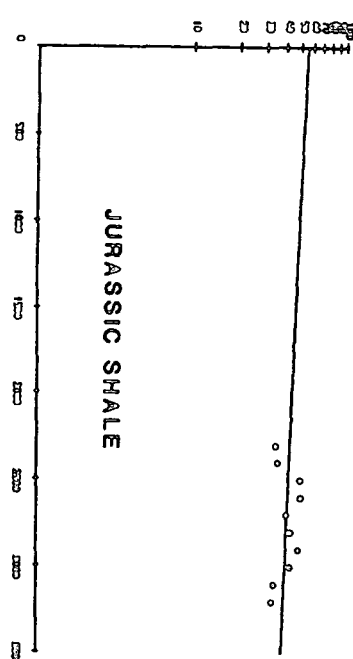
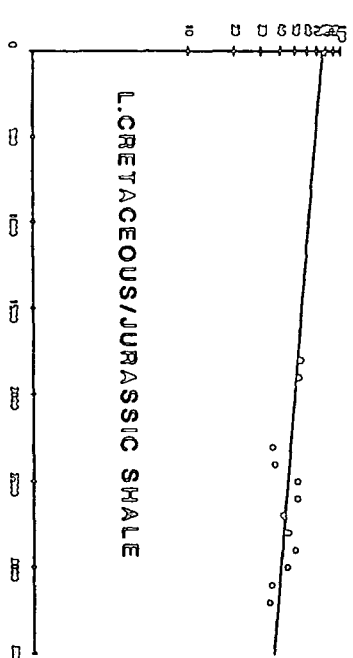
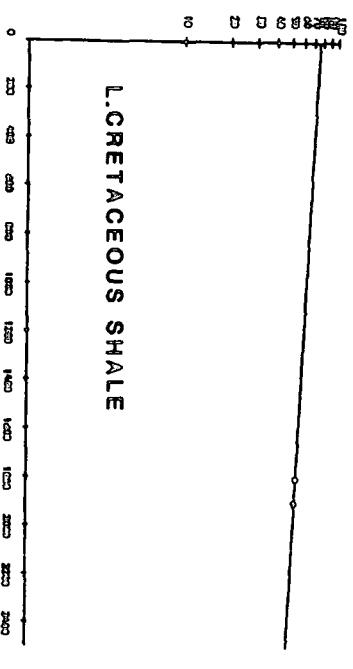
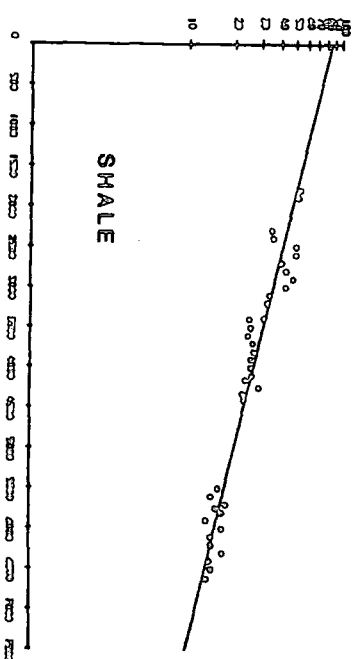
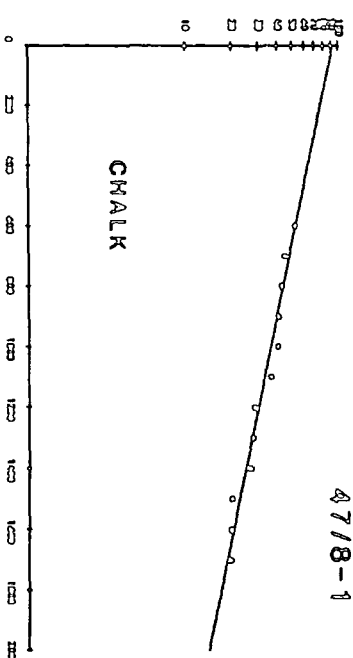


47/4-1

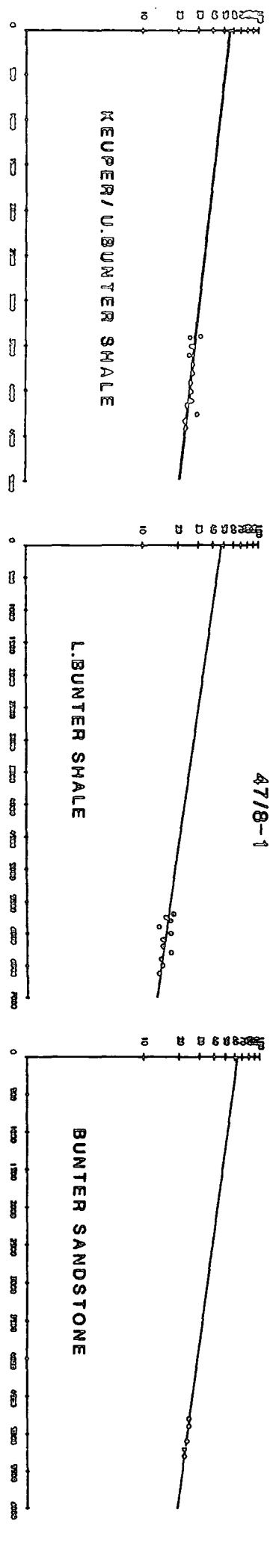
47/5-1



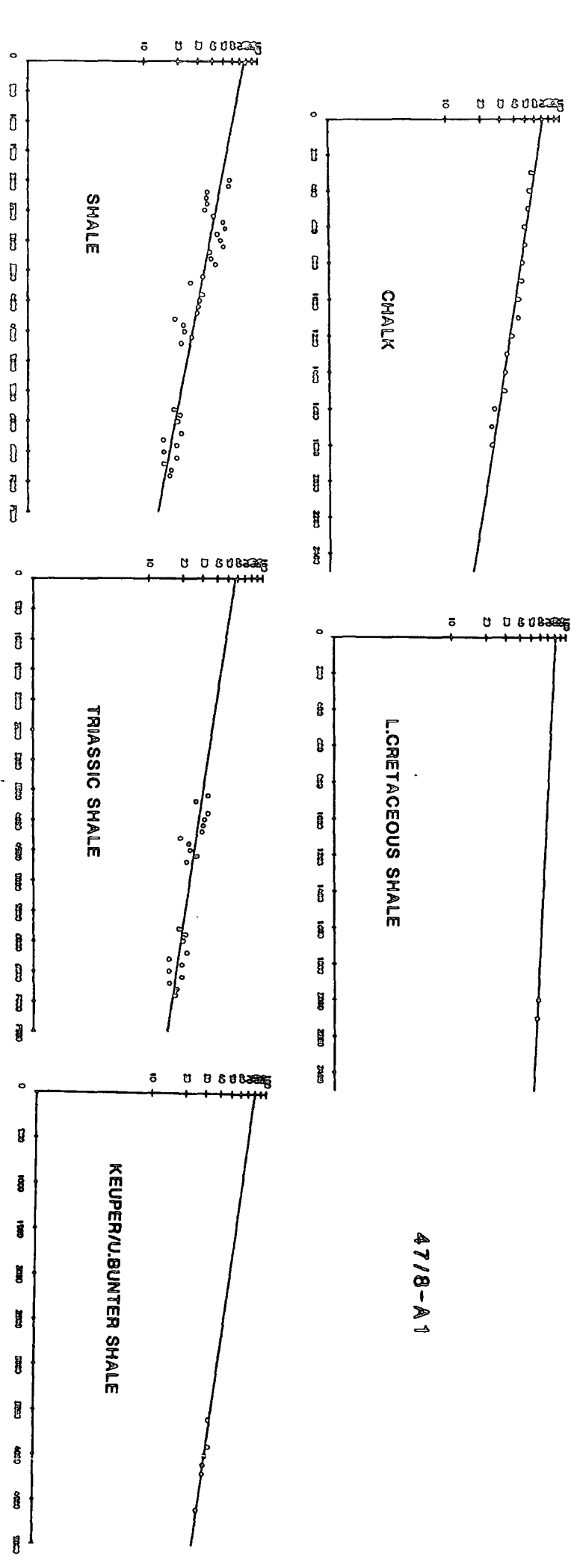
47/8-1



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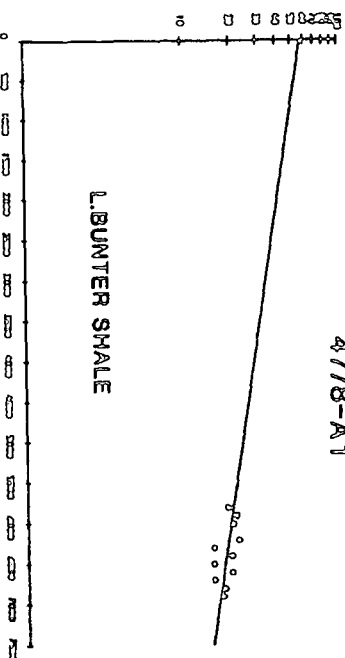


47/8-A1

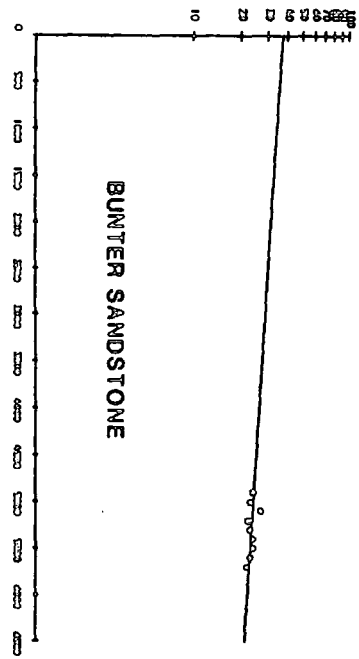


47/8-A1

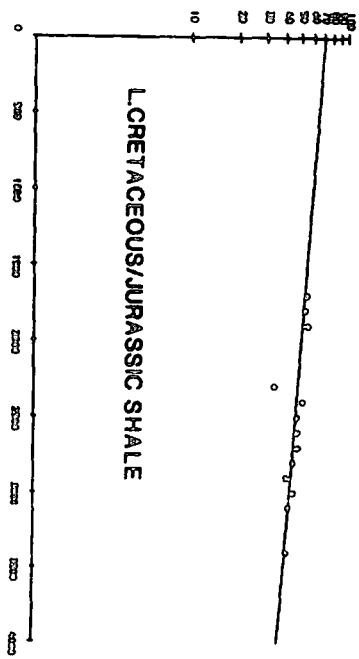
L.BUNTER SHALE



BUNTER SANDSTONE

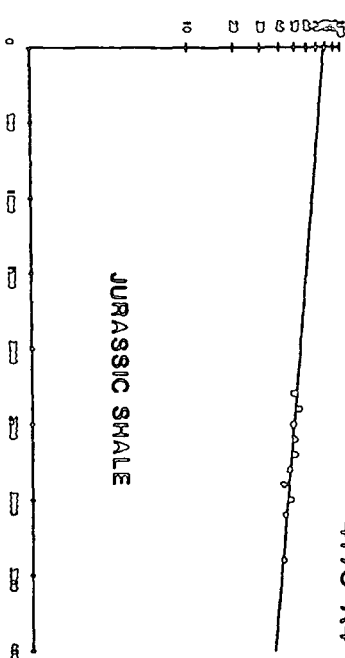


L.CRETACEOUS/JURASSIC SHALE

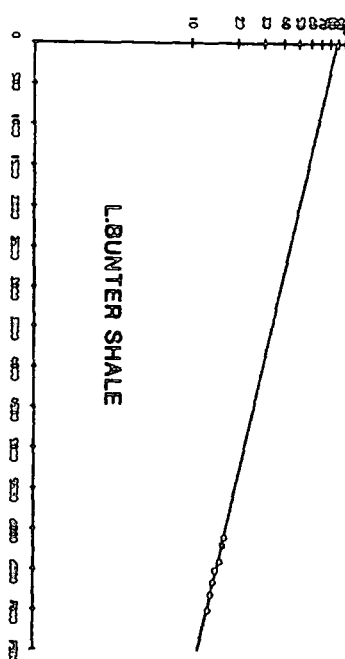


47/8-A4

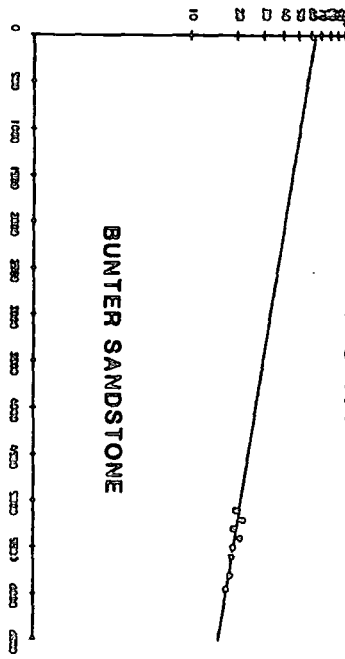
JURASSIC SHALE



L.BUNTER SHALE



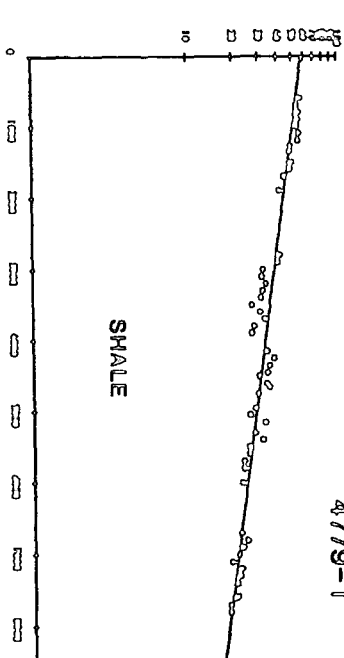
BUNTER SANDSTONE



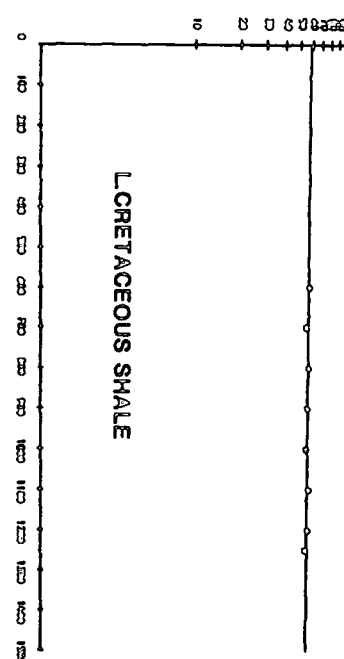
47/8-A4

47/9-1

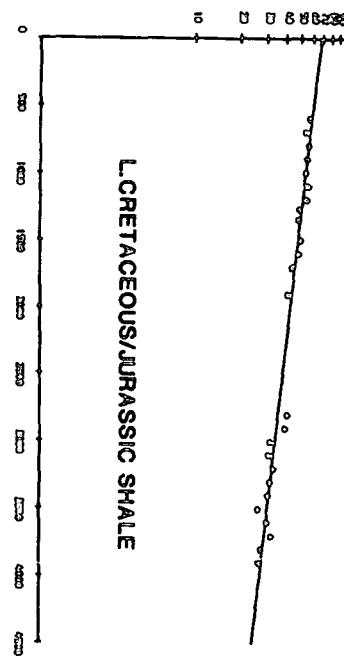
SHALE

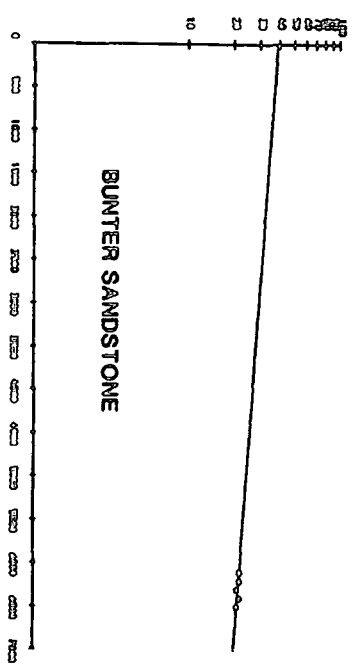
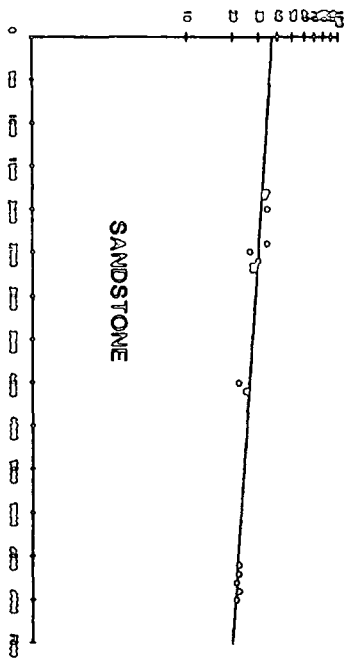
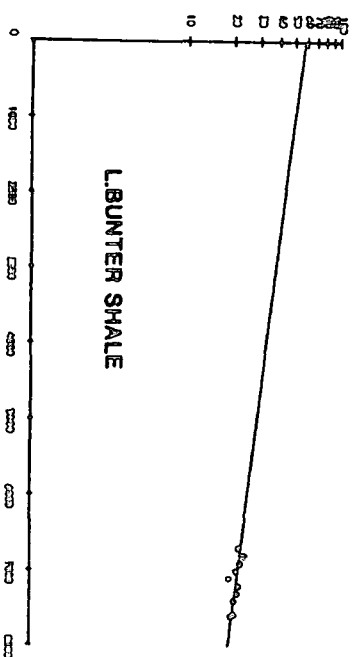
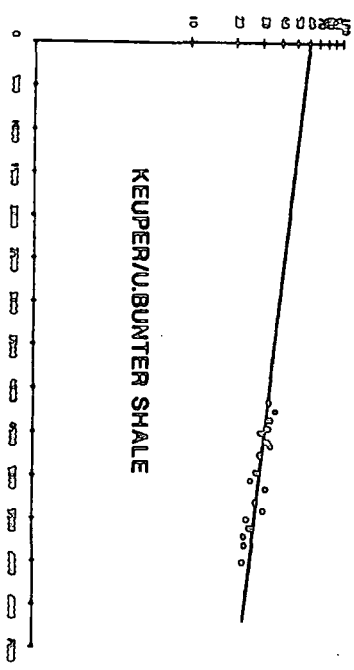
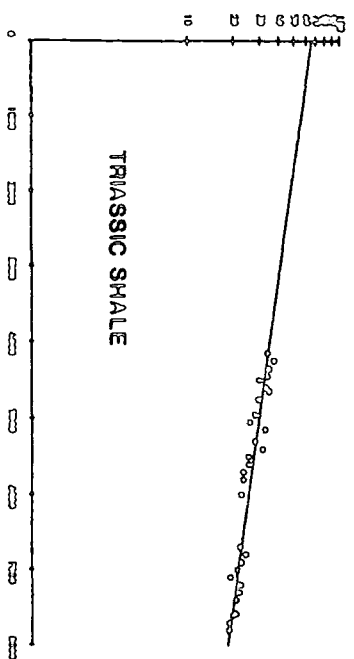
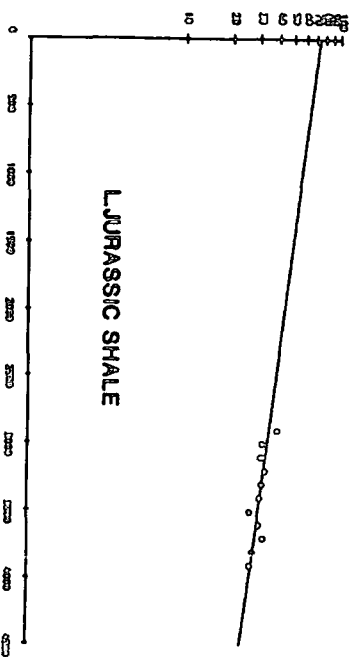
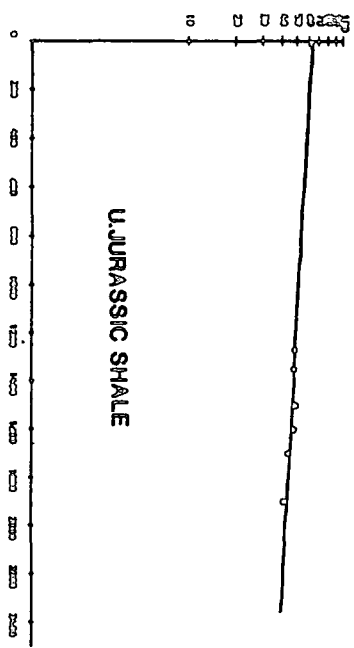
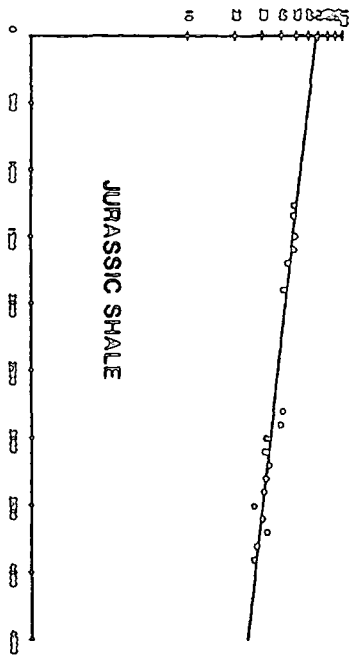


L.CRETACEOUS SHALE



L.CRETACEOUS/JURASSIC SHALE

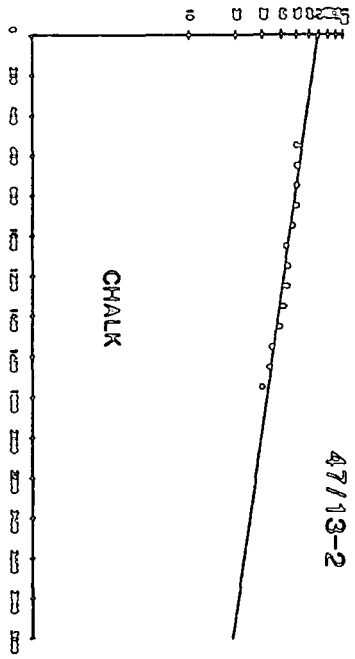




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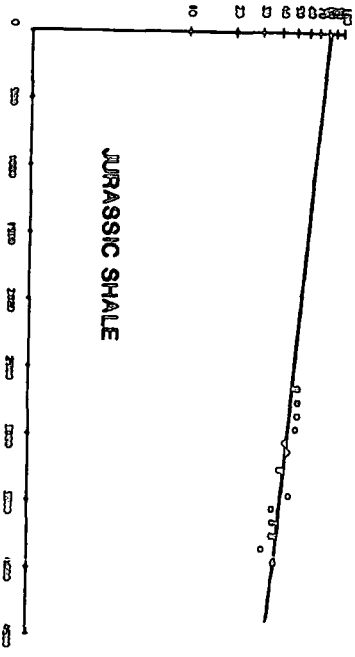
CHALK



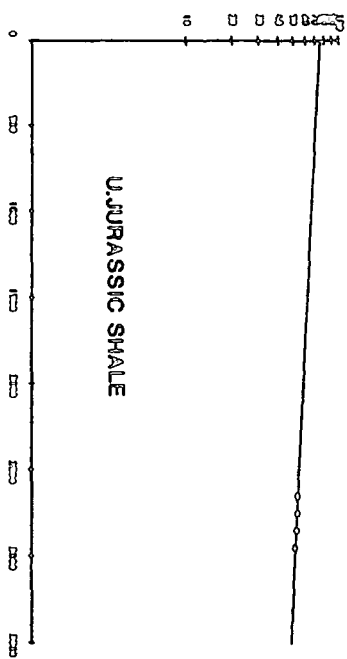
SHALE



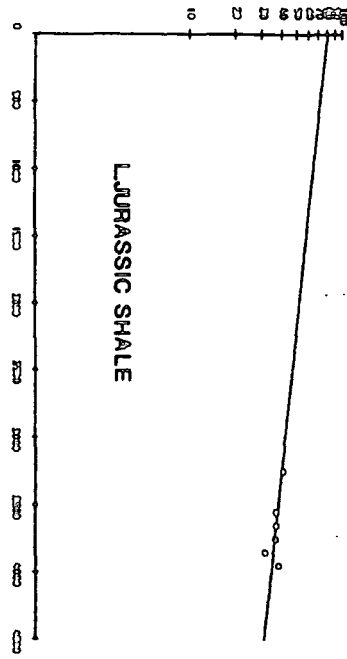
JURASSIC SHALE



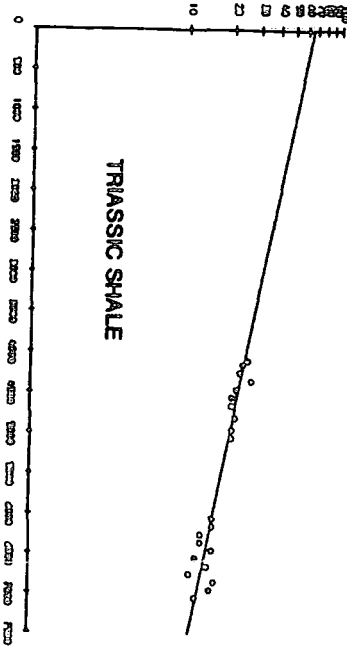
U. JURASSIC SHALE



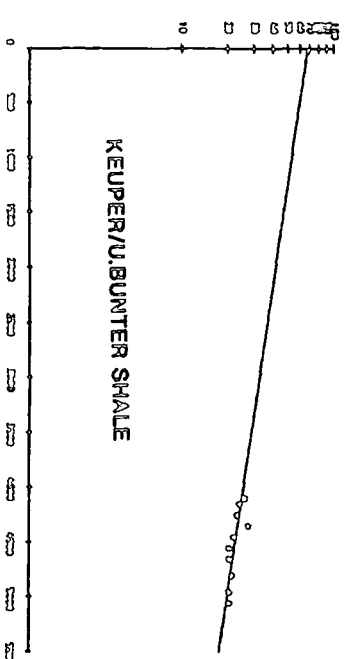
L. JURASSIC SHALE



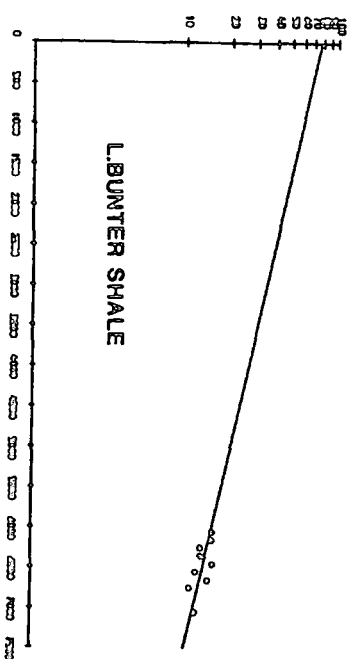
TRIASSIC SHALE



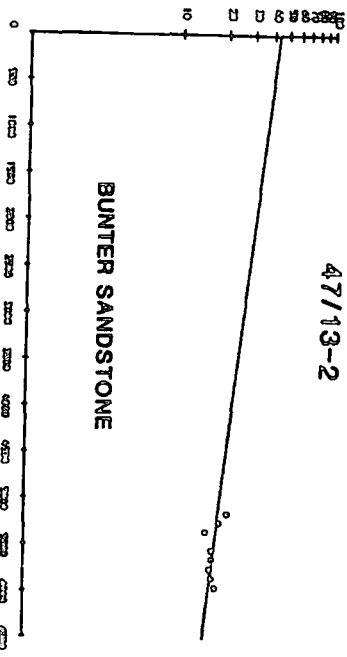
KEUPER/U. BUNTER SHALE



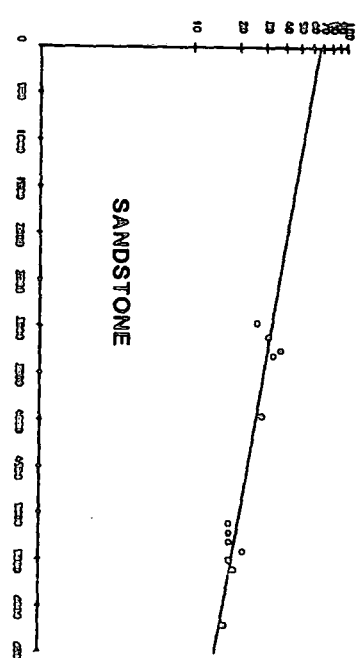
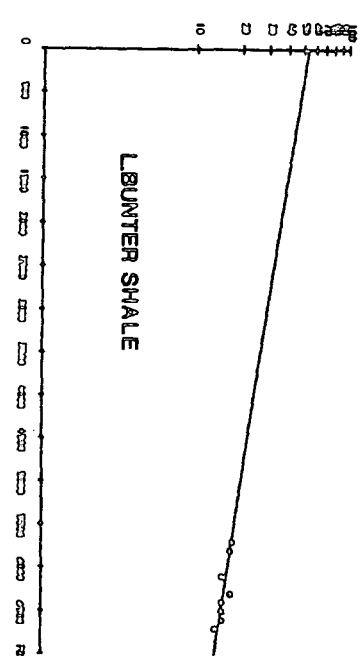
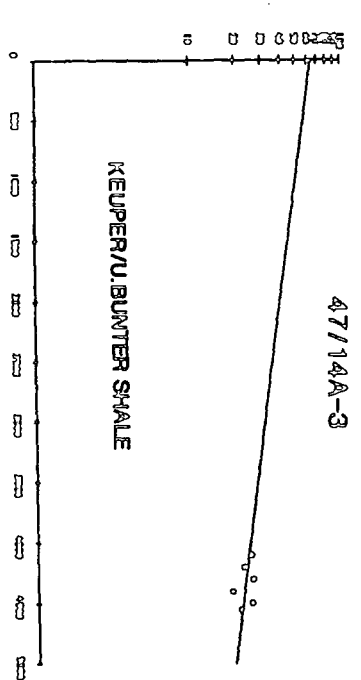
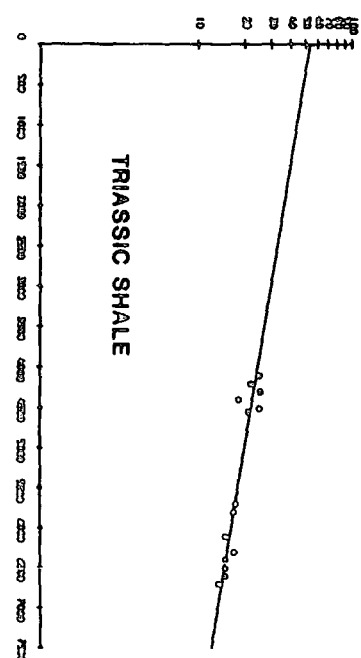
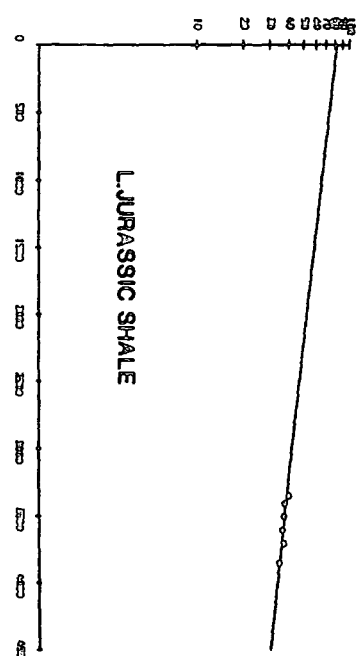
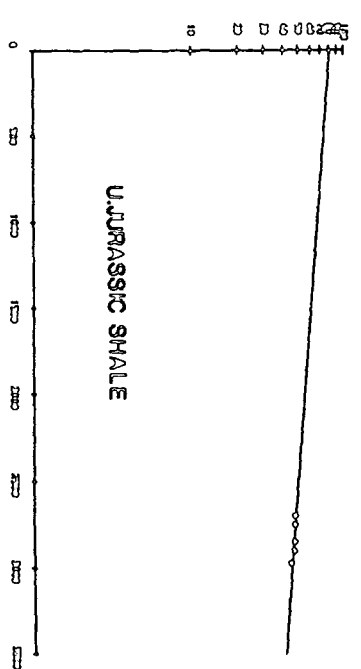
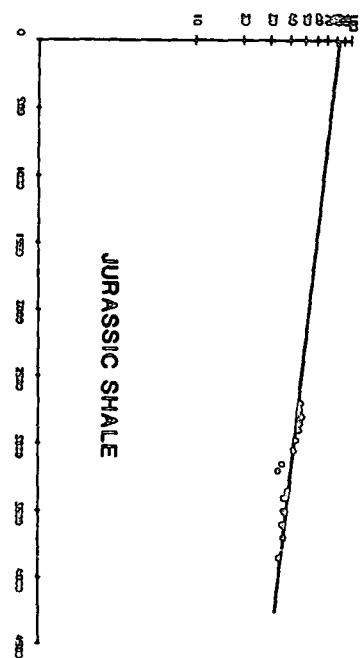
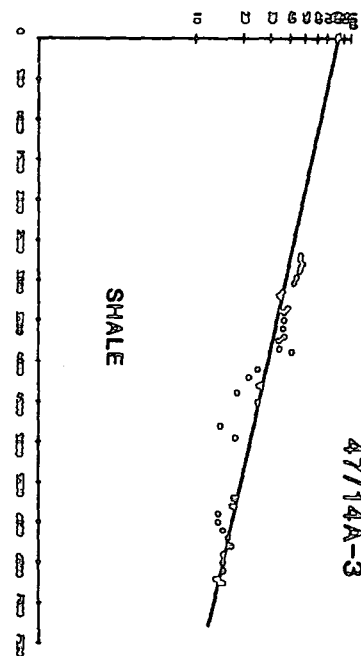
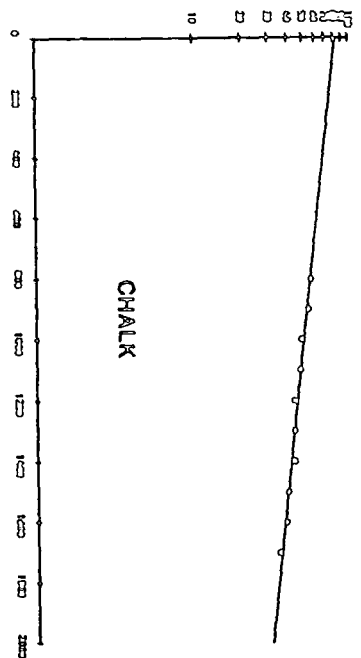
L. BUNTER SHALE

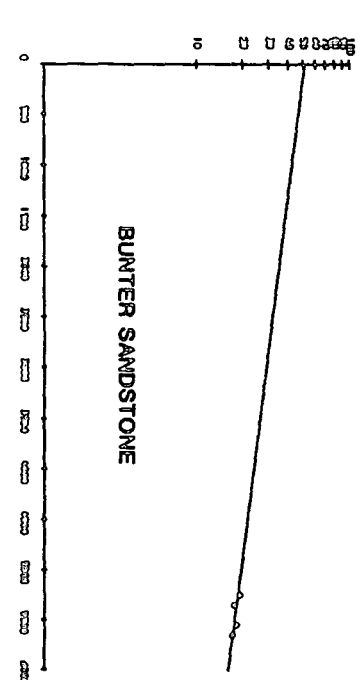
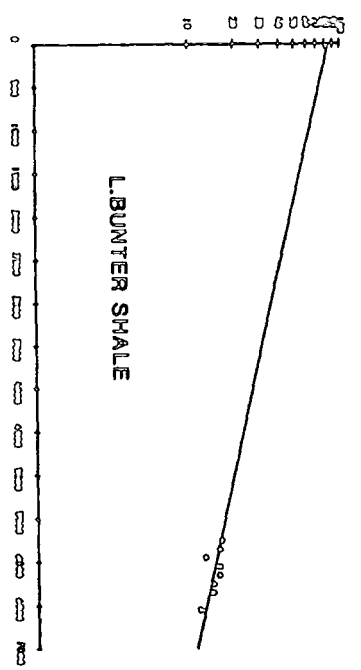
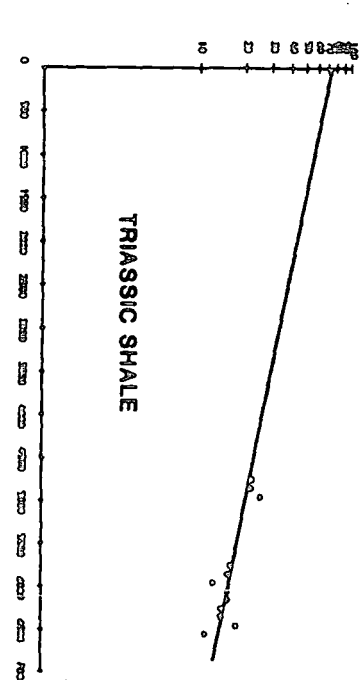
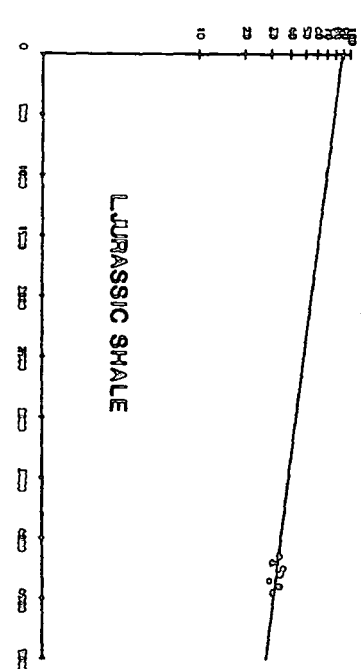
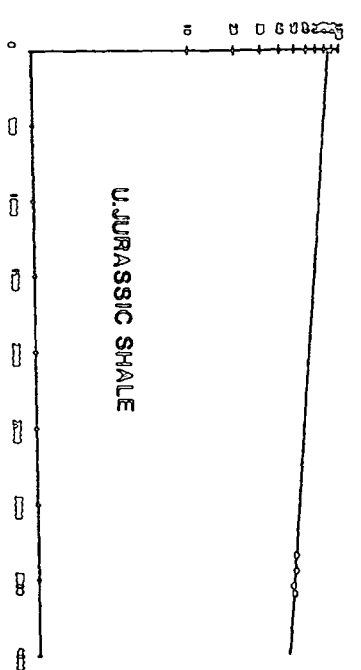
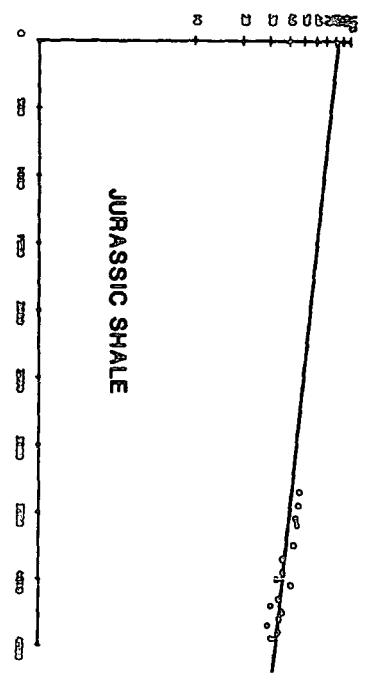
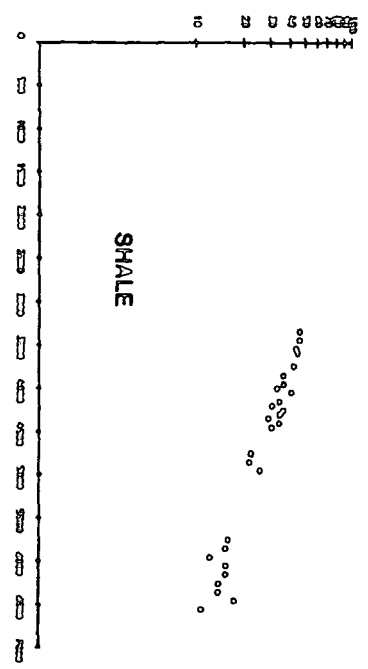
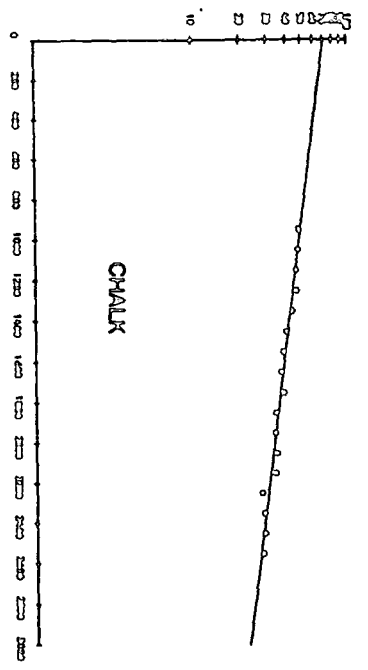


BUNTER SANDSTONE



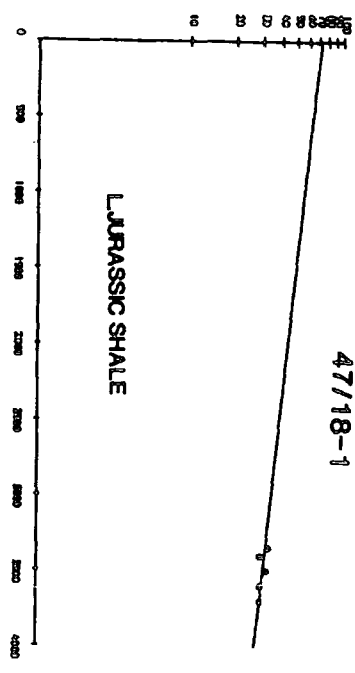
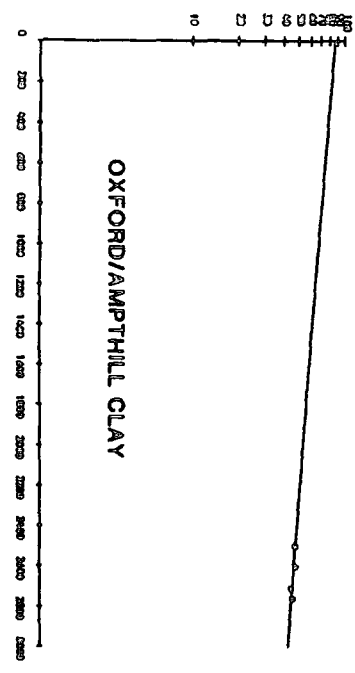
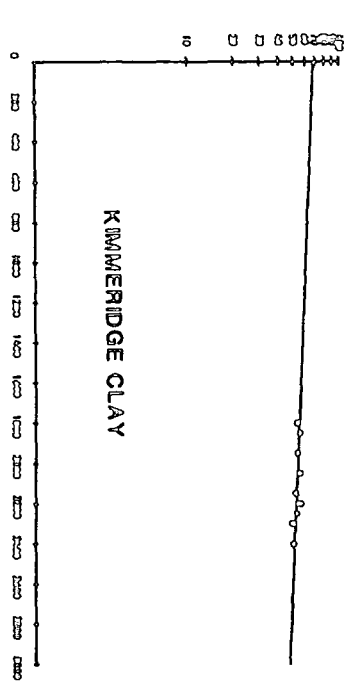
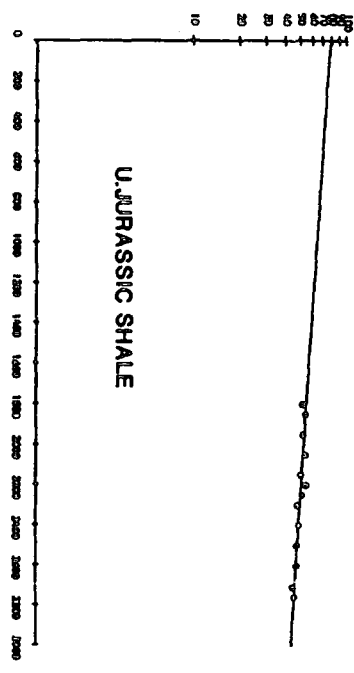
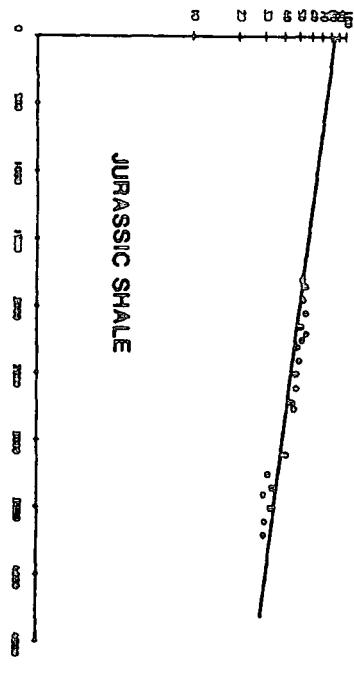
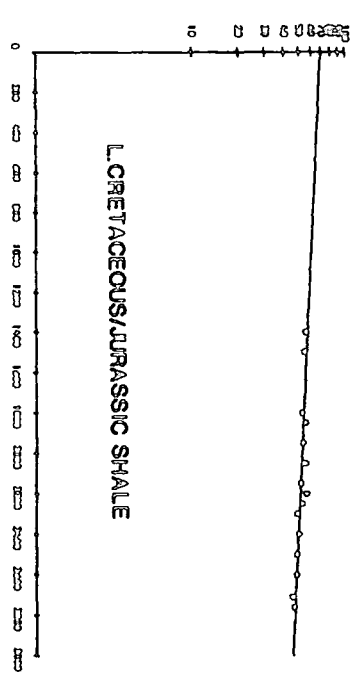
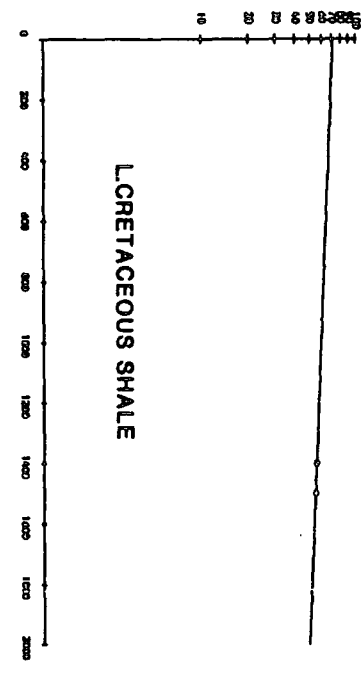
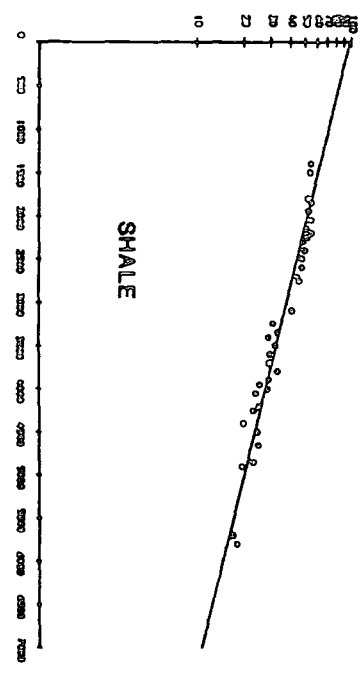
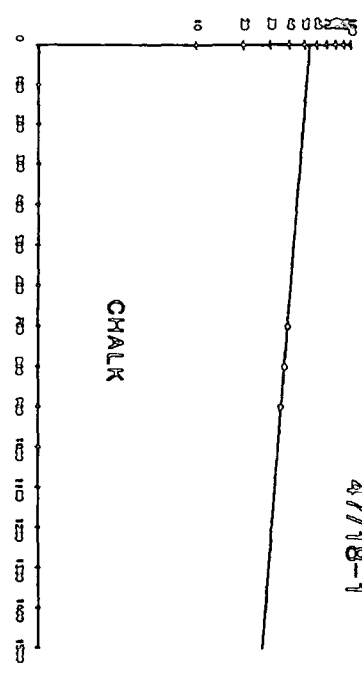
47/13-2



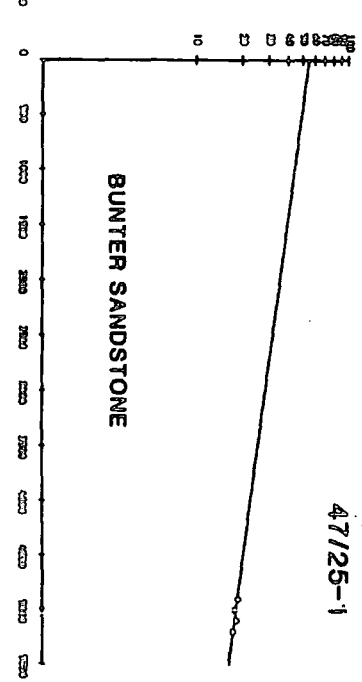
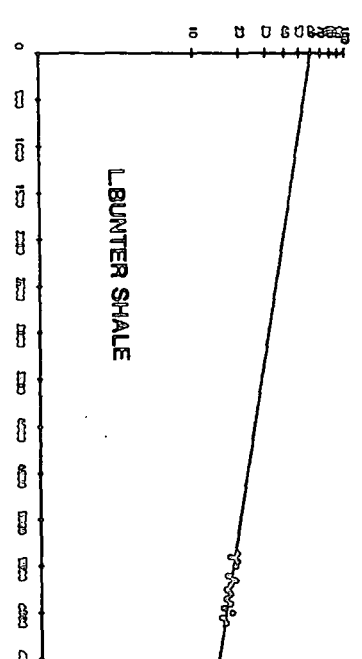
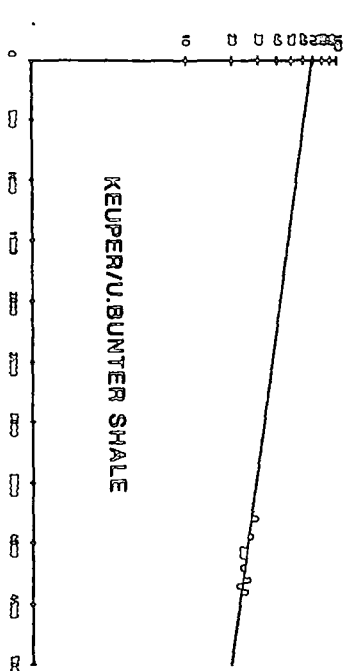
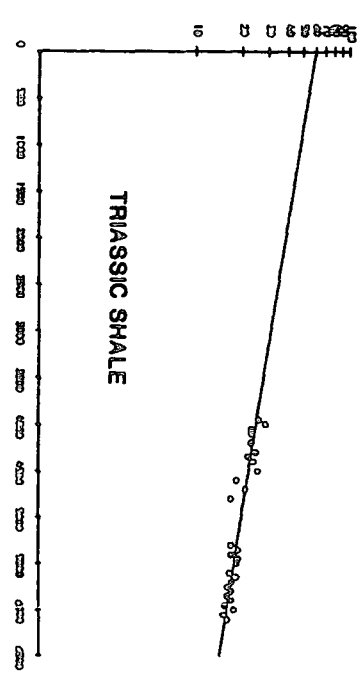
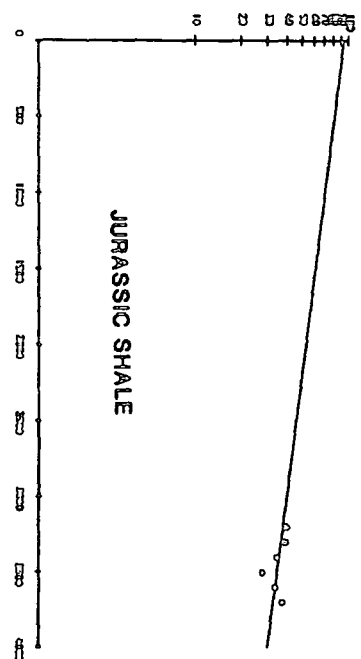
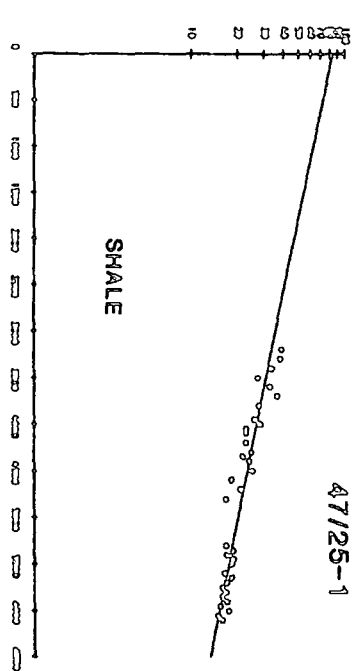
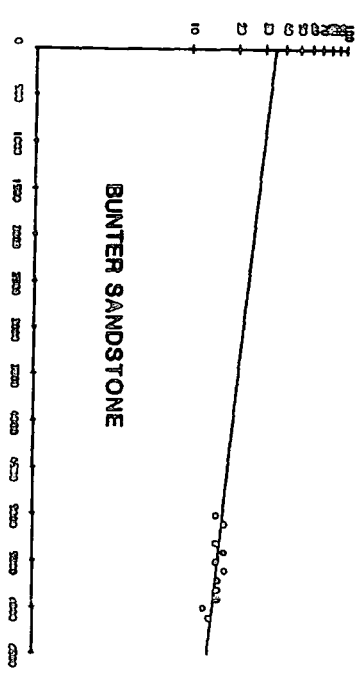
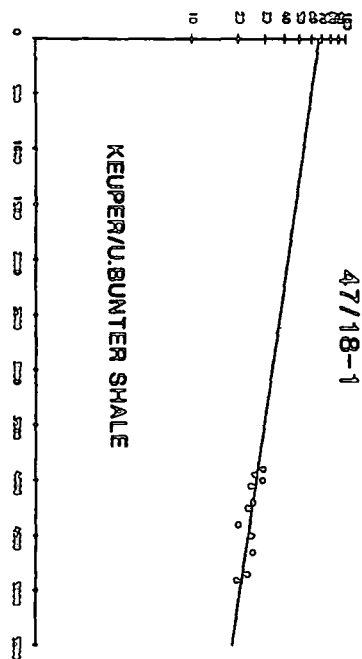
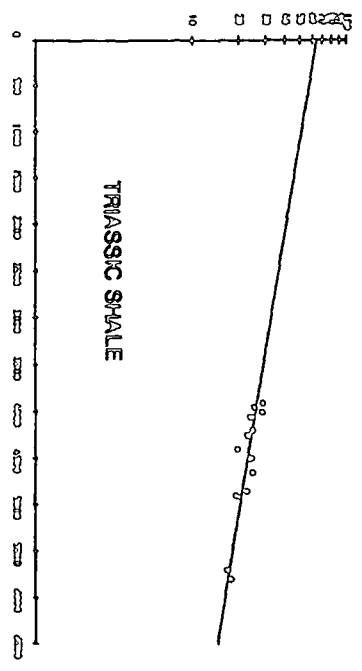


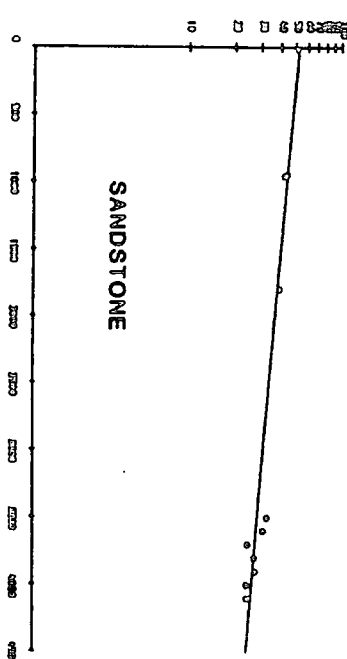
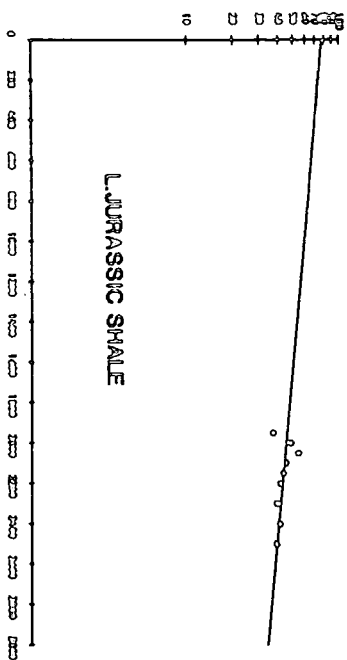
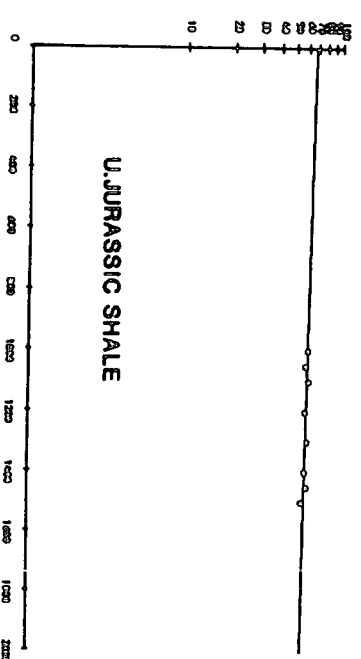
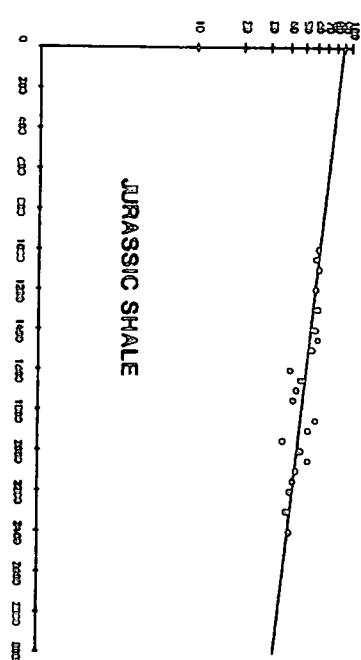
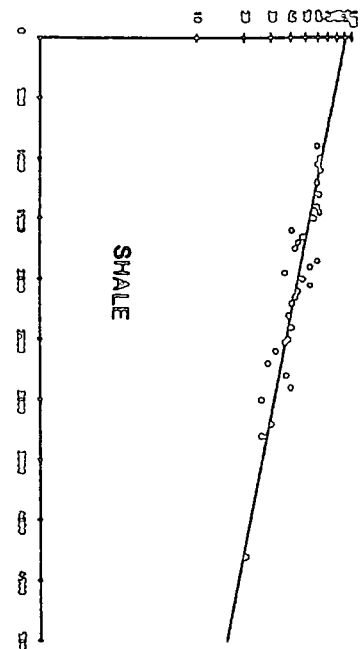
47/15-2

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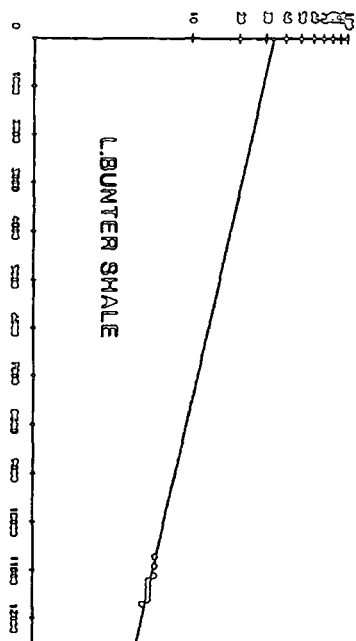


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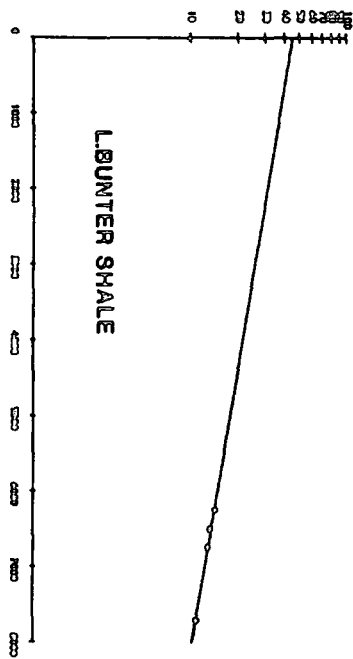




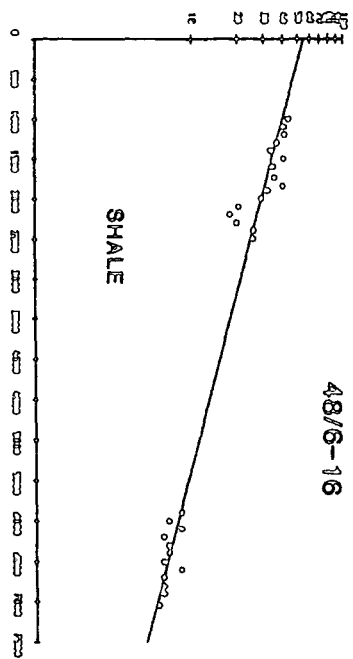
47/29A-1



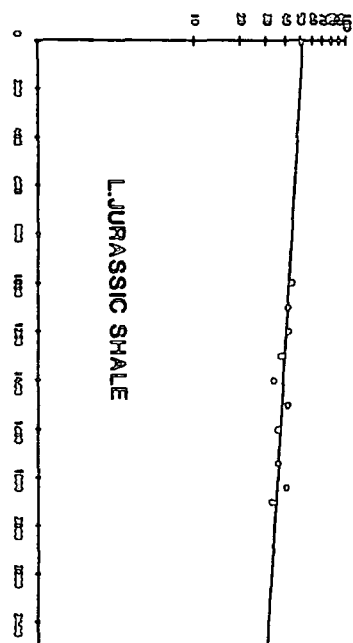
48/3-1



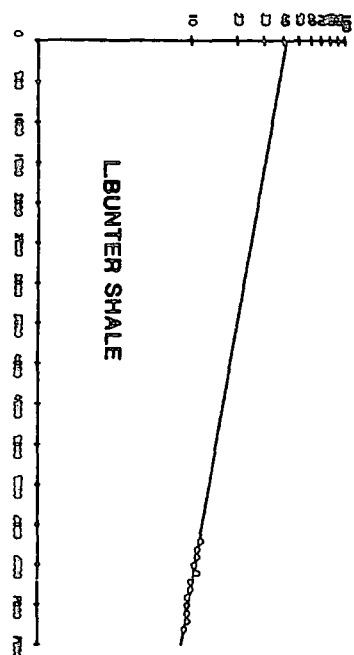
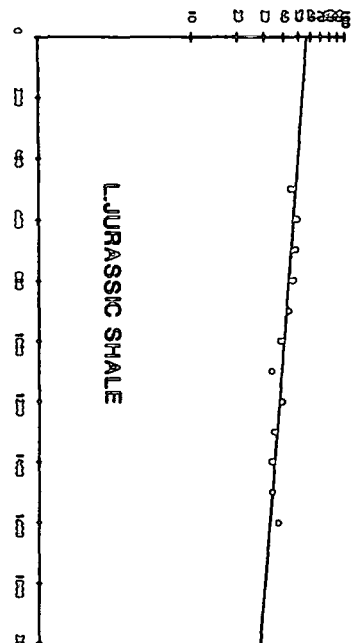
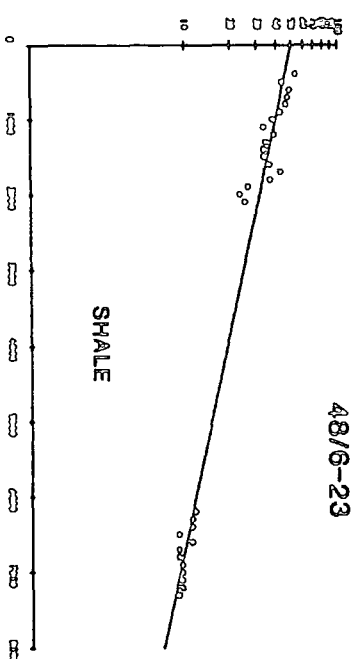
48/6-14

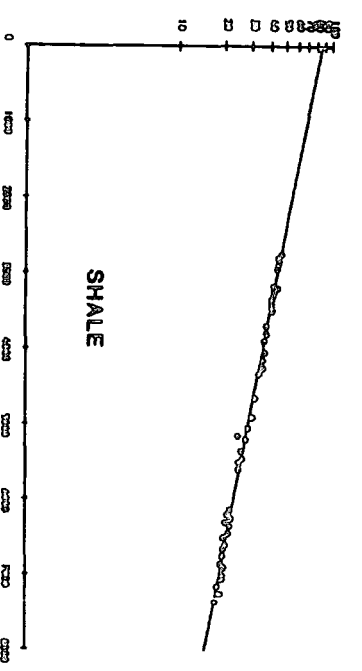
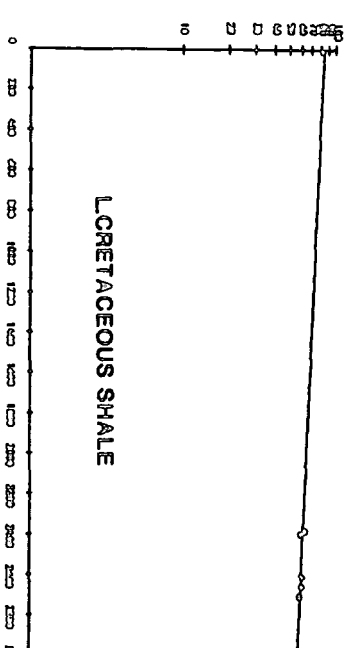
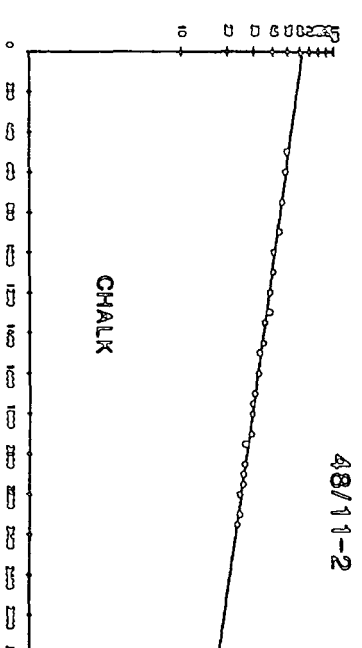
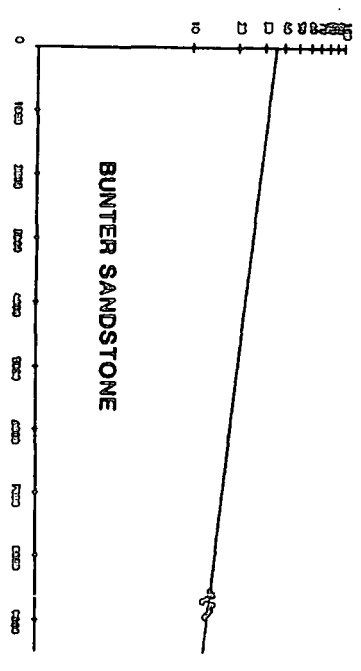
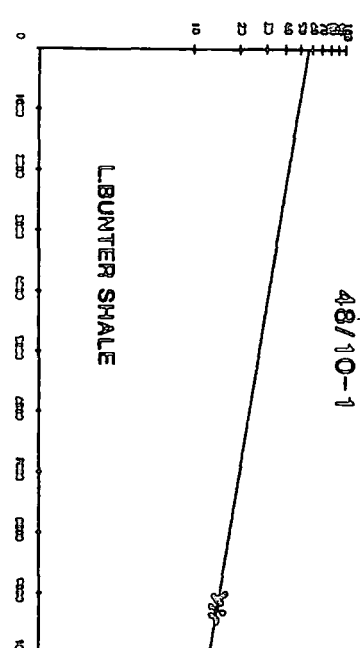
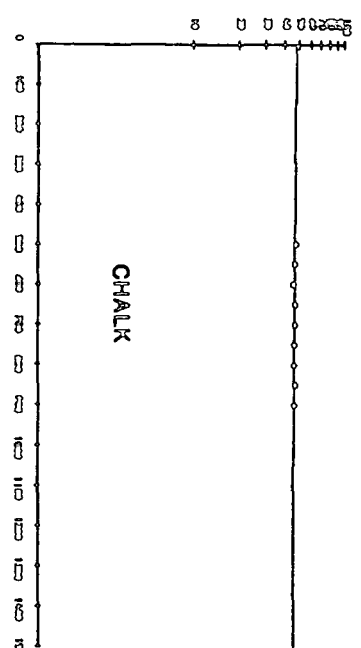
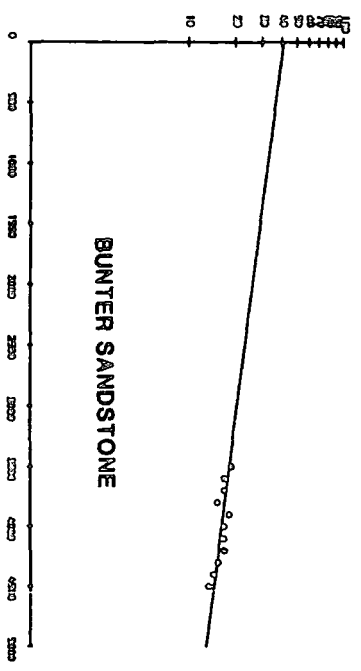
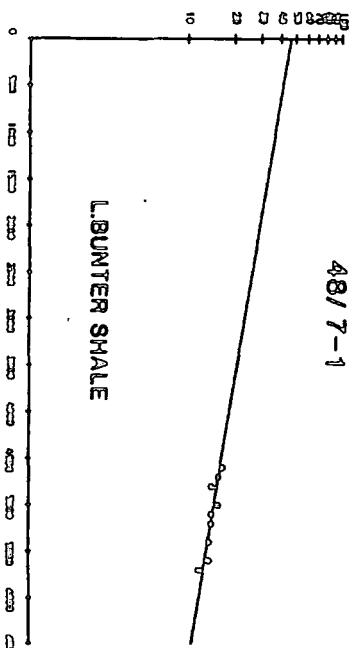
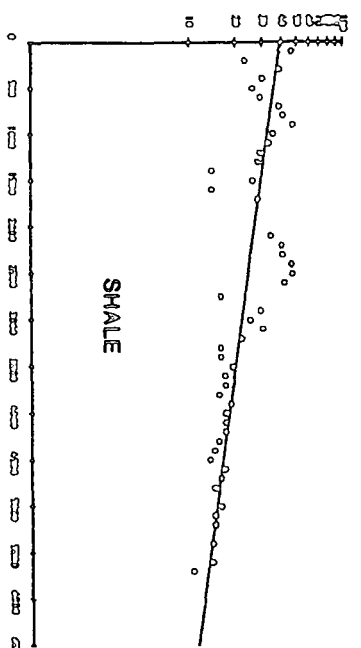


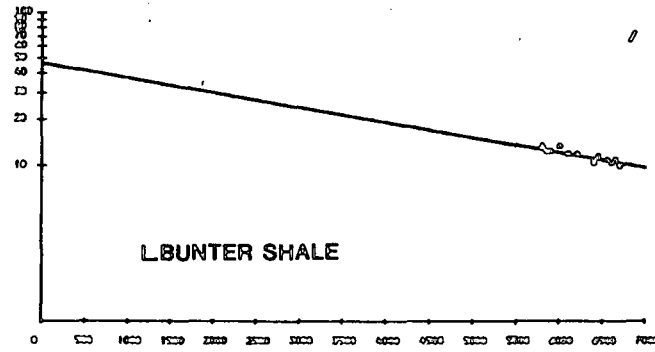
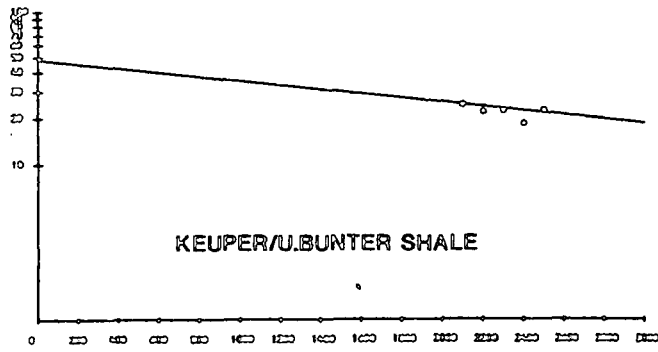
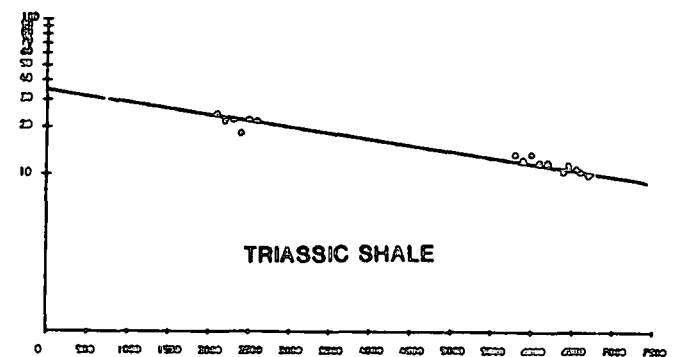
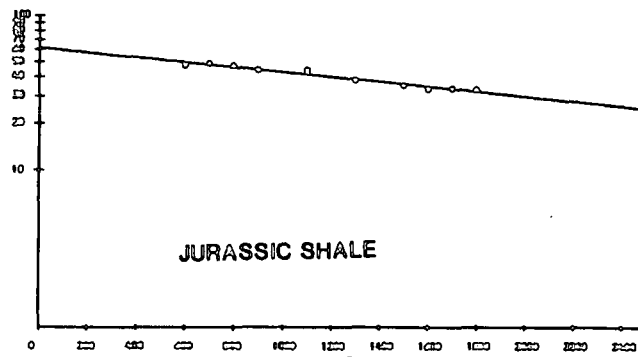
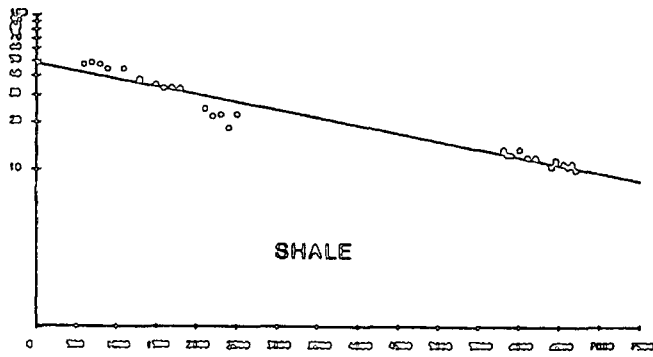
48/6-16



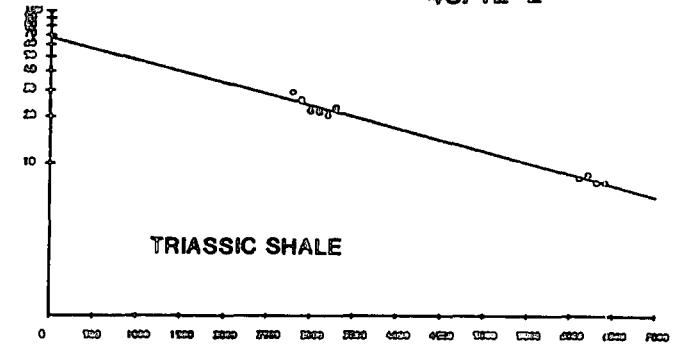
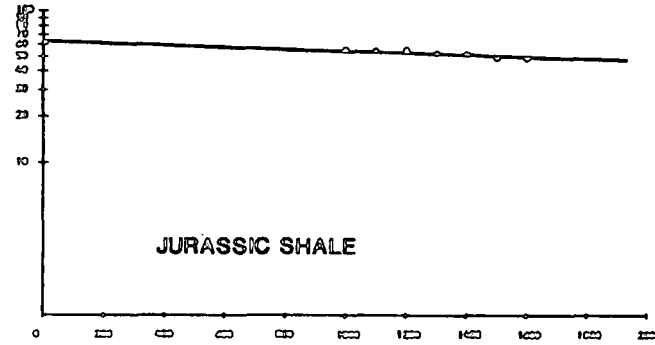
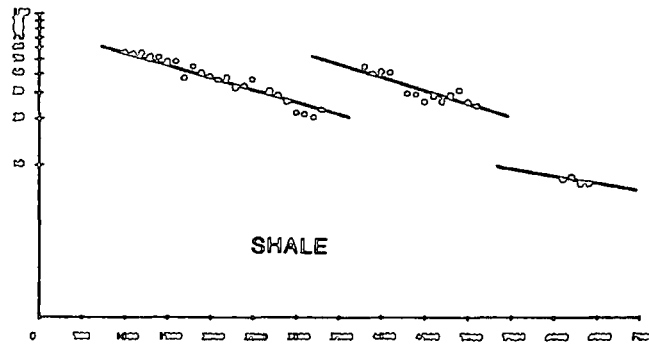
48/6-23



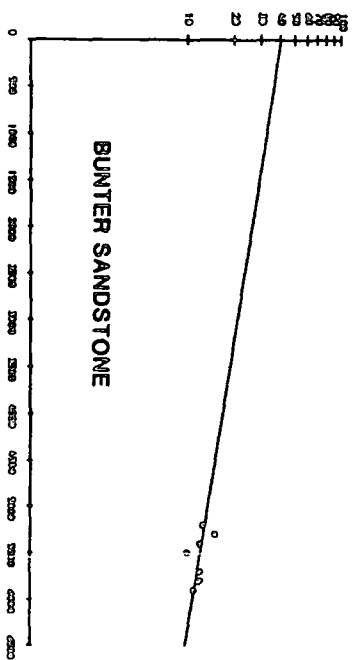
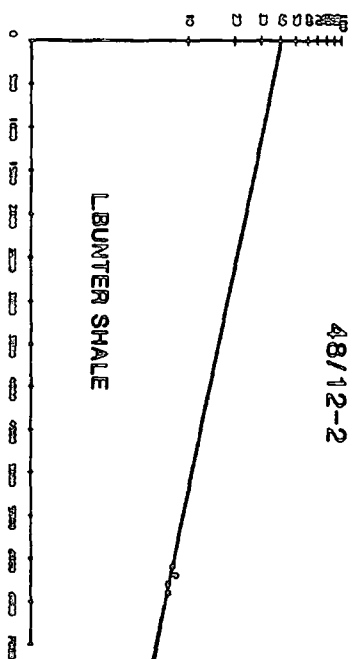
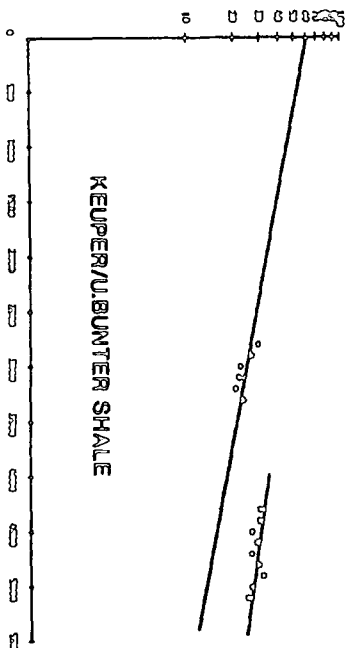




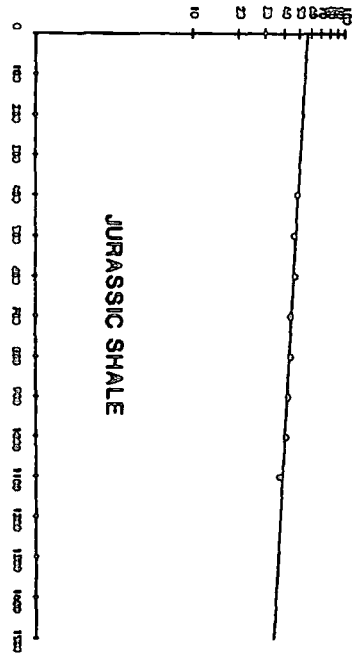
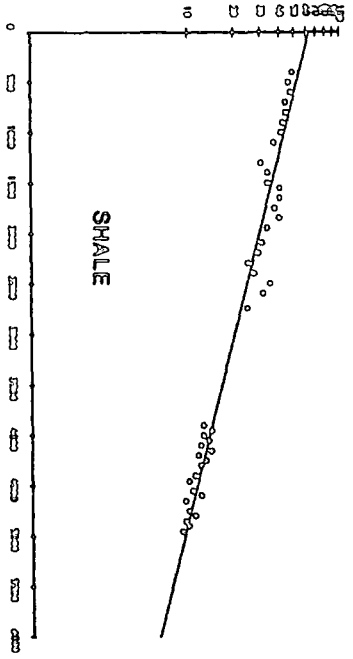
48/12-1



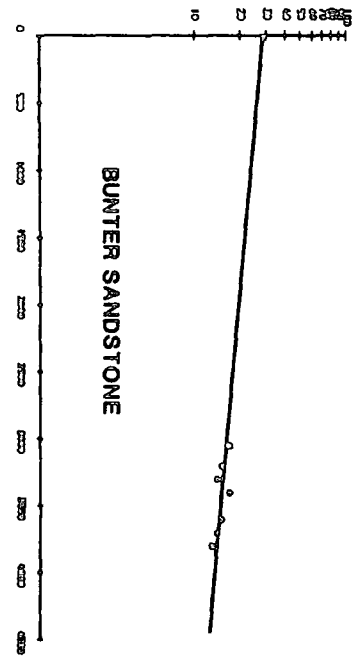
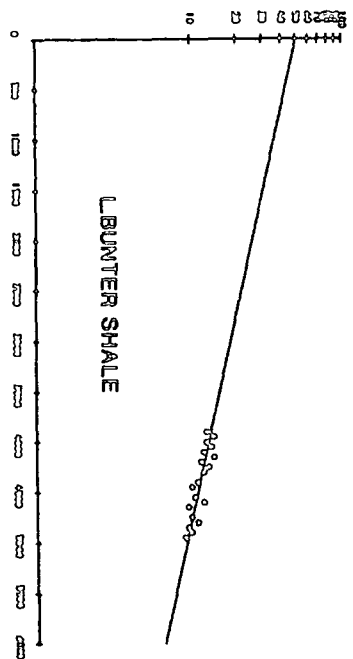
48/12-2



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[illegible]

The graph is titled "CHALK". The vertical axis (y-axis) is labeled from 0 to 150 in increments of 10. The horizontal axis (x-axis) is labeled from 0 to 10 in increments of 1. A vertical line is drawn at x=0, and a horizontal line is drawn at y=0. Data points are plotted as follows:

x	y	Symbol
0	0	+
0	1	+
0	2	+
0	3	+
0	4	+
0	5	+
0	6	+
0	7	+
0	8	+
0	9	+
0	10	+
0	11	+
0	12	+
0	13	+
0	14	+
0	15	+
0	16	+
0	17	+
0	18	+
0	19	+
0	20	+
0	21	+
0	22	+
0	23	+
0	24	+
0	25	+
0	26	+
0	27	+
0	28	+
0	29	+
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9	0	o
10	0	o
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12	0	o
13	0	o
14	0	o
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16	0	o
17	0	o
18	0	

LORETACEOUS SHALE

0 220 460 680 830 1020 1220 1420 1620 1820 2000

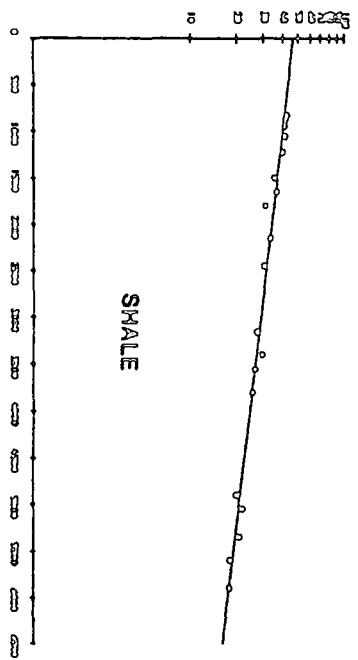
TRIASSIC SHALE

0 1 2 3 4 5 6 7 8 9 10

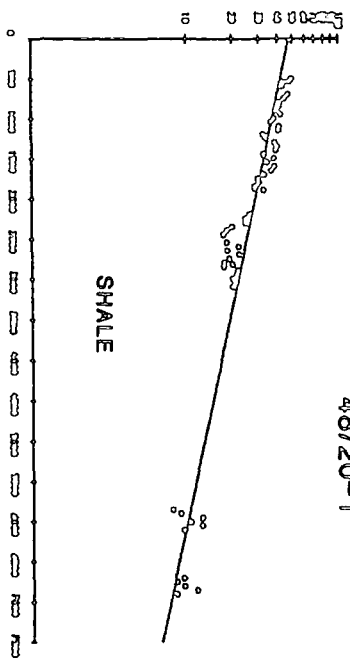
0 1 2 3 4 5 6 7 8 9 10

BUNTER SANDSTONE

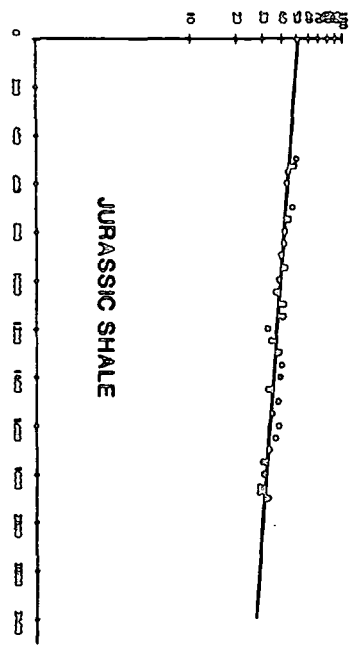
Porosity (%)	Bulk Modulus (10^{10} dynes/cm ^{2})
0	13.5
5	13.2
10	12.8
15	12.2
20	11.5
25	10.8
28	10.2
30	9.8



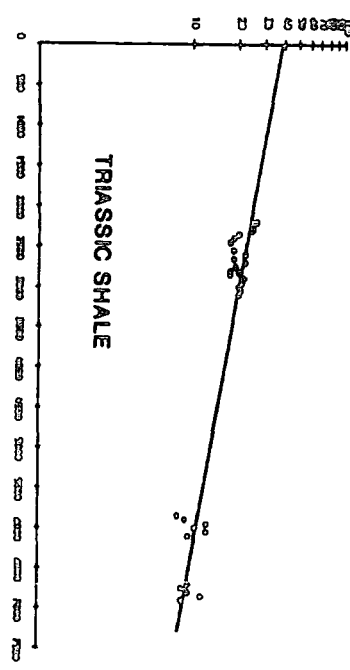
48/19-1



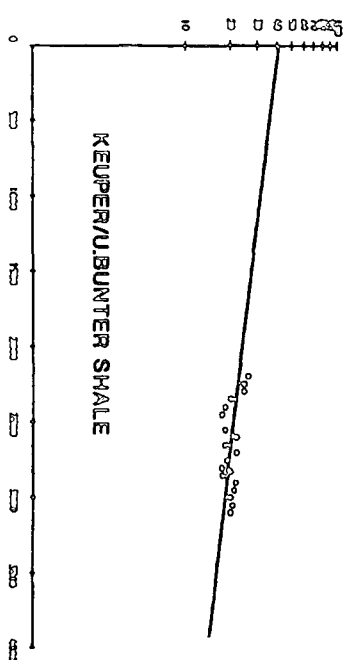
48/20-1



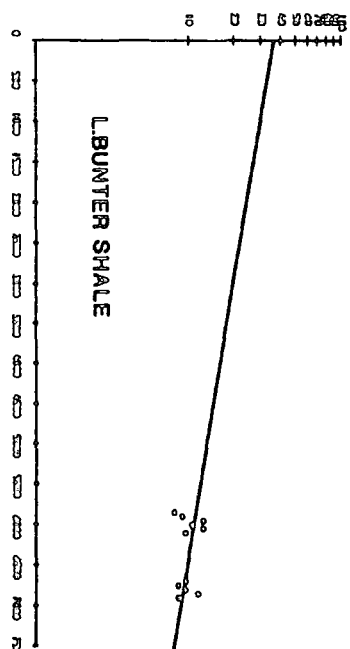
JURASSIC SHALE



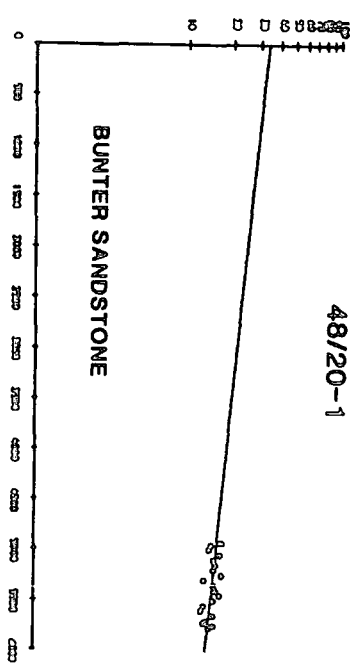
TRIASSIC SHALE



KEUPER/BUNTER SHALE

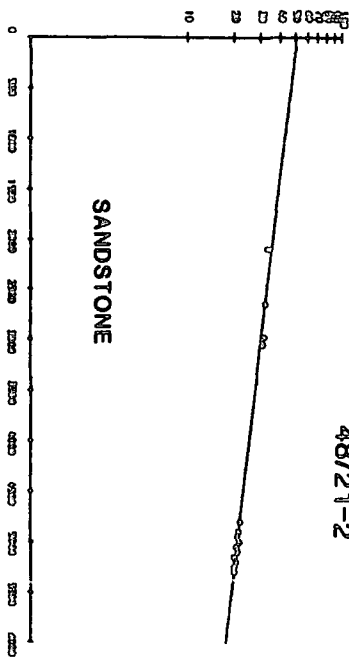
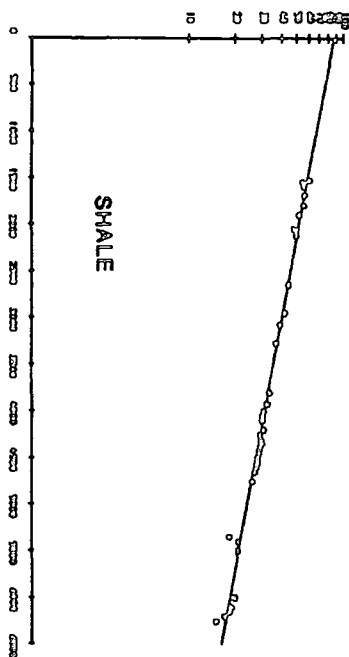
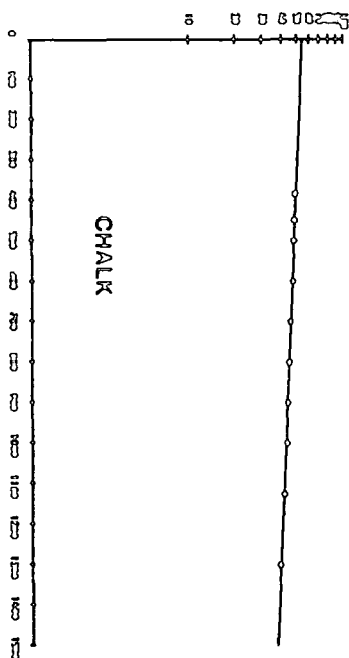


L. BUNTER SHALE

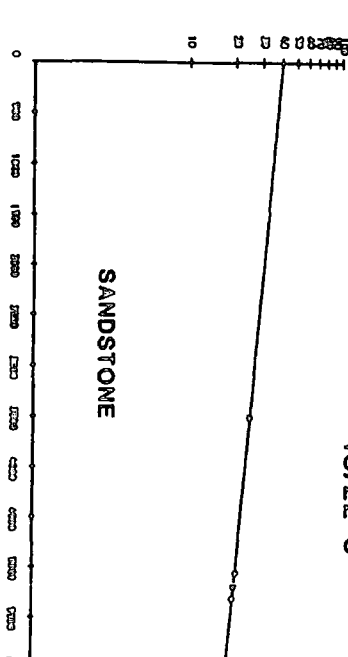
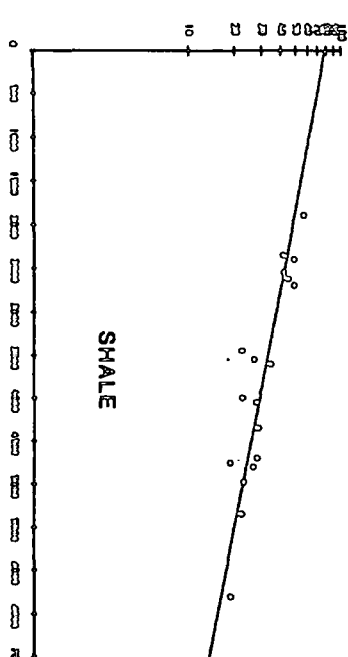
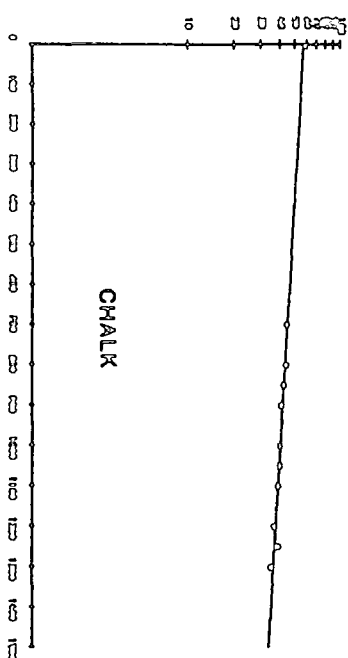


BUNTER SANDSTONE

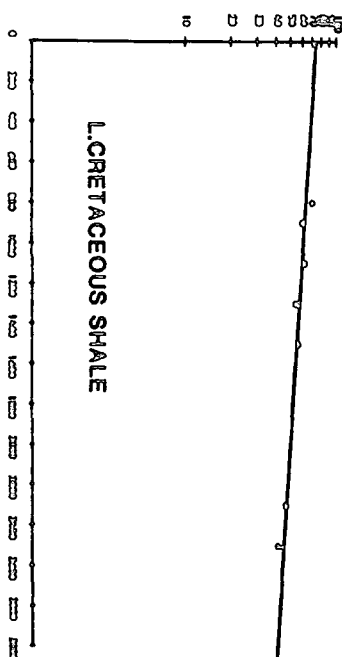
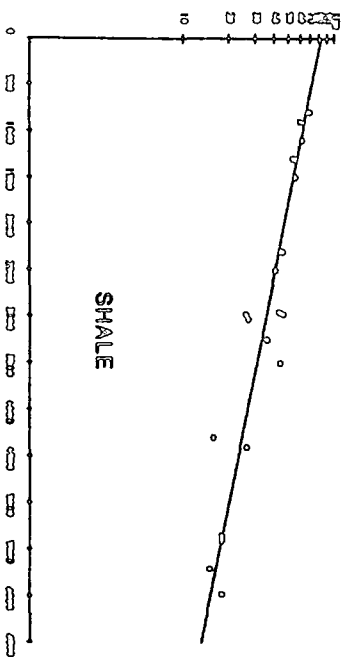
48/20-1



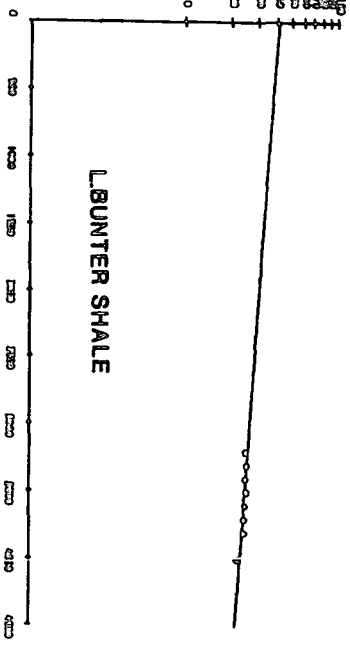
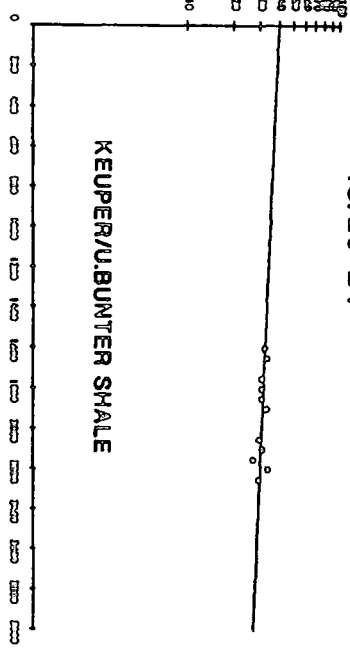
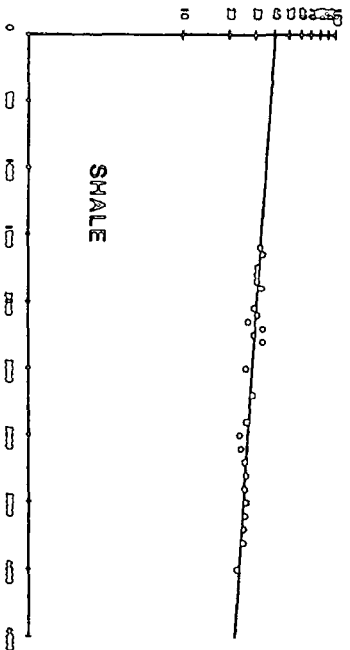
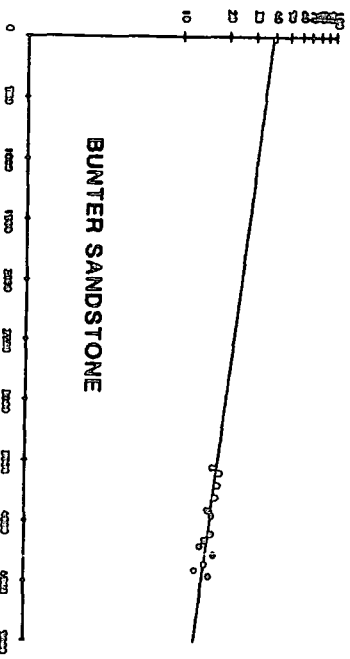
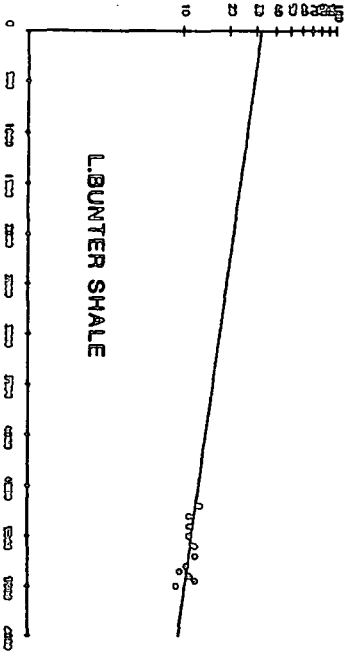
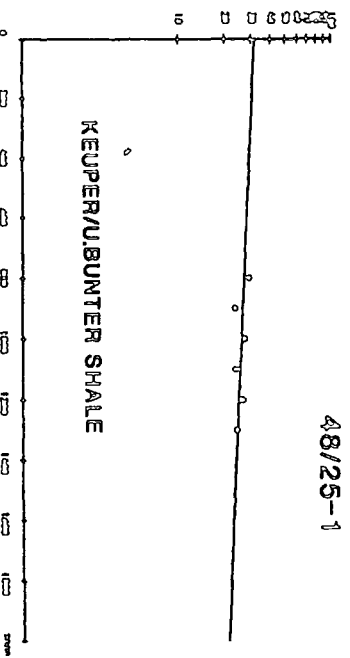
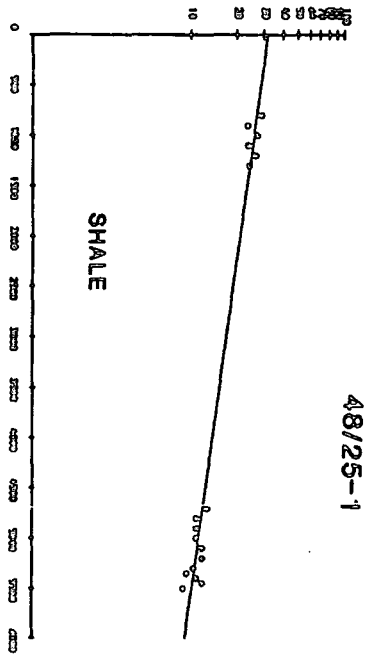
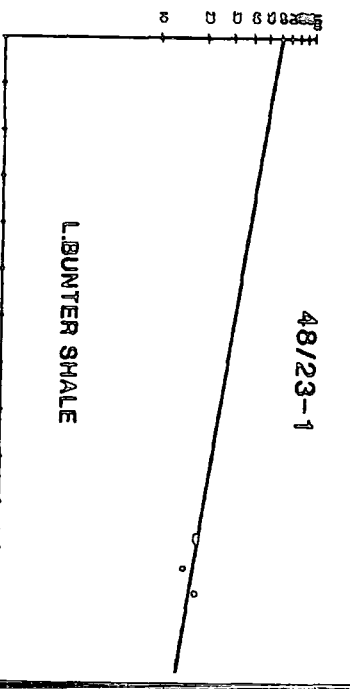
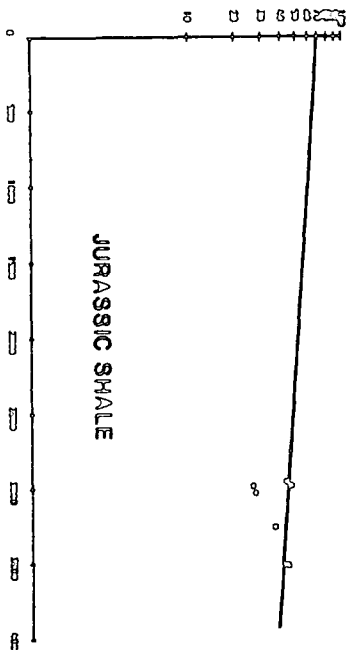
48/21-2

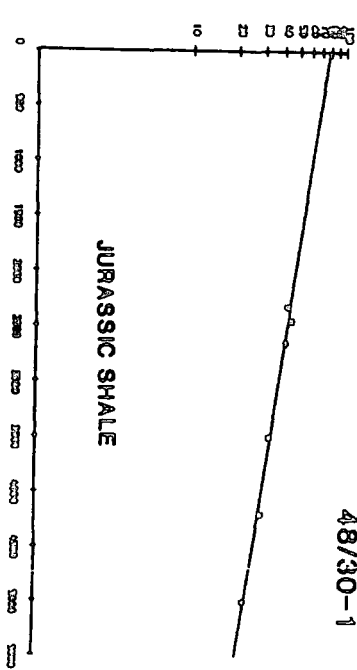
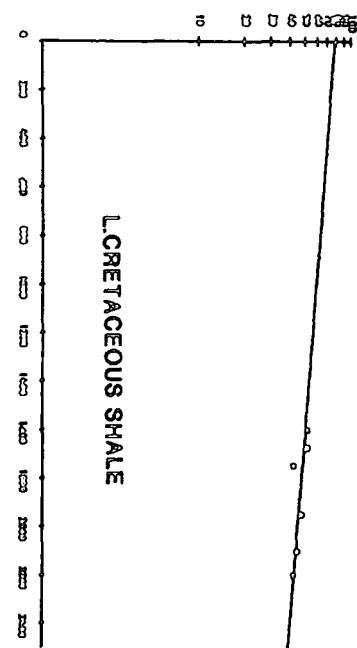
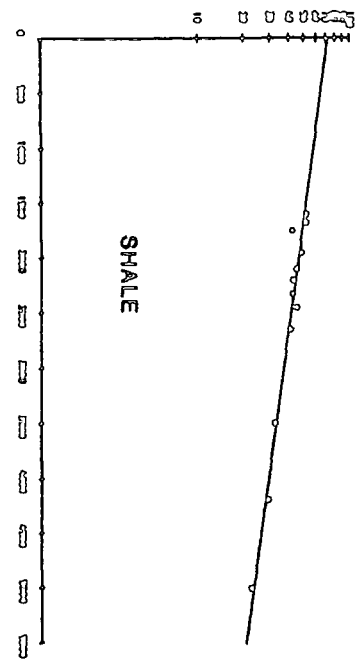


48/22-3

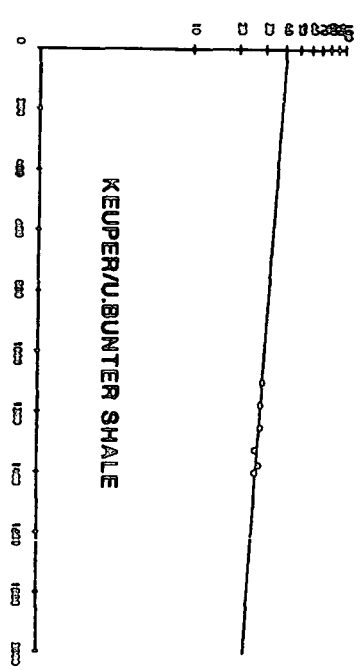
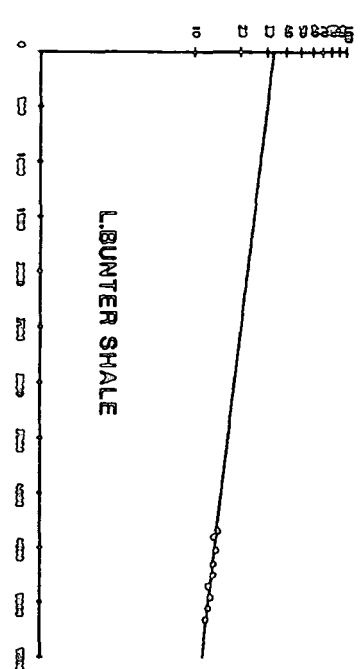


48/23-1

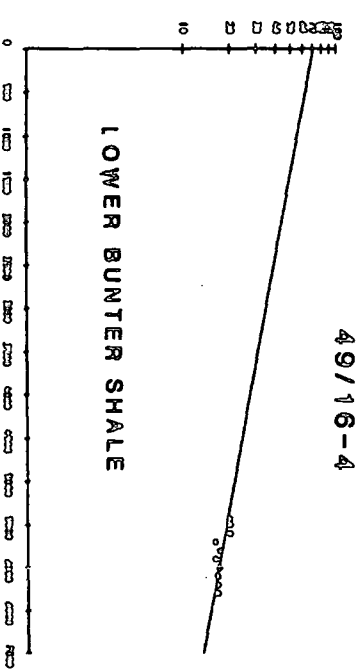
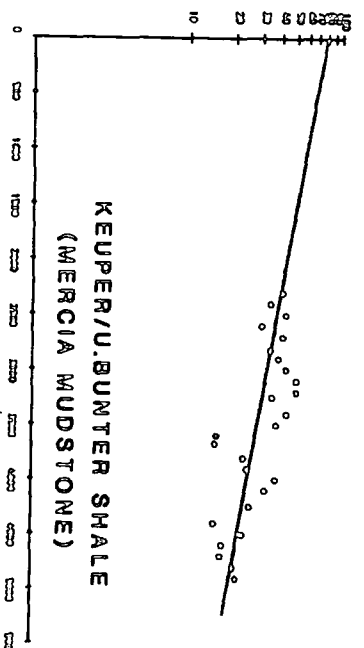
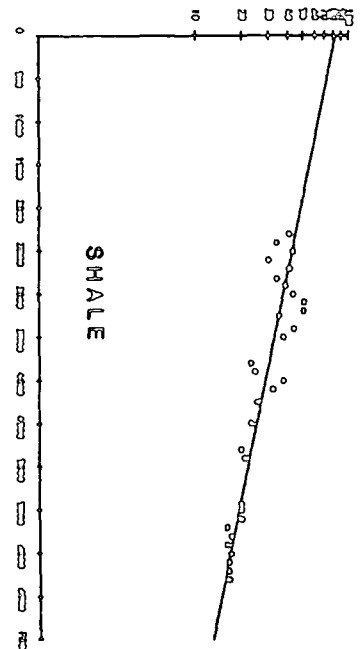




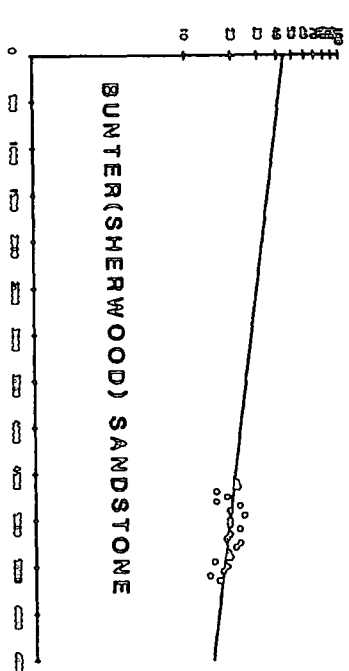
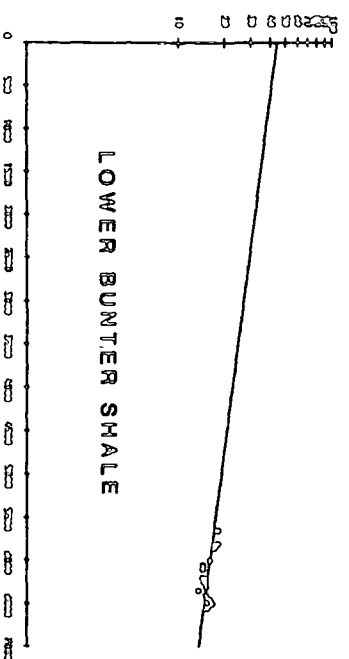
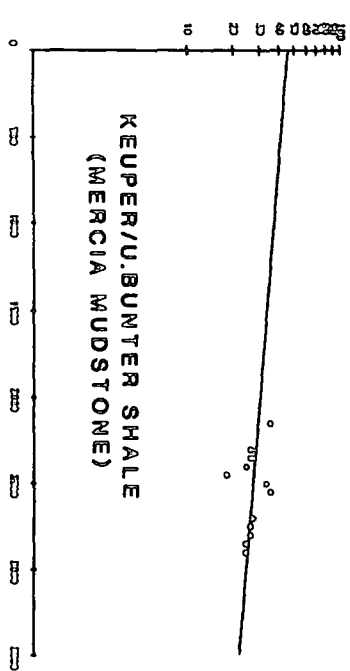
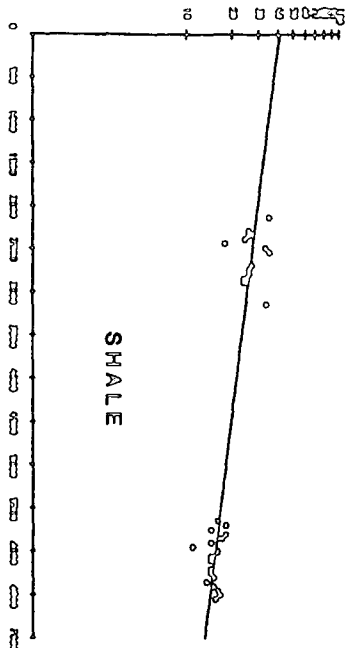
48/30-1



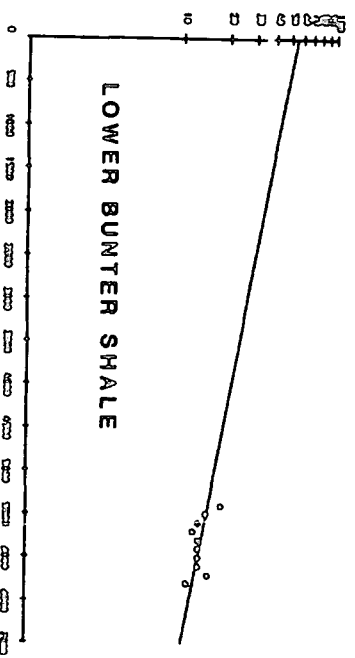
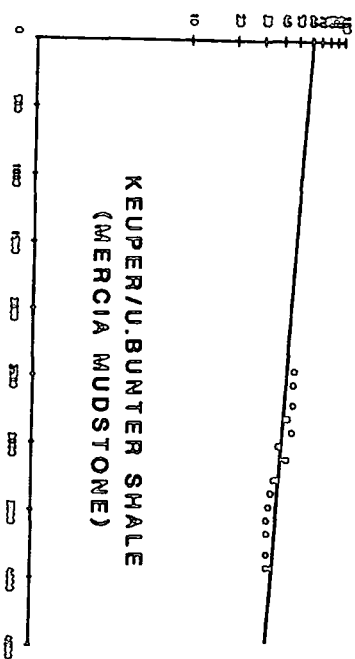
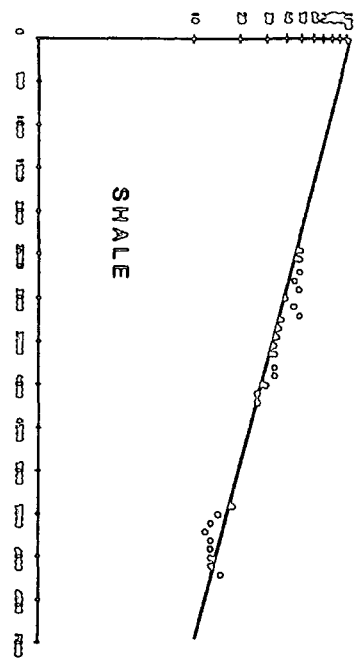
48/30-4



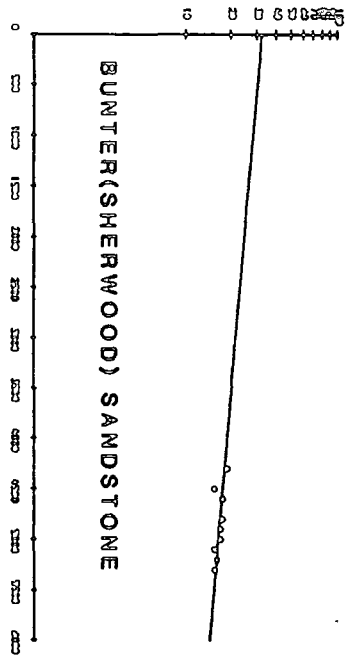
49/16-4



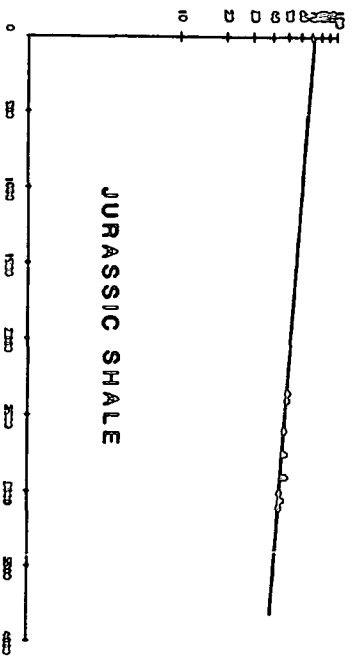
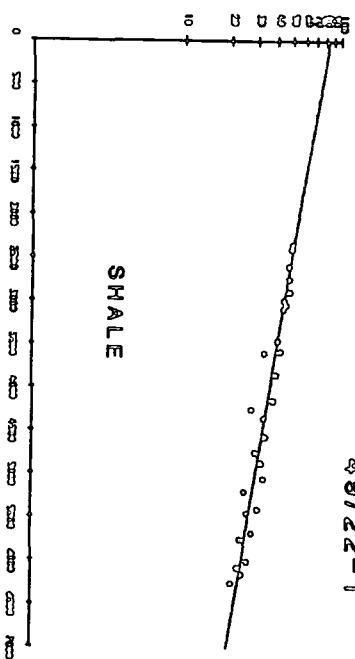
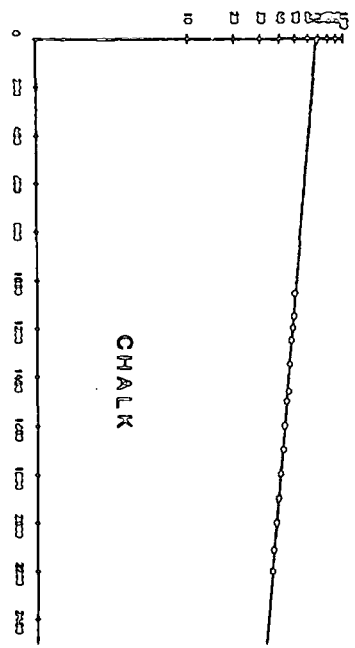
49/21-2

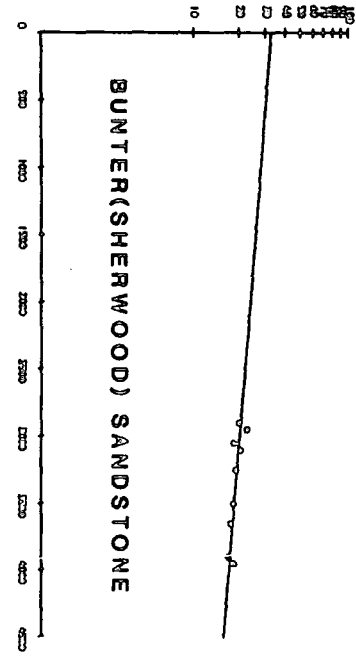
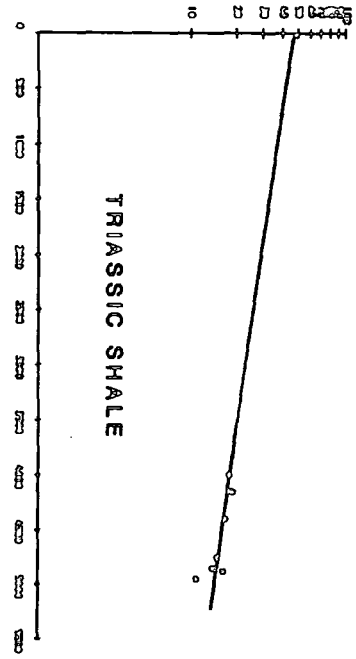
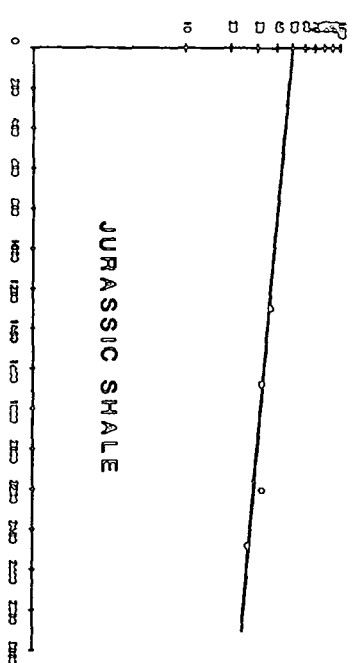
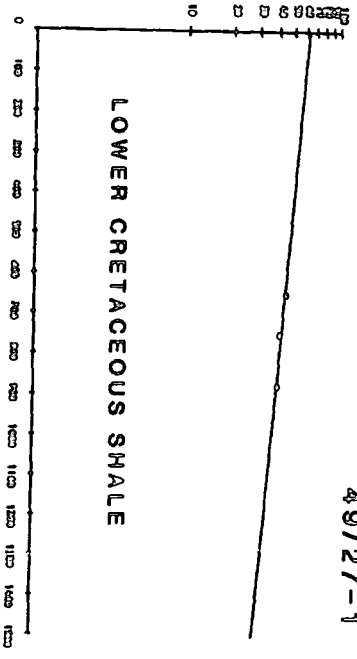
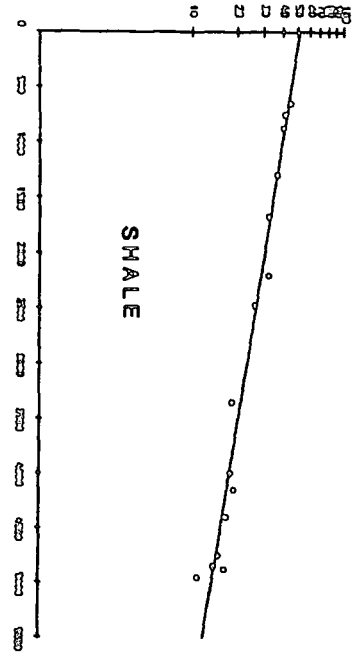
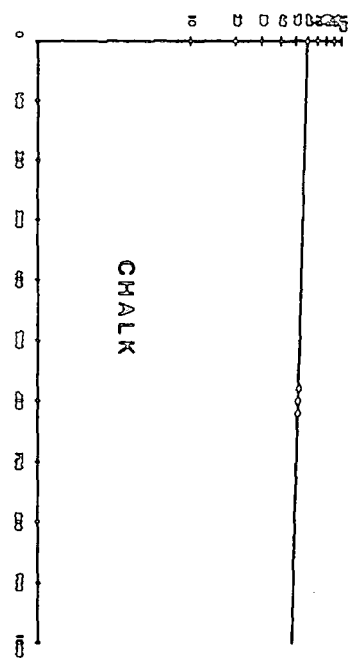
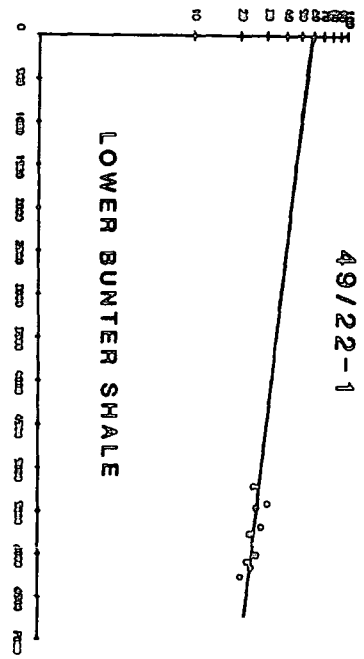
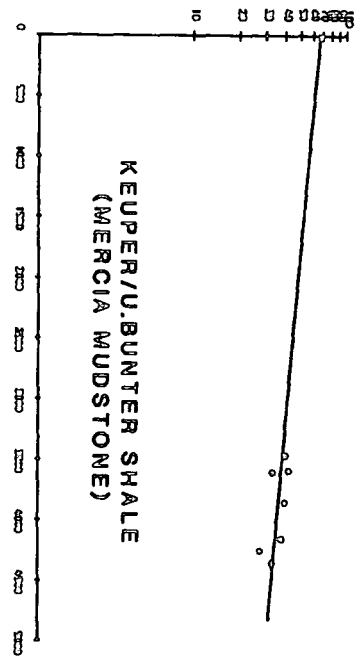
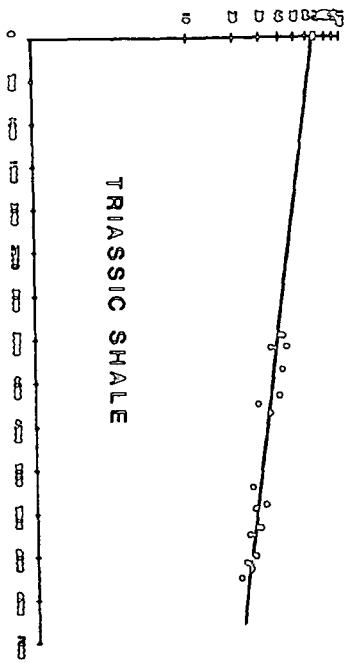


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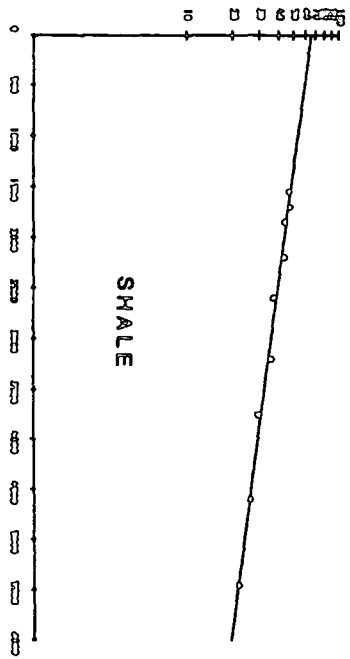
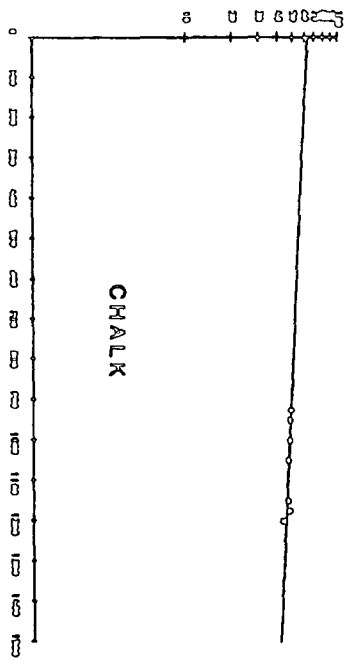
49/22-1





49/22-1

49/27-1



49/28-2

APPENDIX C3: TABLES

		ATWICK	EGTON	FORDON	HARLSEY	HUNMANBY	LANGTOFT
CHALK	Por. Son.	300 1500					
L. CRET SHALES	Por. Son.	1250		1150 0			
OXFD. CLAY	Por. Son.					2000	
LIAS SHALES	Por. Son.		2800 3000	1500		1400 2000	0 500
JUR. SHALES	Por. Son.		2800 3000	1400 1500		2000	0 500
KEUP. SHALES	Por. Son.	1000	1900 3500	1000 2000		2800 2200	0 1000
U. BUNT SHALES	Por. Son.					2800 2200	1000
BUNT. SST.	Por. Son.	1000	3500 3000	2000	5000	2000 1500	0 500
L. BUNT SHALES	Por. Son.	1200	3250 4000	2000	5000	2000 2500	1000 800
TRI. SHALES	Por. Son.	1300	2600 3200		5000	800 2000	500
ALL SHALES	Por. Son.	1000 1500	3200	750 1900	5000	0 2000	1000 500
ALL SST.	Por. Son.	600 1000	3500 3000	3000 2000	5000	1500	0 500
BEST FIT		1500	3000	1800	5000	2000	500

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		LOCKTON	MALTON 1	MALTON 3	POCK'TON	ROSEDALE	STAITHES
CHALK	Por. Son.						
L. CRET. SHALE	Por. Son.						
OXFORD CLAY	Por. Son.			2000			
M. JUR. SHALE	Por. Son.			2200			
LIAS SHALE	Por. Son.	3000	2500 2100	1700 2400		2200 3000	
JUR. SHALE	Por. Son.	2100 2800	2500 2100	1700 2200			
KEUP. SHALE	Por. Son.	2000 2500	2400	2500		1000 3550	
U. BUNT. SHALE	Por. Son.	2000 2800	2400	2500		3500	
BUNT. SST	Por. Son.	3000 3000	2400	2000 2500		2450 3550	
L. BUNT. SHALE	Por. Son.	3000 3000		2400	600 2000	4000	3000
TRIAS. SHALE	Por. Son.	1250 2900	3100 2400	1600 2400	600 2000	3200 3000	
ALL SHALE	Por. Son.	1150 2900	1000 2200	1400 2300		2000 3500	3000
ALL SST	Por. Son.	3000 3000	2600	2000 2500		2400 4000	
BEST FIT		3000	2250	2300	1500	3000	3000

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		STAITHES 4	STAITHES 12	STAITHES 20	WYKEMAM	41/8-1	41/24A-1
LIAS SHALES	Por. Son.	2000 3000	2800 3000	2900 2900	2400 2500		1300 4000
KEUP. SHALES	Por. Son.	2800 3600	2800 2900	2600 3500	1200 3000		2000 5000
U.BUNT. SHALES	Por. Son.	3000 3700	3100 3000	2800	3000		2000 4800
BUNT. SST	Por. Son.	1200 3500	4000	4000 4500	3000	5000 5000	3000 5000
L.BUNT. SHALES	Por. Son.	2800	3500	3000 3000	2500 3200		7000 5000
TRIAS. SHALES	Por. Son.	2500 3500	2400 3100	2900 3100	2600 3000		4500
ALL SHALES	Por. Son.	2500 3300	3200 3000	2200 2900	1400 3100		3500 5500
ALL SST	Por. Son.		4000 3500				3000 5000
BEST FIT	Por. Son.	3000	3000	3000	3000	5000	5000

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		41/25A-1	41/20-2	42/13-1	42/14-1	42/33-1	42/26-1
CHALK	Por. Son.			0 700			0 1000
L.CRET. SHALES	Por. Son.			500 300			1850 500
KIMM. CLAY	Por. Son.						0
L.CRET. + KIMM.	Por. Son.						1000
OXFORD CLAY	Por. Son.						0
LIAS SHALES	Por. Son.				1700 500	1700	
JUR. SHALES	Por. Son.			200 400	1700 1400	1600 1600	0
KEUP. SHALES	Por. Son.	5000	2500 5000		1250 1300	1600 2200	800
U.BUNT. SHALES	Por. Son.	5000 5300	2500 5200		0 1300		
BUNT. SST	Por. Son.	5000	5000		0 700		0 0
L.BUNT. SHALES	Por. Son.	7000 5500	8000 6000		1200 1500	2600	
TRIAS. SHALES	Por. Son.	5500	6000		1750 1500	350 1800	
ALL SHALES	Por. Son.	15500 6000		500 1000	800 1800	0 500	
BEST FIT		5500	6000	500	1200	2000	500

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		42/28-1	42/29-1	42/30-1	43/3-1	43/16-1	43/21-1
CHALK	Por. Son.	500		0			
L.CRET. SHALES	Por. Son.	1800 0	0 0	0			
KIMM. CLAY	Por. Son.	0 0	0 200				
OXFORD CLAY	Por. Son.	0 0					
M. JUR. SHALES	Por. Son.	0 0	0 500				
M. JUR. SST	Por. Son.	1500					
LIAS SHALES	Por. Son.	0 1000	2000 500	1750			
JUR. SHALES	Por. Son.	0 500	0	1750			
KEUP. SHALES	Por. Son.	500 1200	500	2300		1500	1800
U.BUNT. SHALES	Por. Son.		500			2000	
BUNT. SST	Por. Son.		0 1000	2400		2000	2000
L.BUNT. SHALES	Por. Son.		0	2000		2000	2000
TRIAS. SHALES	Por. Son.	500 800	0 0		1000	1800	1900
ALL SHALES	Por. Son.	0 500	0 0	2000		1800	2500 2200
BEST FIT		800	200	2000	0-1000	2000	

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		48/3-1	48/6-14	48/6-16	48/6-23	48/7-1
LIAS SHALES	Por. Son.			1650 2000	1000 2250	2500
KEUP. SHALES	Por. Son.			2200	2500	3000 3000
U. BUNT. SHALES	Por. Son.					
BUNT. SST	Por. Son.					2000 3000
L. BUNT. SHALES	Por. Son.		3500 3000	3000 2800	3000 2200	3000 4000
TRIAS. SHALES	Por. Son.		3500 3000	2500	2400	3500
ALL SHALES	Por. Son.	5300 5000		1400 2600	2000 2500	3500 3300
BEST FIT		5300	3500	2500	2300	3500

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		48/10-1 FAULTED	48/11-2	48/12-1	48/12-2	48/13-1	48/17-1
CHALK	Por. Son.	1500 750	300 500				700 1000
L. CRET. SHALES	Por. Son.		0 0				450 500
KIMM. CLAY	Por. Son.		0				300
OXFORD CLAY	Por. Son.		0				
M. JUR. SHALES	Por. Son.		0				600
M. JUR. SST	Por. Son.		0				
LIAS SHALES	Por. Son.		500	800 2800	1500 2000	1200 2300	800
JUR. SHALES	Por. Son.		0	800 2800	1500 2000	1200 2300	0 200
KEUP. SHALES	Por. Son.		500	2000 3000	1500 2200	2500	1000
U. BUNT. SHALES	Por. Son.		0	2000 3100	0 0	2500	1000
BUNT. SST	Por. Son.		250	3500	1800 2000	3000 2500	600
L. BUNT. SHALES	Por. Son.	0	800	3000 2700	2500 2500	2100 3000	1000
TRIAS. SHALES	Por. Son.		400	4400 3500	2300	3000	1000
ALL SHALES	Por. Son.	2900 2500	0 300	2500 2500	300 2000	1000 3000	200 500
BEST FIT		2000	300	3000	2100	2500	500

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		48/18B-2	48/19-1	48/20-1	48/21-2	48/22-3
CHALK	Por. Son.				700 1000	1500 800
L.CRET. SHALES	Por. Son.				0	0
KIMM. CLAY	Por. Son.				500	500
OXFORD CLAY	Por. Son.				0	500
LIAS SHALES	Por. Son.		3400 3500	2000 2200	0 500	500
JUR. SHALES	Por. Son.	2000 3000	3400 3500	2000 2200	500	500
KEUP. SHALES	Por. Son.	2800	3000 3200	2400 2600	0 900	800
U.BUNT. SHALES	Por. Son.		3000 2500	2400 2500		1000
BUNT. SST	Por. Son.	3500 3000	3000	2800 3000	0 1000	1000
L.BUNT. SHALES	Por. Son.	3200 2000	3000 3800	3600 2500	0 1000	1100
TRIAS. SHALES	Por. Son.	2700	3300	3200 2800	1000	900
ALL SHALES	Por. Son.	3000	3600 3500	2500 2500	0 500	400 500
BEST FIT		3000	3600	2500	700	500

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		48/23-1	48/25-1	48/29-B1	48/30-1	48/30-4
CHALK	Por. Son.					
L.CRET. SHALE	Por. Son.	800 600			400 500	
KIMM. CLAY	Por. Son.	1500			500	
OXFORD CLAY	Por. Son.					
LIAS SHALE	Por. Son.	2000		3000	0	
JUR. SHALE	Por. Son.	1400 2100		3000	400 500	
KEUP. SHALE	Por. Son.	2500	3400 3900	4000 3000	1000	2000 3000
U.BUNT. SHALE	Por. Son.		3200	3500 2900		3500
BUNT. SST	Por. Son.		2000 4000	2000	800	3100
L.BUNT. SHALE	Por. Son.	1700 2000	4000 3000	4500 2500	1000	4000 3500
TRIAS. SHALE	Por. Son.	2200	3500	3000	400 800	3300
ALL SHALE	Por. Son.	0 2800	4700 3500	4000 3500	700 900	3500 3500
BEST FIT		2000	3500	3500	700	3500

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		AXHOLME	RISBY	S.ROSS	SOMERTON	S.CREAKE	U.CROSS
CHALK	Por. Son.				400 1000		
L.CRET. SHALES	Por. Son.				0 0		
OXFORD CLAY	Por. Son.					500	
LIAS SHALES	Por. Son.					800	0
JUR. SHALES	Por. Son.					1000 700	0
KEUP. SHALES	Por. Son.				0 400		800
U.BUNT. SHALES	Por. Son.				0 0		
BUNT. SST	Por. Son.				0 0		1000
L.BUNT. SHALES	Por. Son.						700
TRIAS. SHALES	Por. Son.				0 500	1300 1000	1500 1000
PERMIAN DOLOM.	Por. Son.		1100	1400 1400			
CARB. SHALES	Por. Son.	2000		1500 1500			
CARB. SST	Por. Son.	1400 1000					
ALL SHALES	Por. Son.				500	700 1000	0 500
BEST FIT		1500	1100	1500	500	1000	700

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		WHELDRAKE	WIG'HALL	47/3d-C1	47/4-1	47/5-1
CHALK	Por. Son.					
L.CRET. SHALES	Por. Son.				0	
JUR/CR. SHALES	Por. Son.				0 0	
KIMM. CLAY	Por. Son.				0	
OXFORD CLAY	Por. Son.		800			
LIAS SHALES	Por. Son.		1000	500 800	400 300	
JUR. SHALES	Por. Son.		600 900	0 0	0	
KEUP. SHALES	Por. Son.			0 400	0 500	3000 3500
U.BUNT. SHALES	Por. Son.			0 300		3000 4000
BUNT. SST	Por. Son.			900 0		4500 4000
L.BUNT. SHALES	Por. Son.			500		3900 4300
TRIAS. SHALES	Por. Son.			1000 300	0 500	4000
PERMIAN DOLOM.	Por. Son.	1000 1000				
CARB. SHALES	Por. Son.	1750 1800				
CARB. SST	Por. Son.	1750 1700				
ALL SHALES	Por. Son.		200 1000	0	0 0	4000
BEST FIT		1750	900	300	100	4000

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		47/8-1	47/8-A1	47/8-A4	47/9-1	47/13-2
CHALK	Por. Son.	0 1500	0 500	0		0 0
L. CRET. SHALES	Por. Son.	300 900	0 0	0 0	1900 1500	0
JUR/CR SHALES	Por. Son.	250 500		750 500	700 1500	
KIMM. CLAY	Por. Son.				1200 1000	0
OXFORD CLAY	Por. Son.				1200 1000	0
LIAS SHALES	Por. Son.	1000	250	600	500 1200	0 300
JUR. SHALES	Por. Son.	1900 1000	0	0 400	800 1000	0 0
KEUP. SHALES	Por. Son.	1800 1200	0 800	500	2000 1900	550 500
U. BUNT. SHALES	Por. Son.	1800 1200	0 800		2000 1900	550 500
BUNT. SST	Por. Son.	0 800	1500 500	0 0	2500 2000	600 250
L. BUNT. SHALES	Por. Son.	2700 1000	1500 800	0 700	2200 2000	100 700
TRIAS. SHALES	Por. Son.	1000 1000	1400 800	0 0	1250 2000	700 0
ALL SHALES	Por. Son.	0 800	200 200	500	2100 2000	0 0
BEST FIT		1200	500	400	1900	0

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

		47/14A-3	47/15-2	47/18-1	47/25-1	47/29A-1
CHALK	Por. Son.	0 0	0 400	500 1000		
L. CRET. SHALES	Por. Son.		0	650 0		0
JUR/CR. SHALES	Por. Son.			1000 700		
KIMM. CLAY	Por. Son.	0 0	0 0	0 500		1000 0
OXFORD CLAY	Por. Son.	0 0		0 500		0
LIAS SHALES	Por. Son.	0 0	0 0	300 700	0 300	200 0
JUR. SHALES	Por. Son.	0 0	0 0	0 500	0 0	
KEUP. SHALES	Por. Son.	1100 500	0	500 1100	700 500	500
U. BUNT. SHALES	Por. Son.		0	500 1000	700 500	
BUNT. SST	Por. Son.	800	0 0	1500 1400	0 1000	0 0
L. BUNT. SHALES	Por. Son.	1500 600	0 500	0 800	1500 900	500
TRIAS. SHALES	Por. Son.	1200 400	0 0	1100 800	1400 800	0
ALL SHALES	Por. Son.	0 0	0 0	0 800	0 0	0 0
BEST FIT		0	0	700	400	0

REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

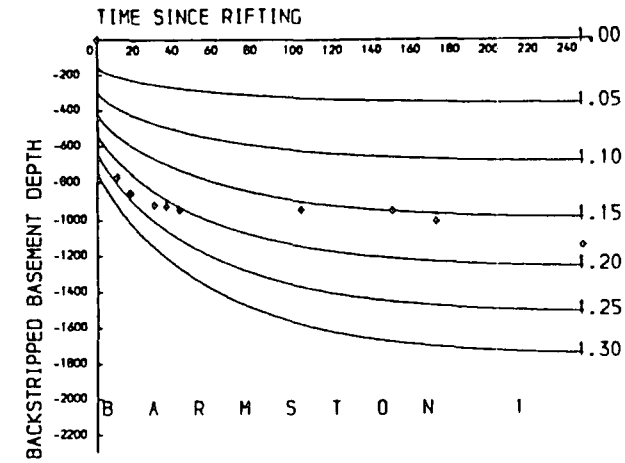
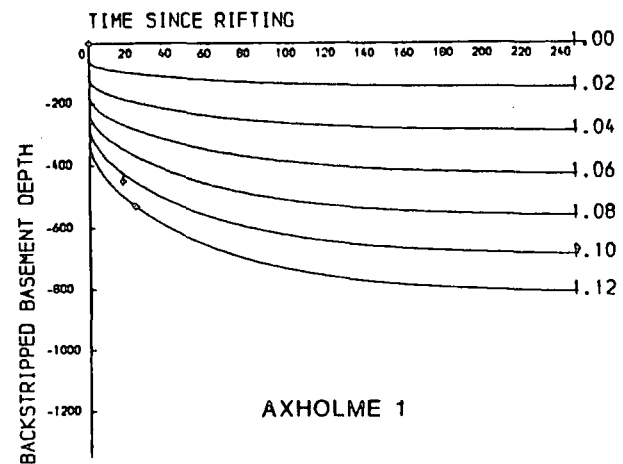
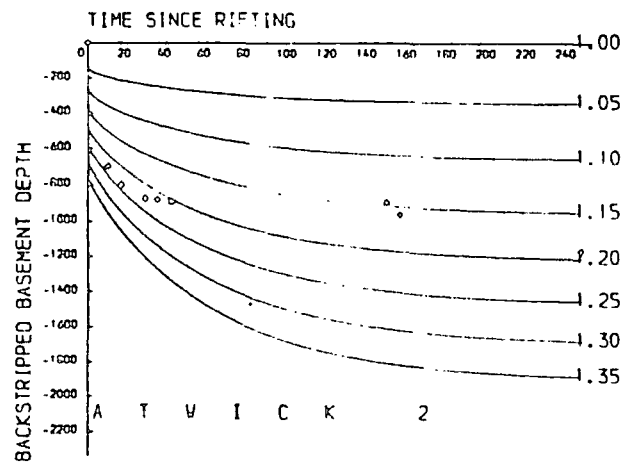
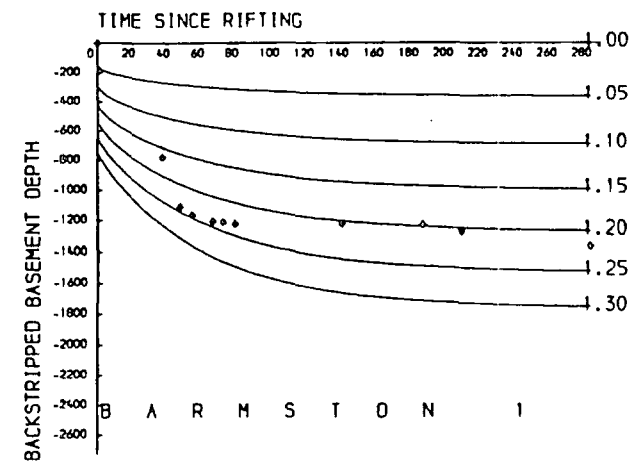
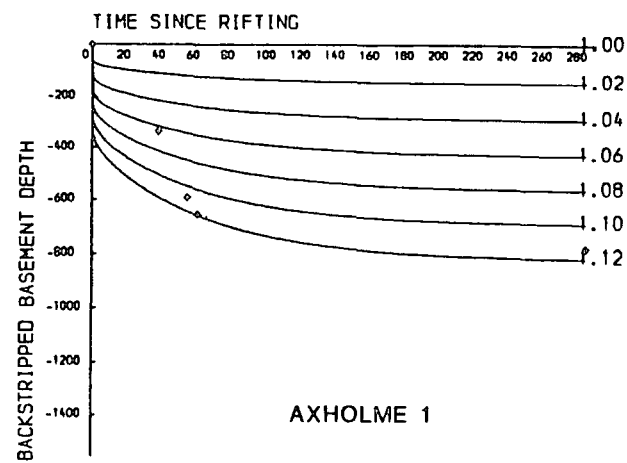
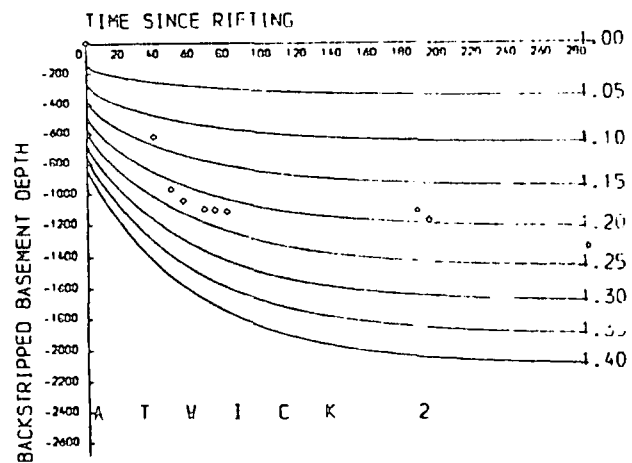
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CHALK	Por. Son.				0 1000	1000 1000	500 1000
L.CRET. SHALES	Por. Son.				0 0	800 0	
JUR. SHALES	Por. Son.				500 0	1600 1500	
KEUP. SHALES	Por. Son.	0 0	2250 1000	1500 2000	1200 500	1400	800
U.BUNT. SHALES	Por. Son.	0 0	2250 1000	1500 2000	1200 500	1500	900 500
BUNT. SST	Por. Son.	0	1500 1000	2800 2000	0	2000 1500	800
L.BUNT. SHALES	Por. Son.	400 500	3600 2000	1750 1800	1400 800	2000 1200	1000
TRIAS. SHALES	Por. Son.	0	3500 1900	0 1500	1200 700	2000 1500	1200 800
ALL SHALES	Por. Son.	0 0	3500 1900	0 1500	0 400	1500 1200	1200 900
BEST FIT		0	2500	2000	1000	1200	900

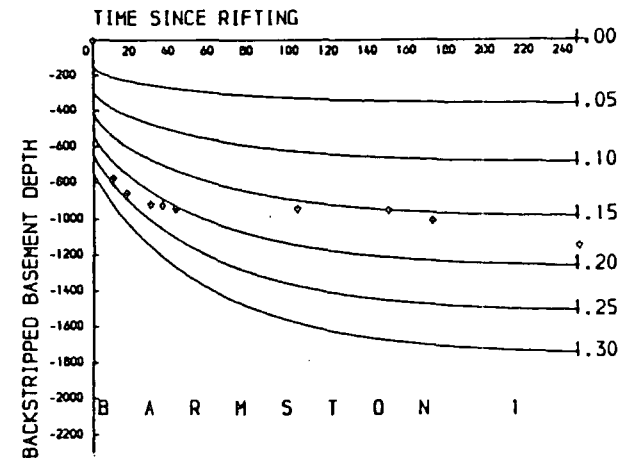
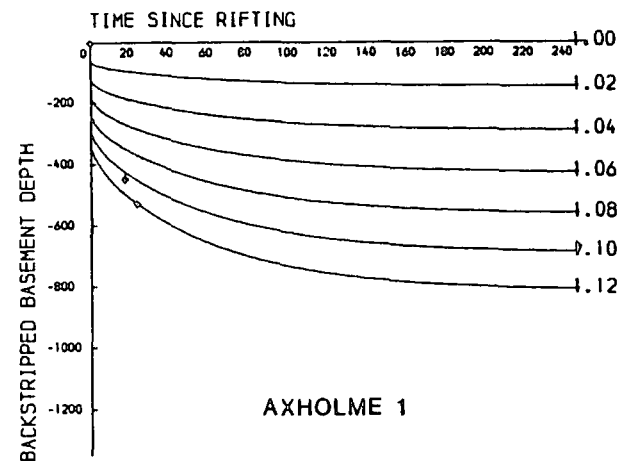
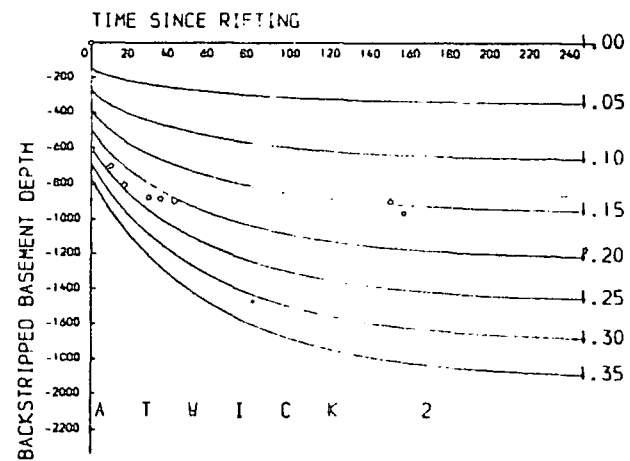
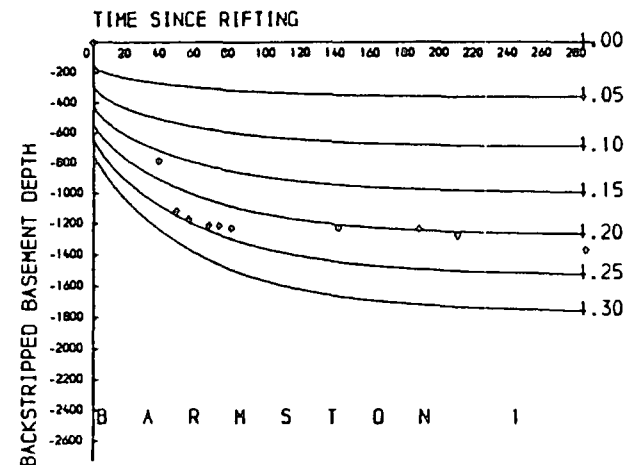
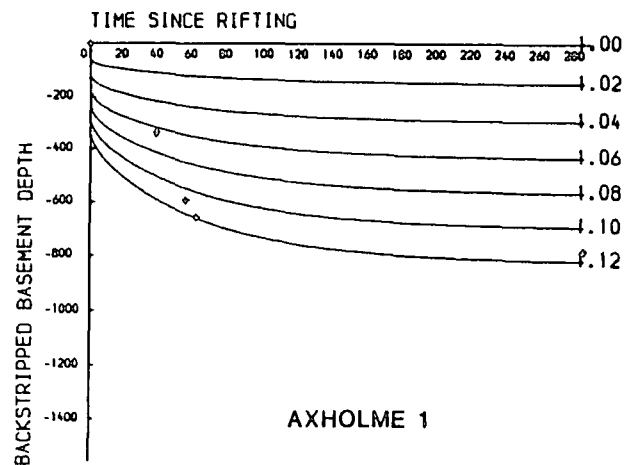
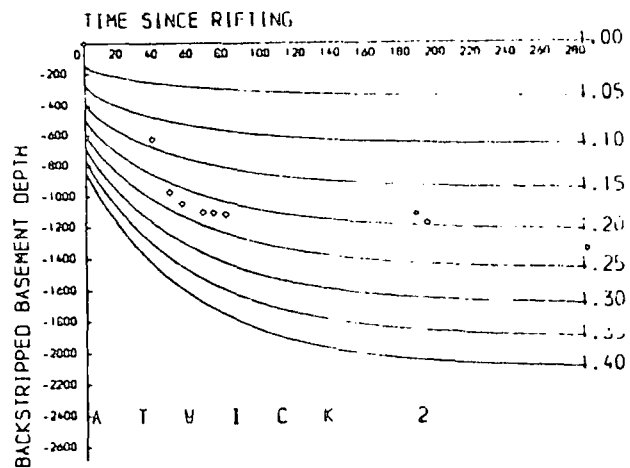
REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

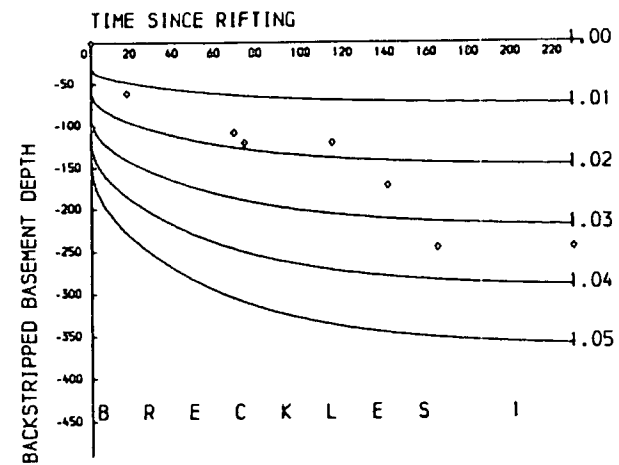
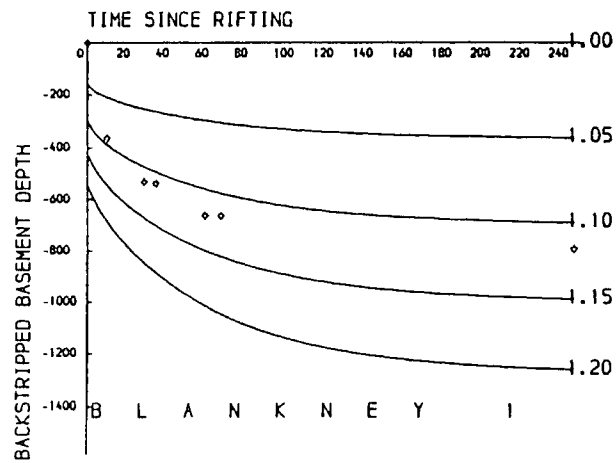
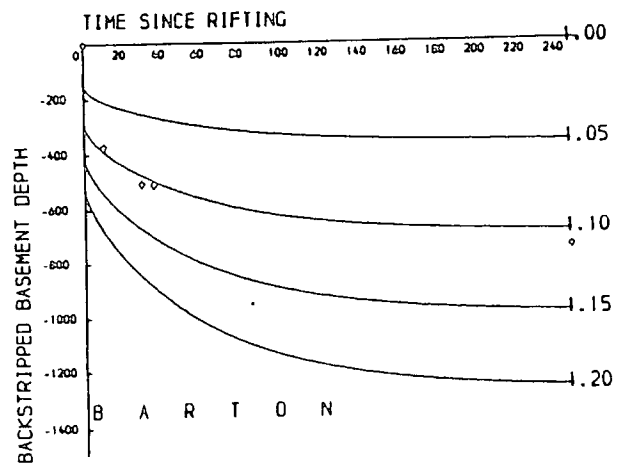
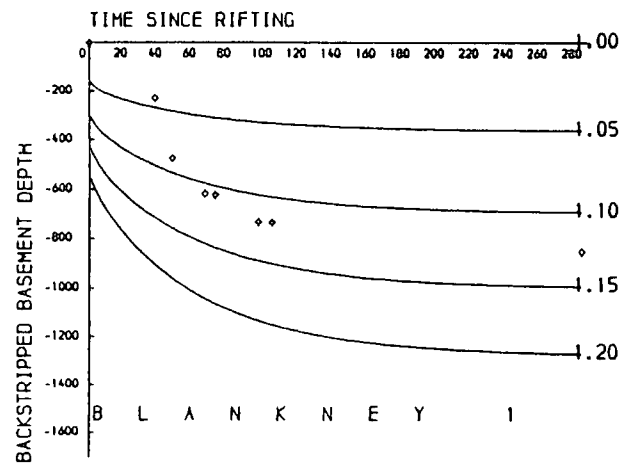
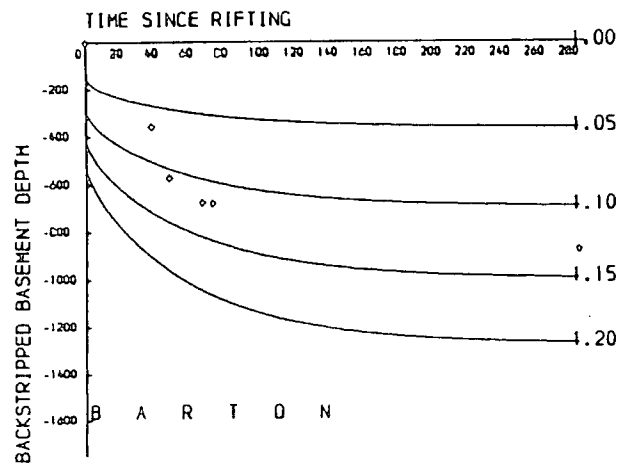
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CHALK	Por. Son.				0 1000	1000 1000	500 1000
L.CRET. SHALE	Por. Son.				0 0	800 0	
JUR. SHALE	Por. Son.				500 0	1600 1500	
KEUP. SHALE	Por. Son.	0 0	2250 1000	1500 2000	1200 500	1400	800
U.BUNT. SHALE	Por. Son.	0 0	2250 1000	1500 2000	1200 500	1500	900 500
BUNT. SST	Por. Son.	0	1500 1000	2800 2000	0	2000 1500	800
L.BUNT. SHALE	Por. Son.	400 500	3600 2000	1750 1800	1400 800	2000 1200	1000
TRIAS. SHALE	Por. Son.	0	3500 1900	0 1500	1200 700	2000 1500	1200 800
ALL SHALE	Por. Son.	0 0	3500 1900	0 1500	0 400	1500 1200	1200 900
BEST FIT		0	2500	2000	1000	1200	900

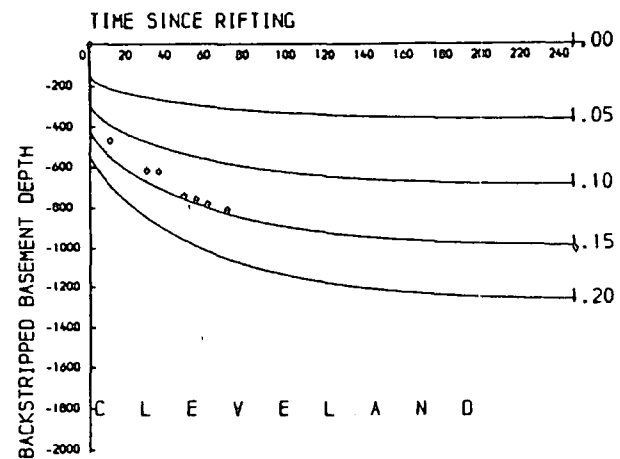
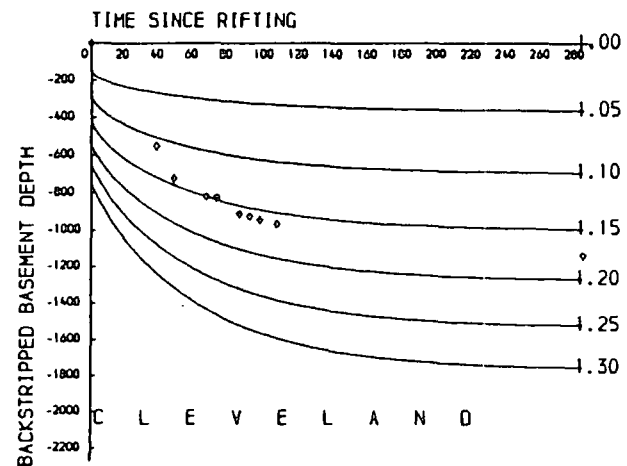
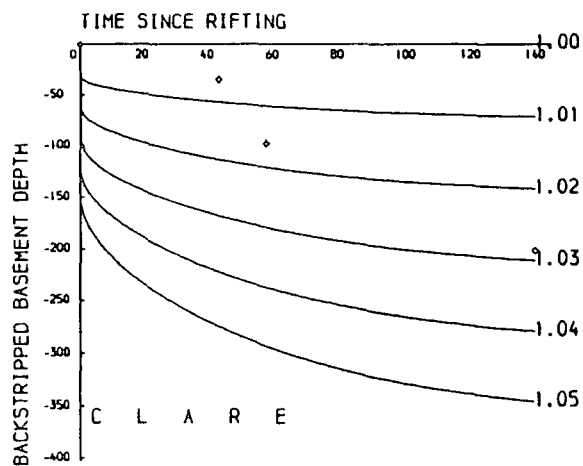
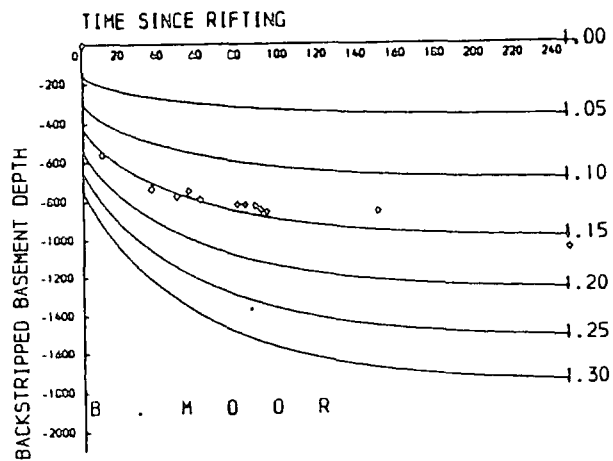
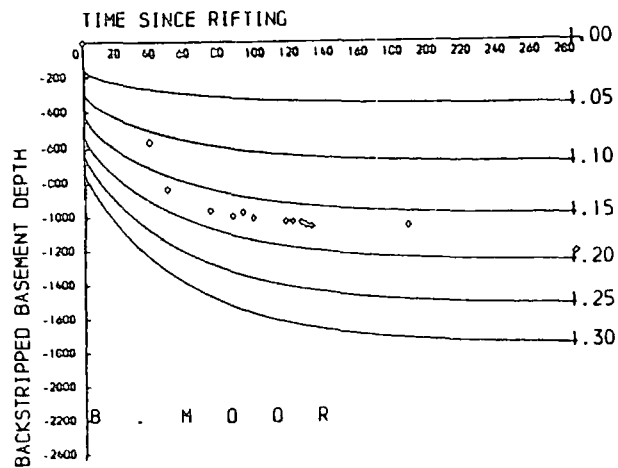
REGIONAL UPLIFT VALUES COMPUTED FROM ANALYSIS OF POROSITY
AND INTERVAL TRANSIT TIME

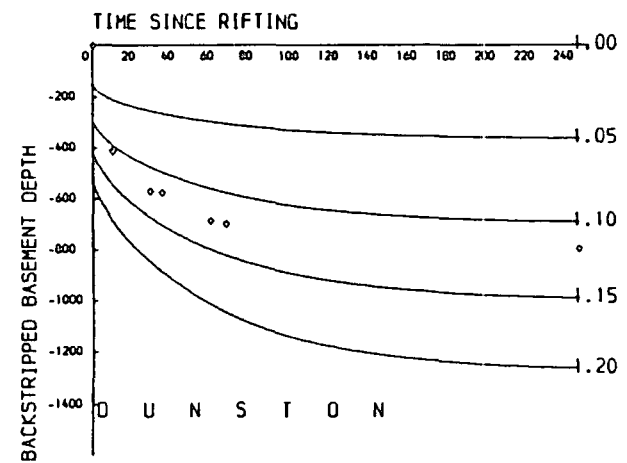
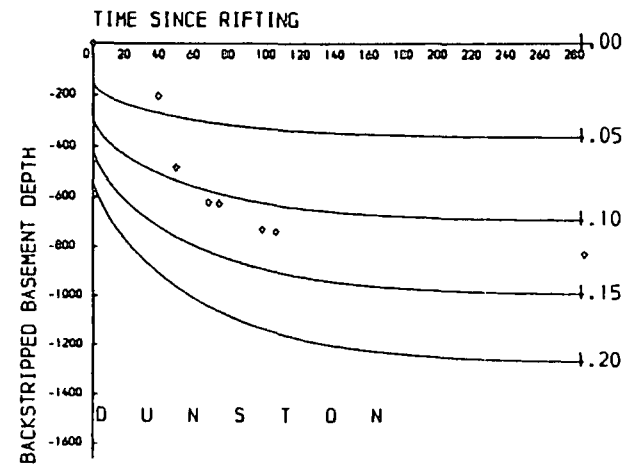
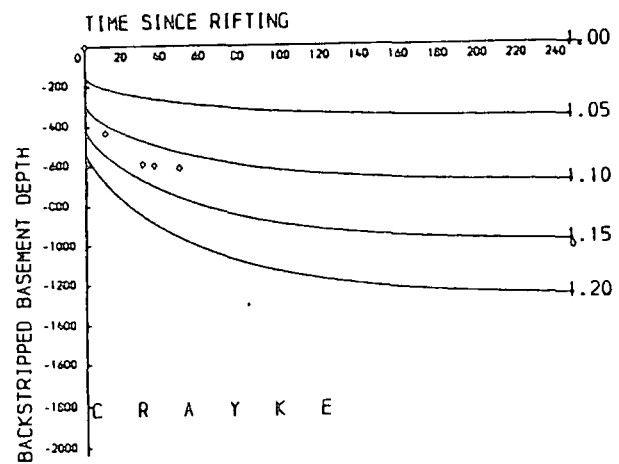
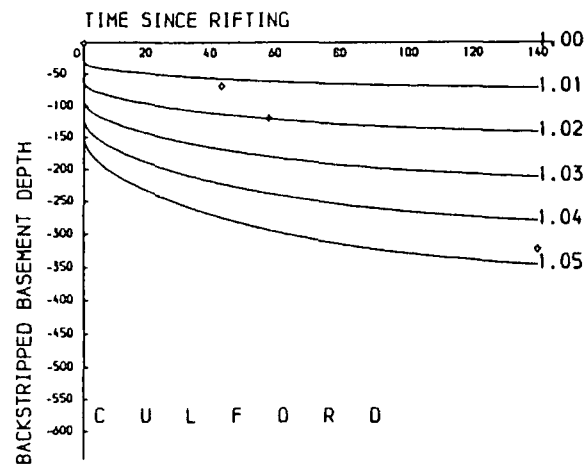
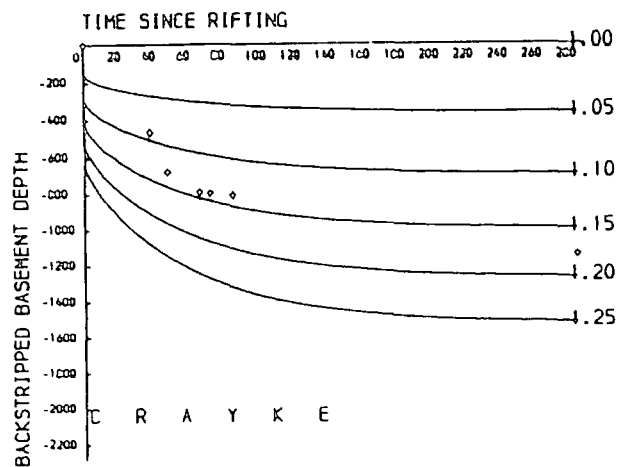
APPENDIX C4

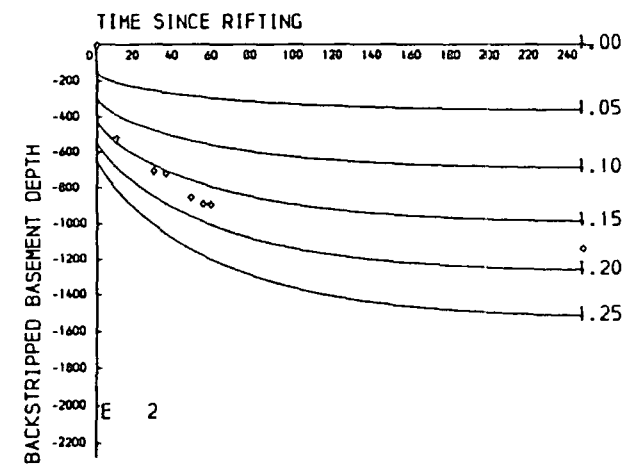
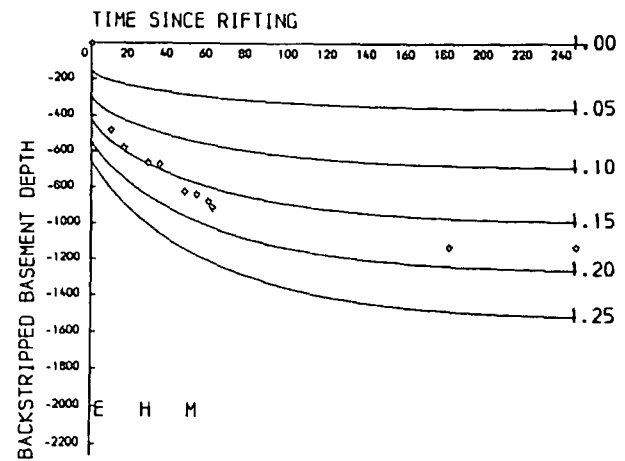
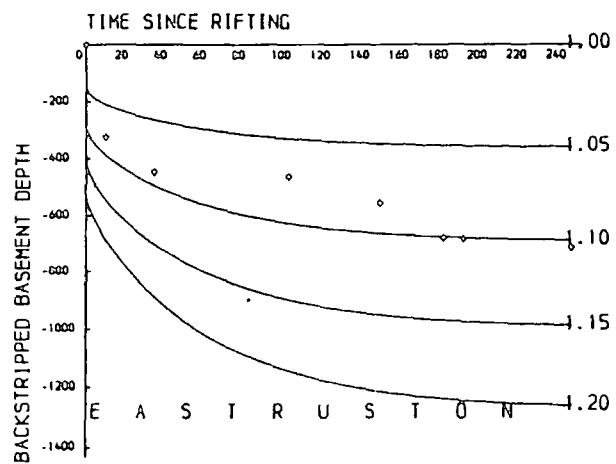
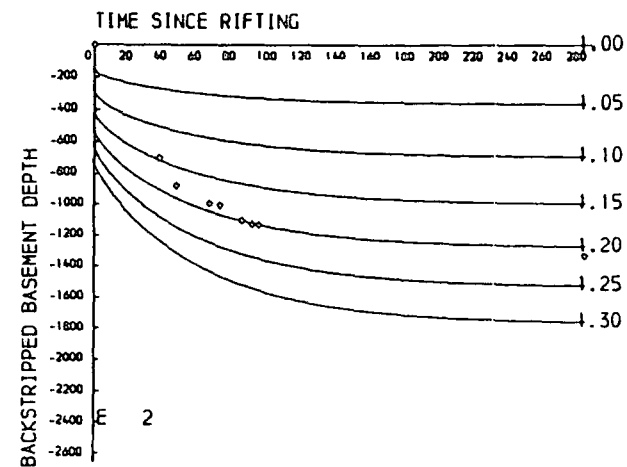
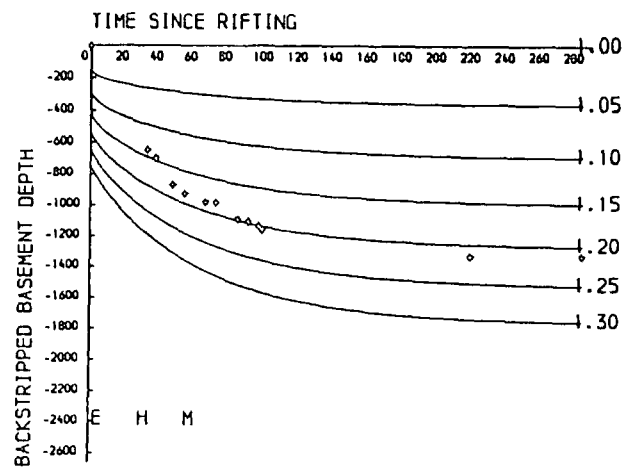
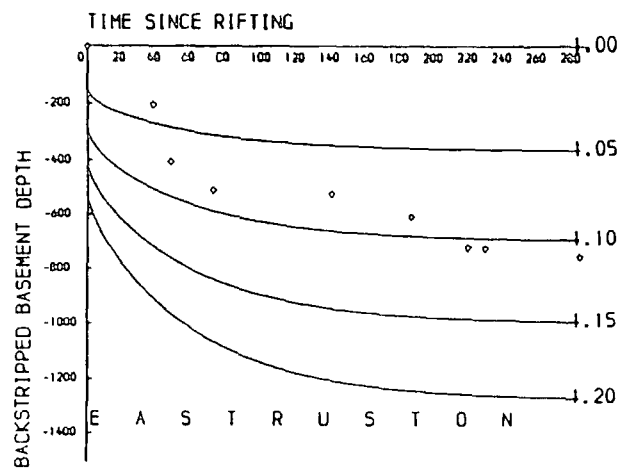


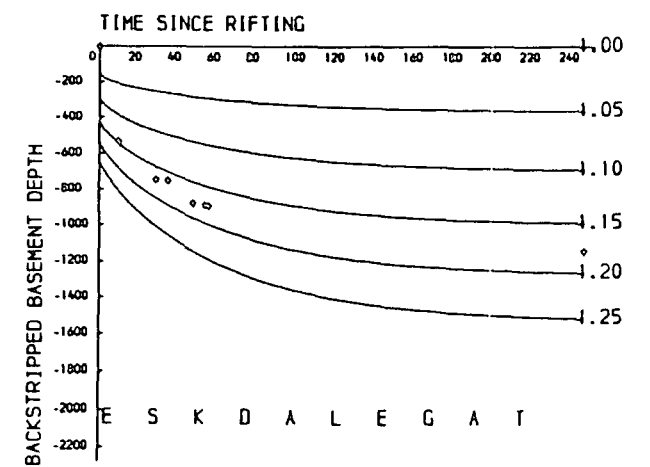
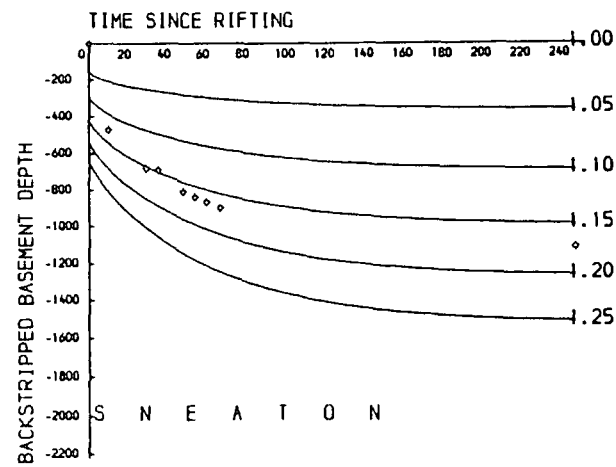
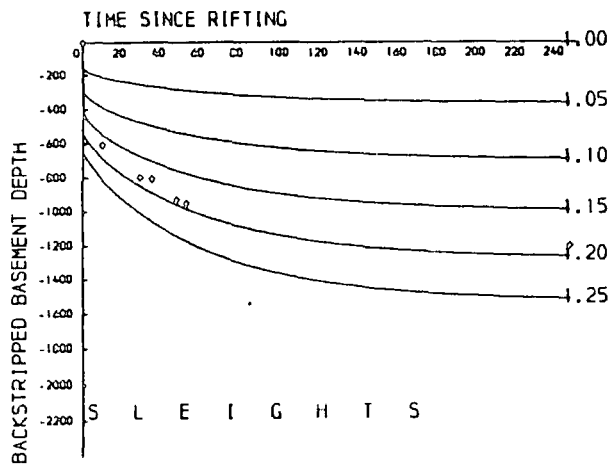
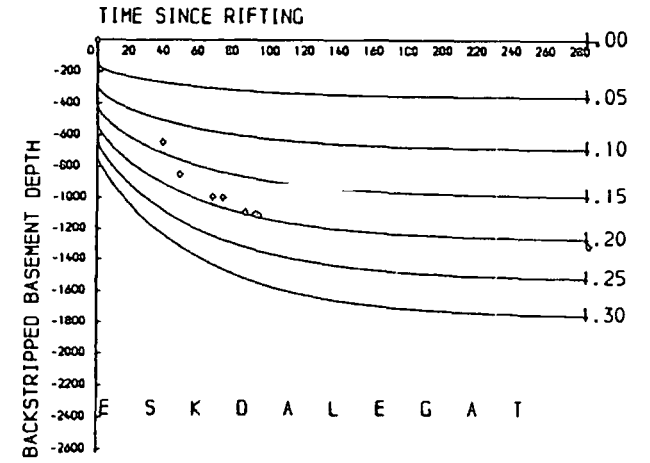
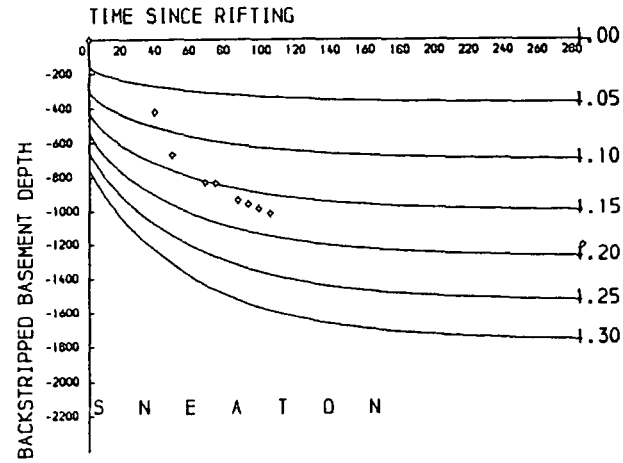
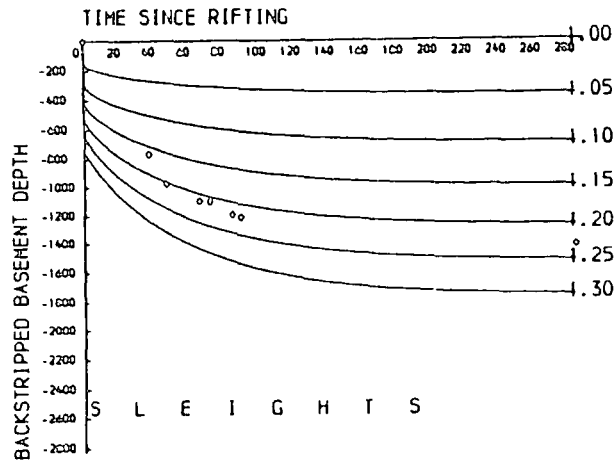


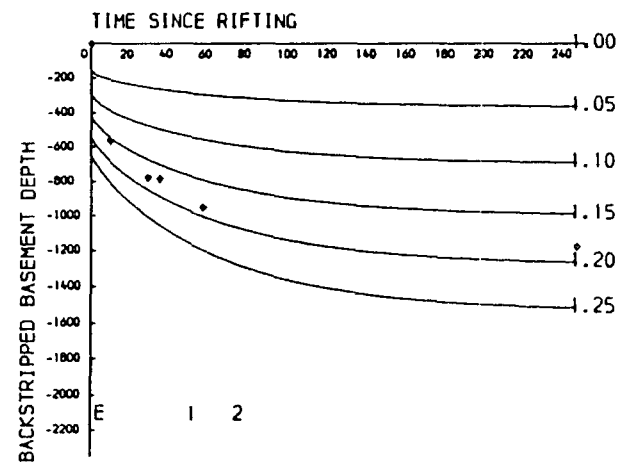
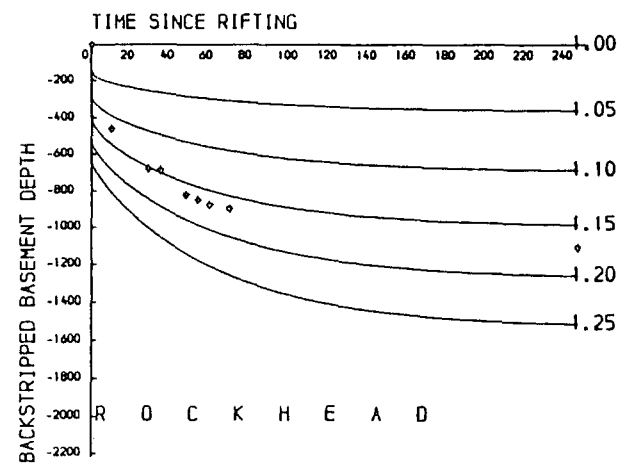
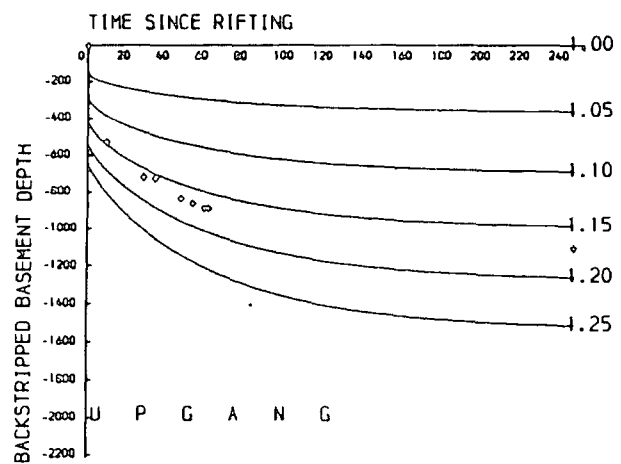
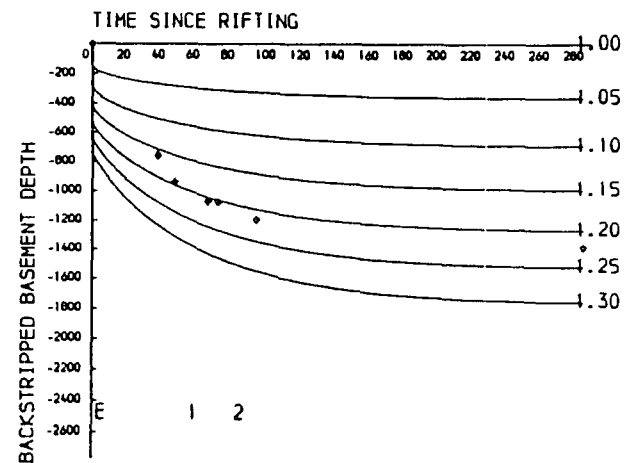
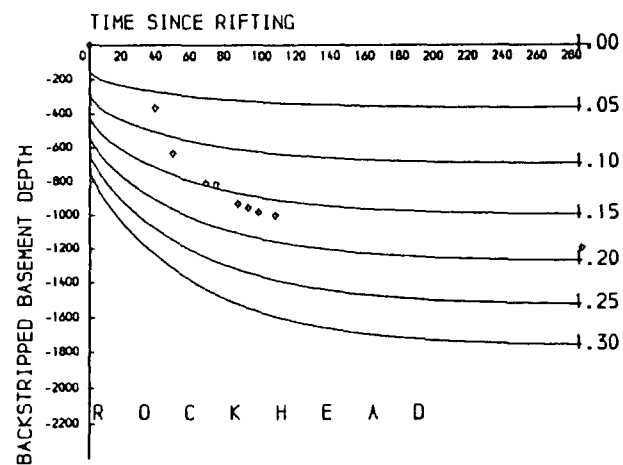
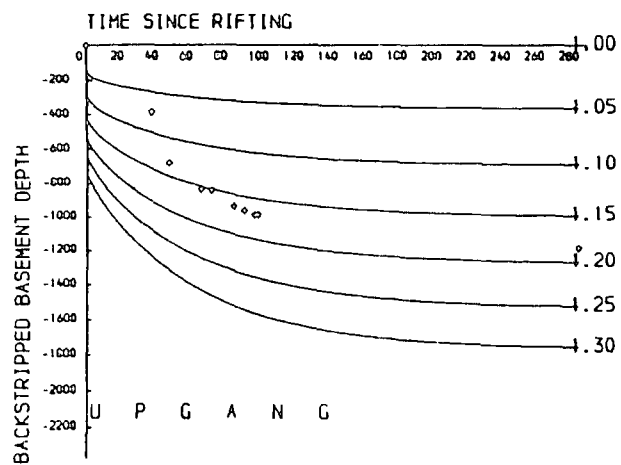


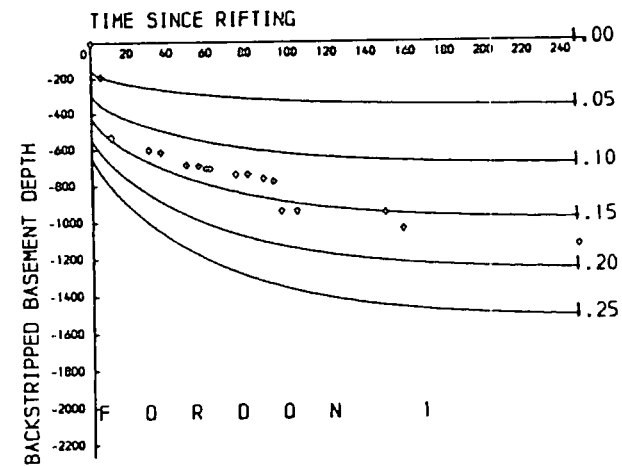
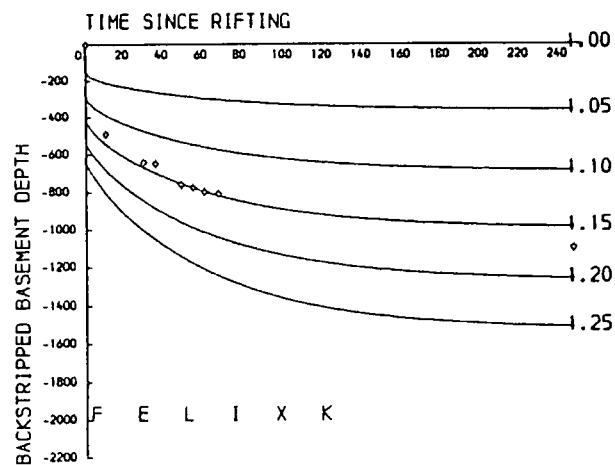
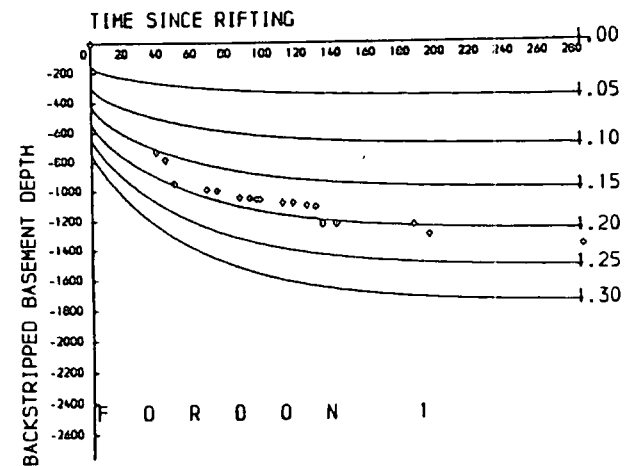
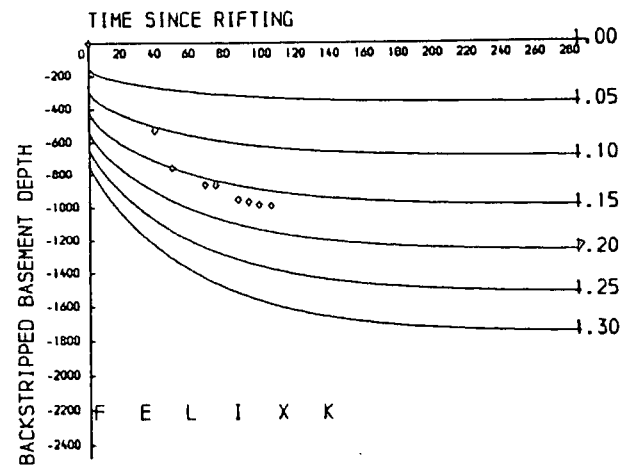
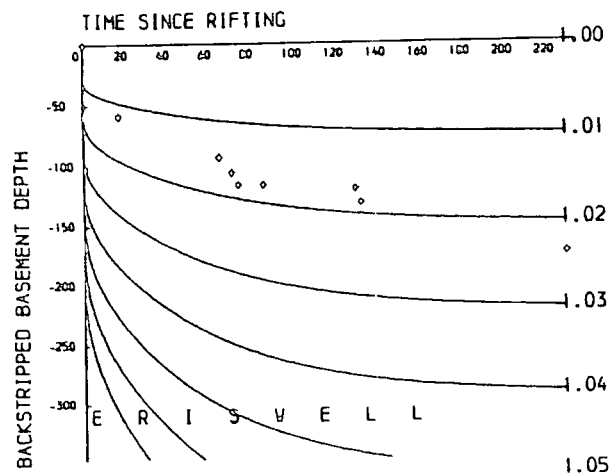


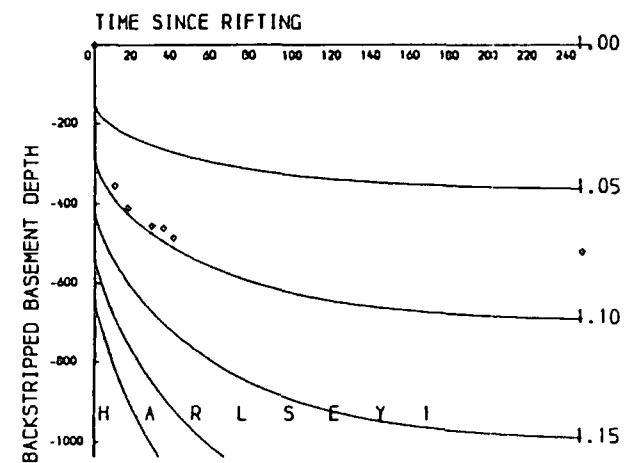
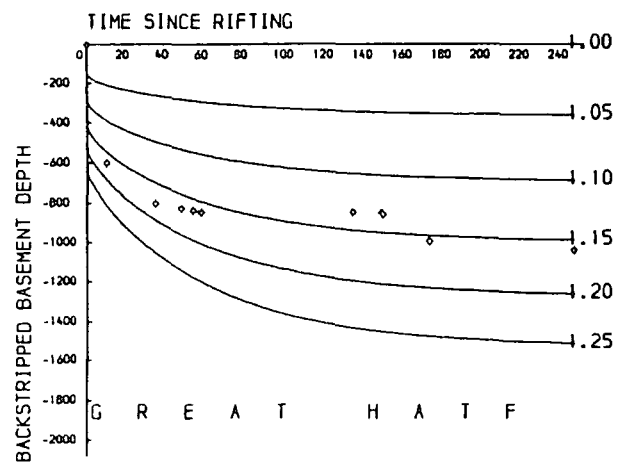
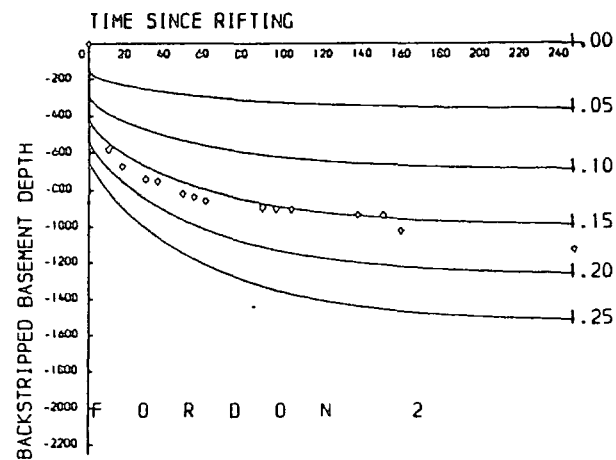
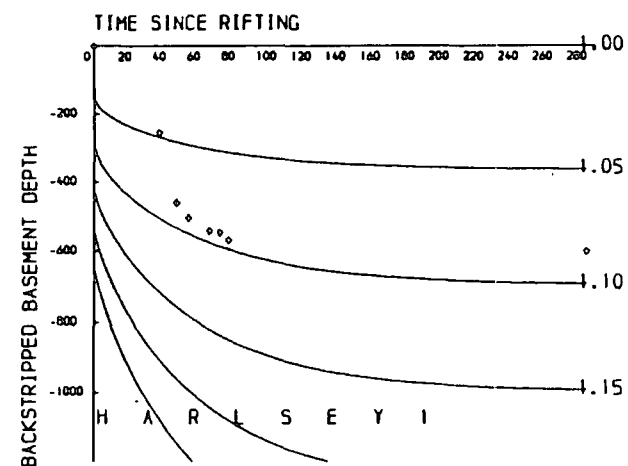
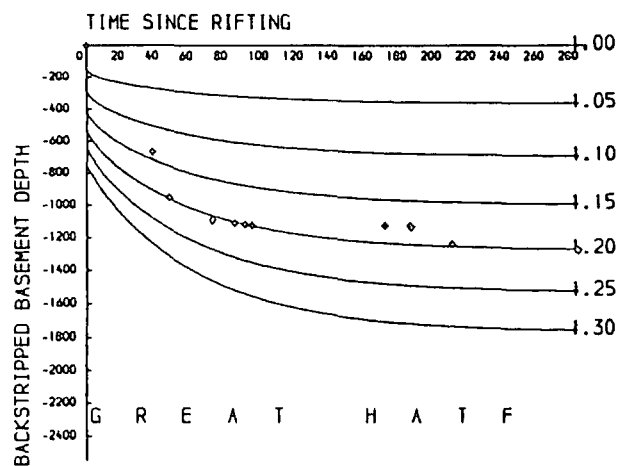
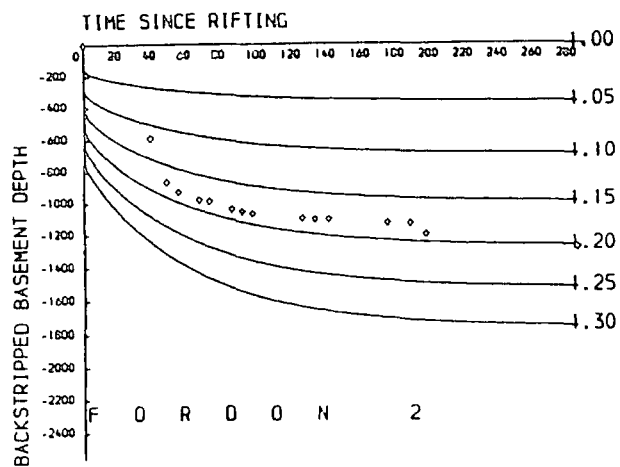


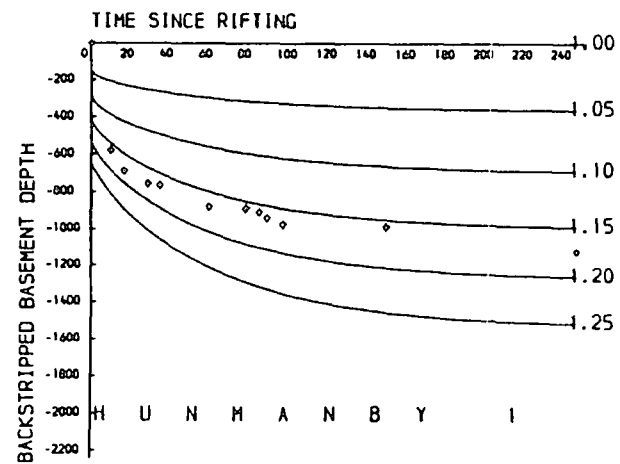
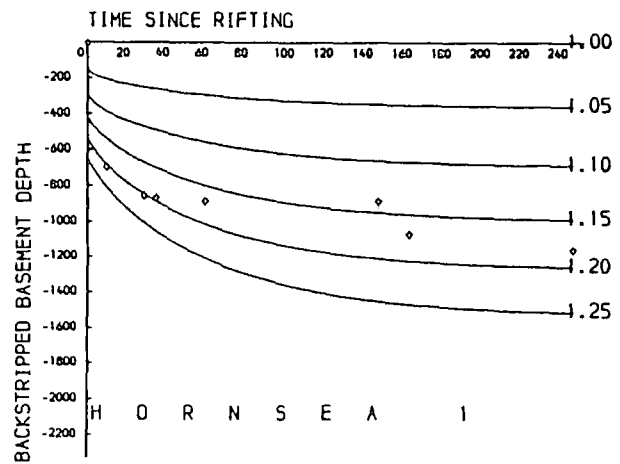
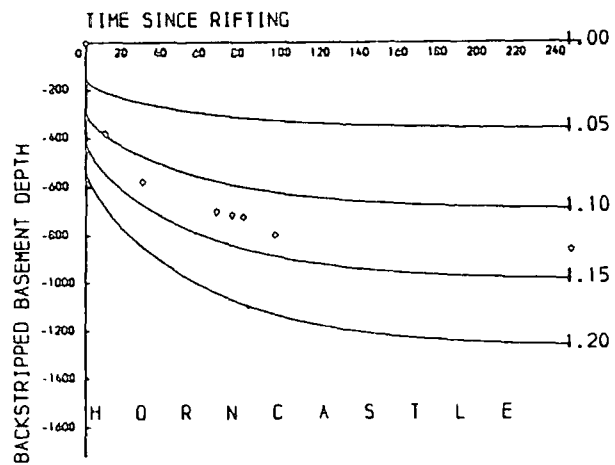
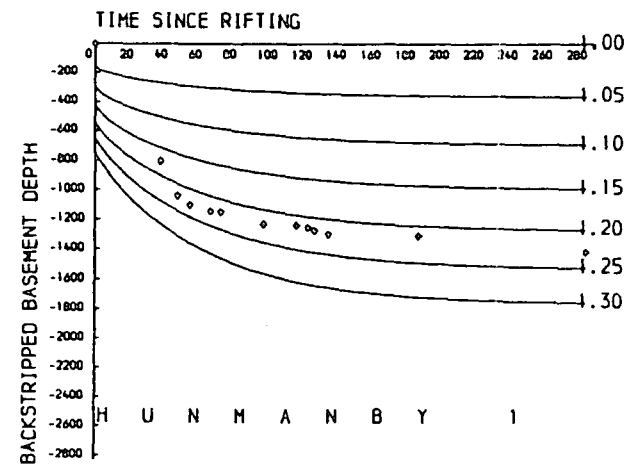
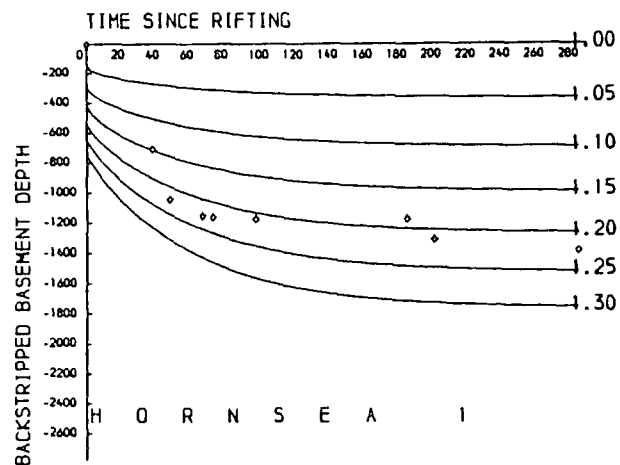
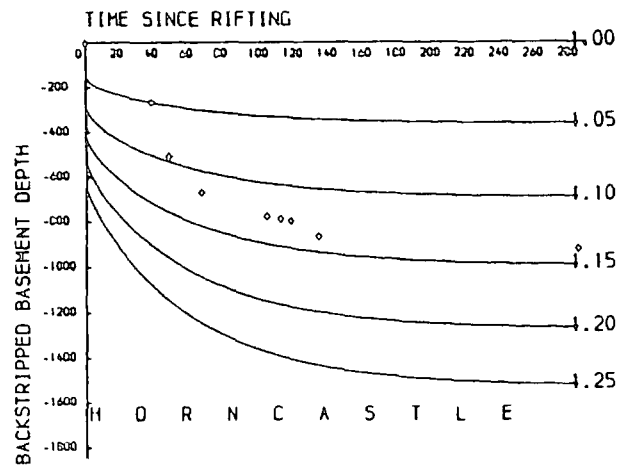


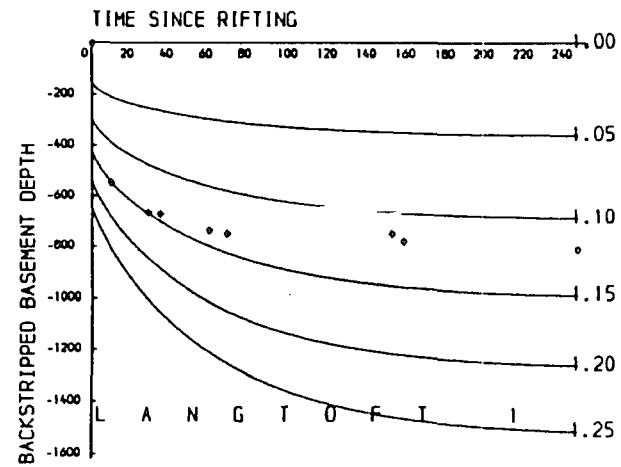
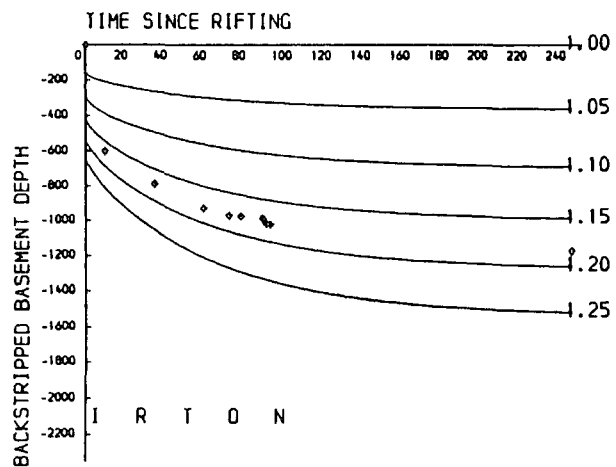
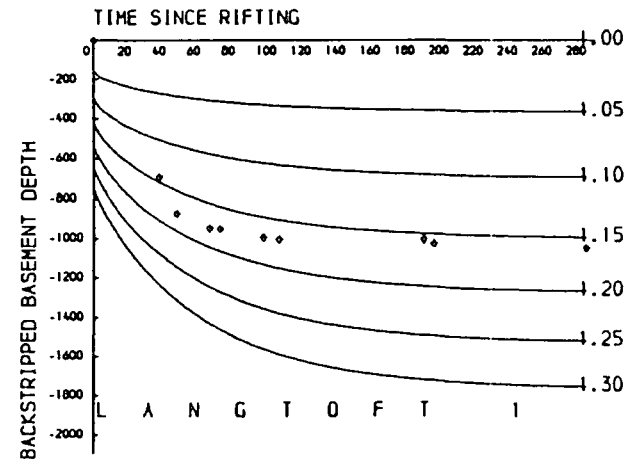
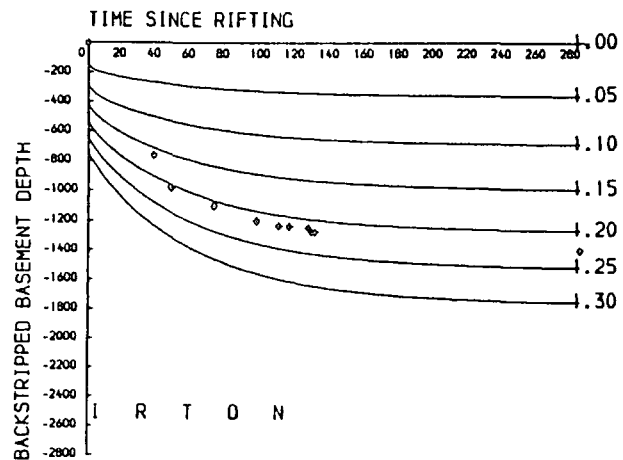
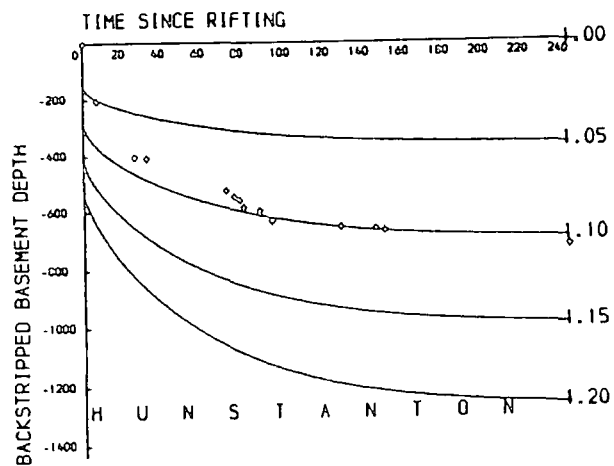


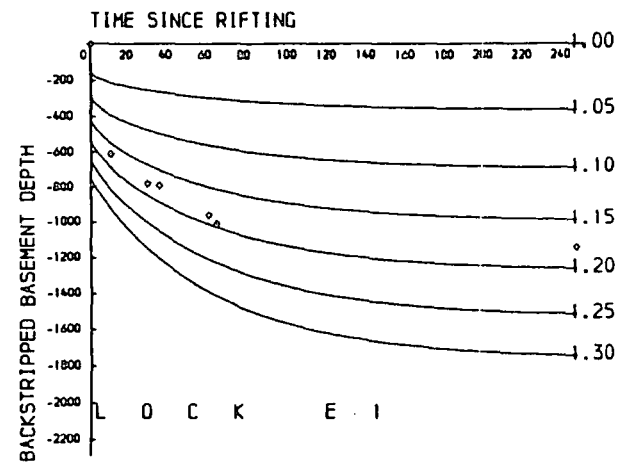
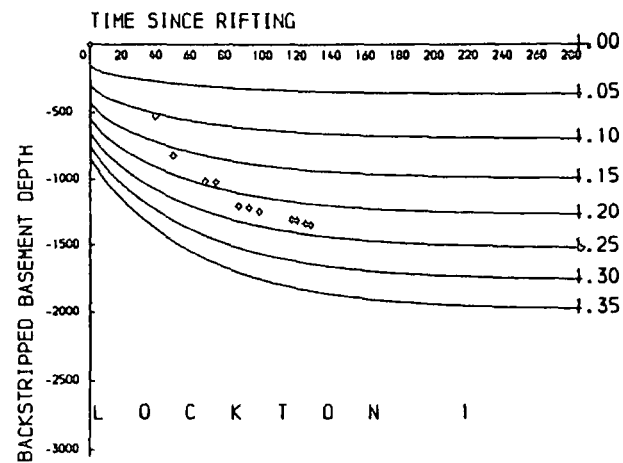
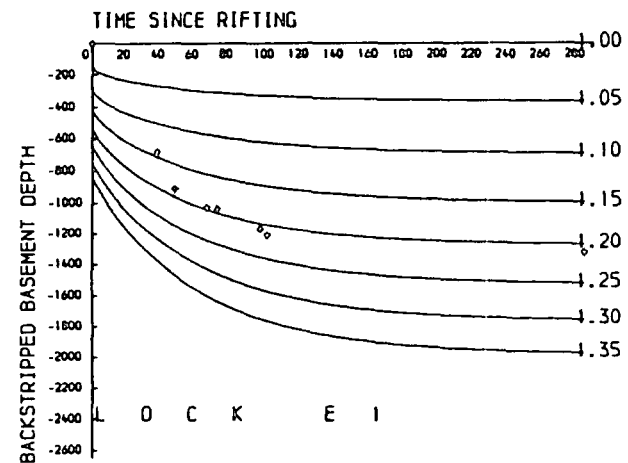
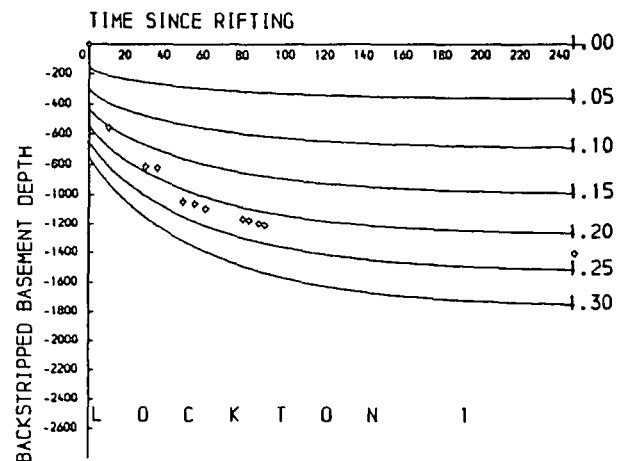
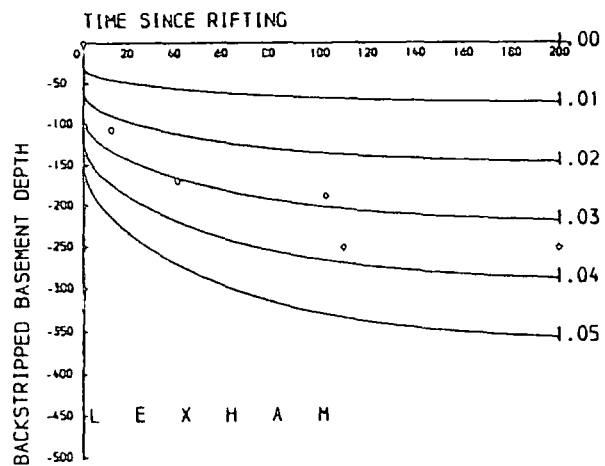


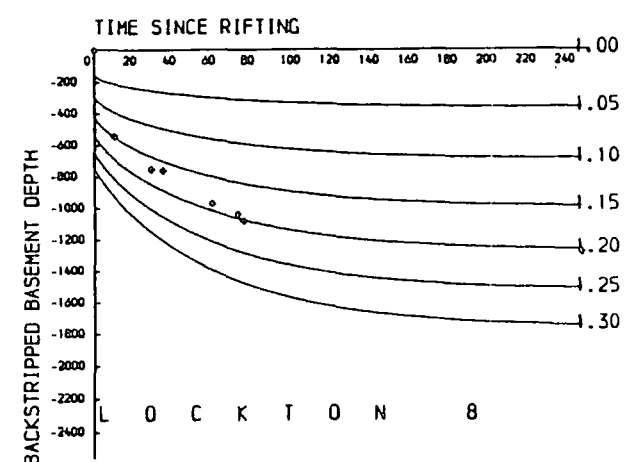
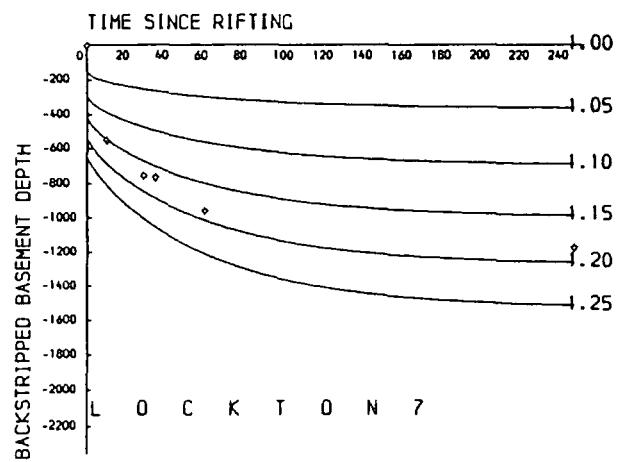
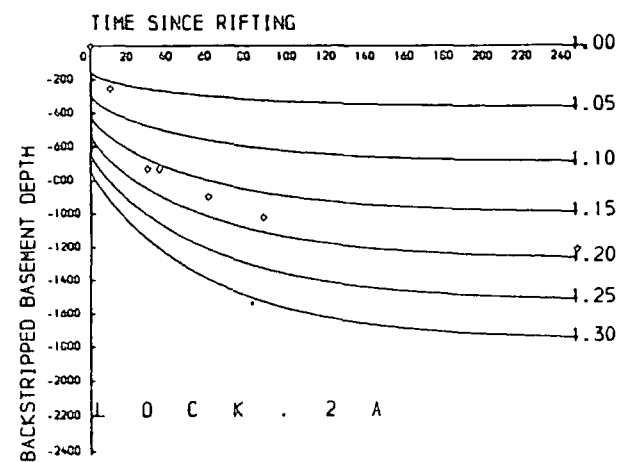
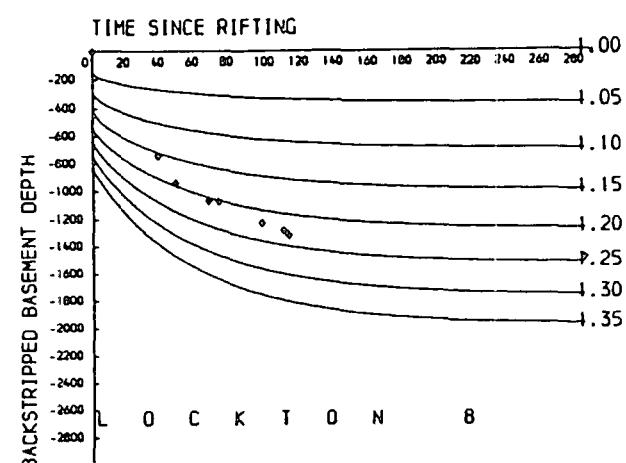
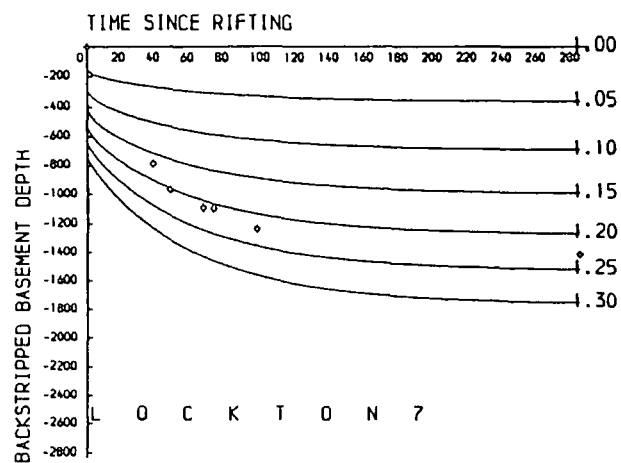
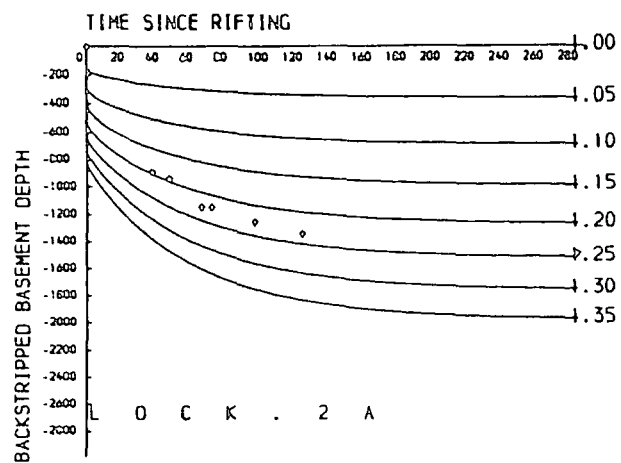


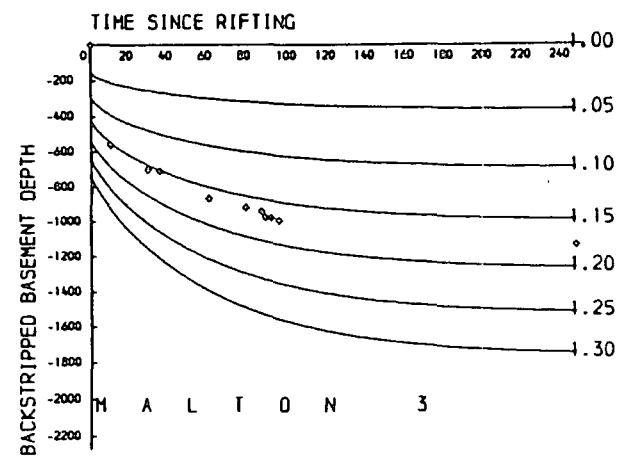
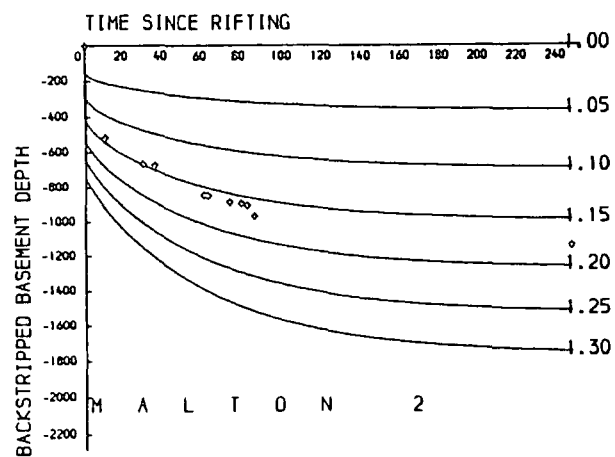
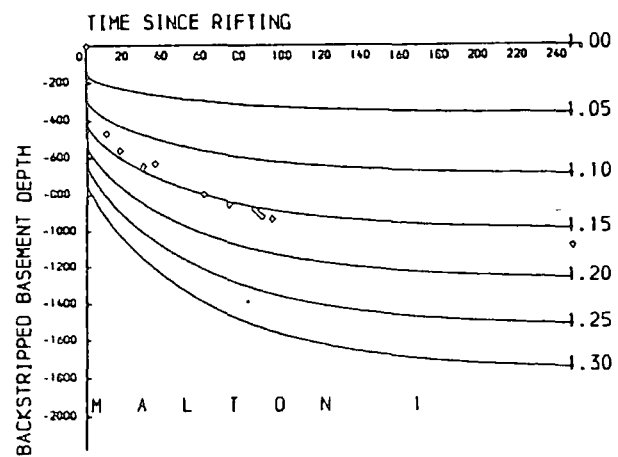
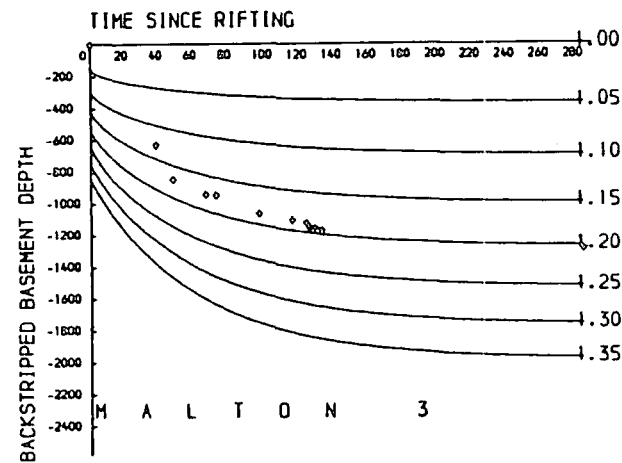
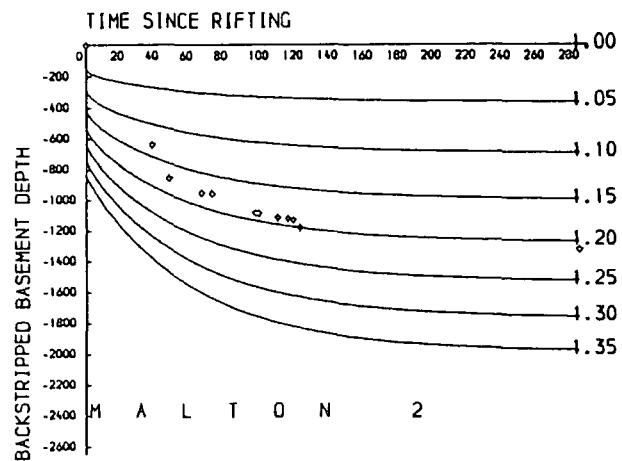
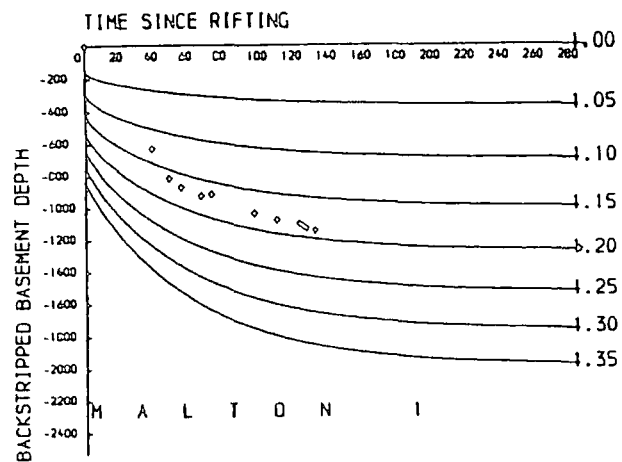


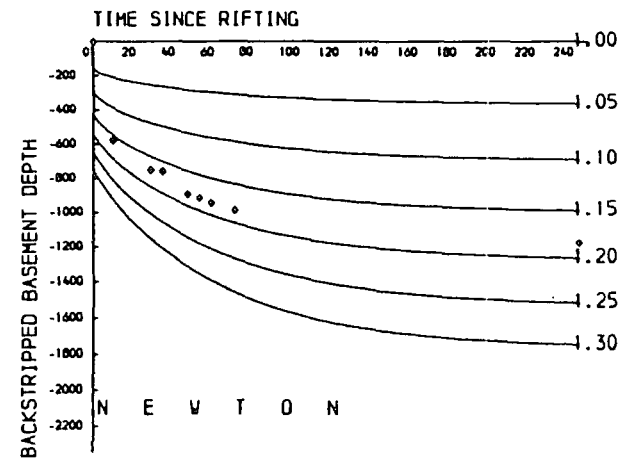
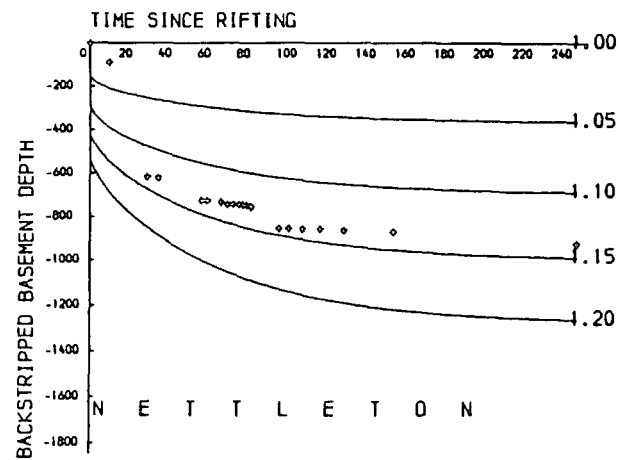
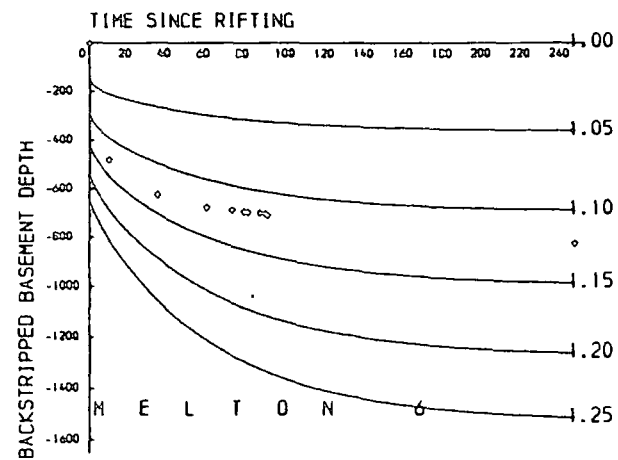
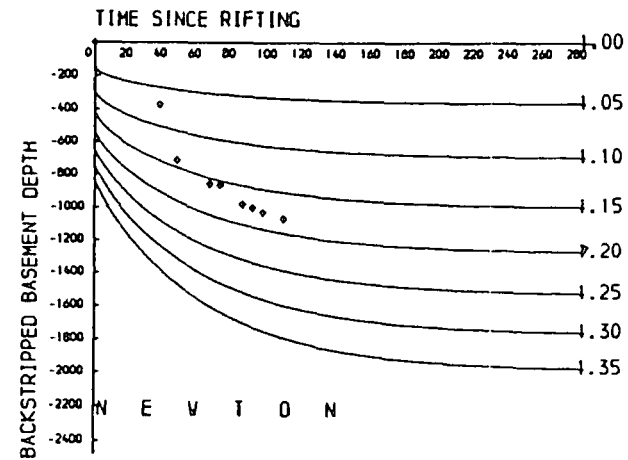
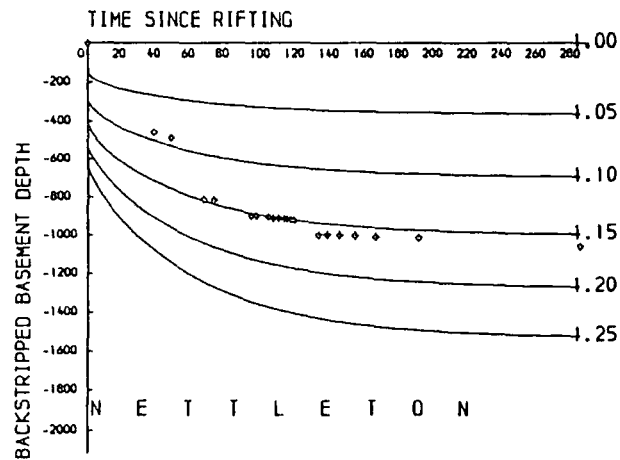
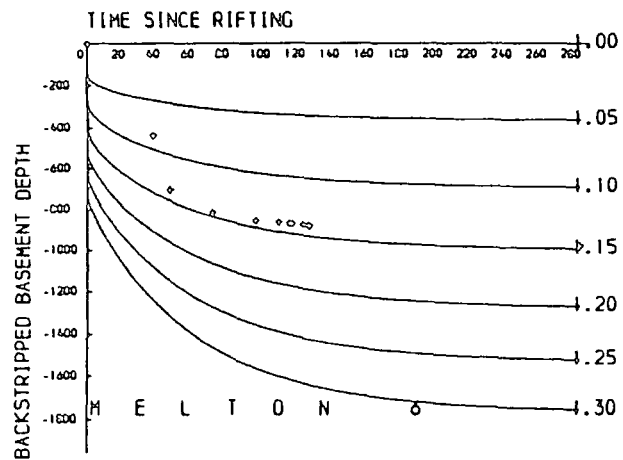


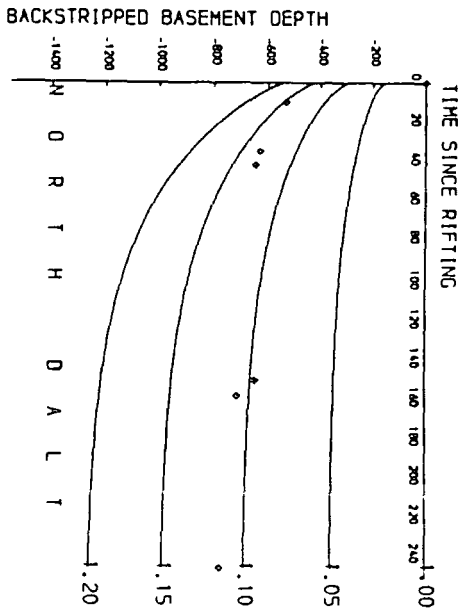
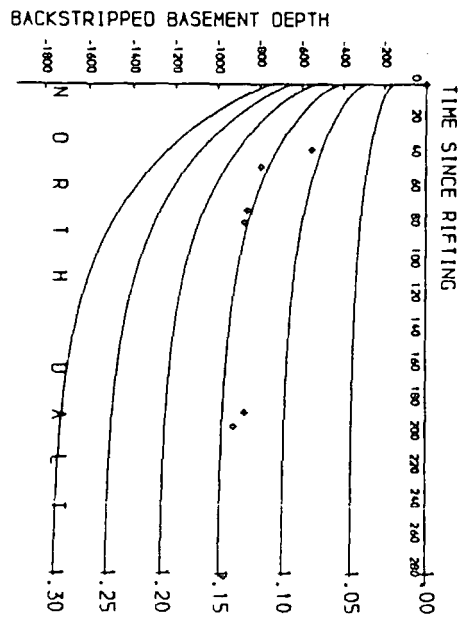
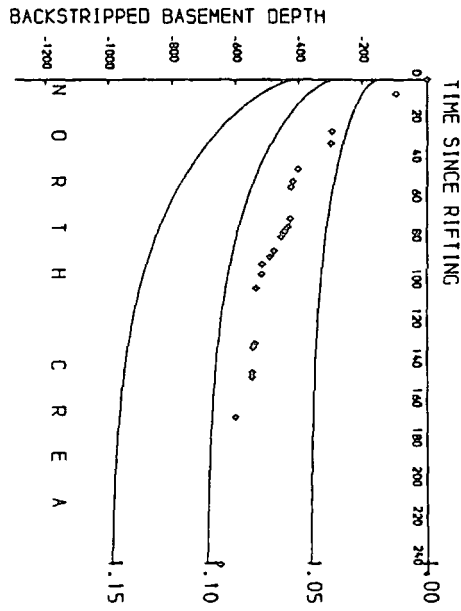
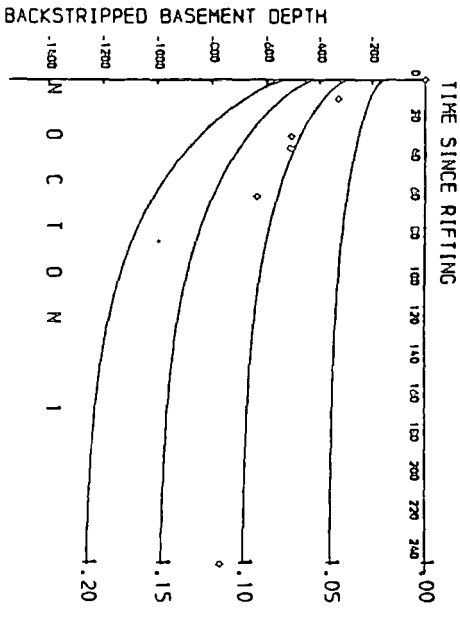
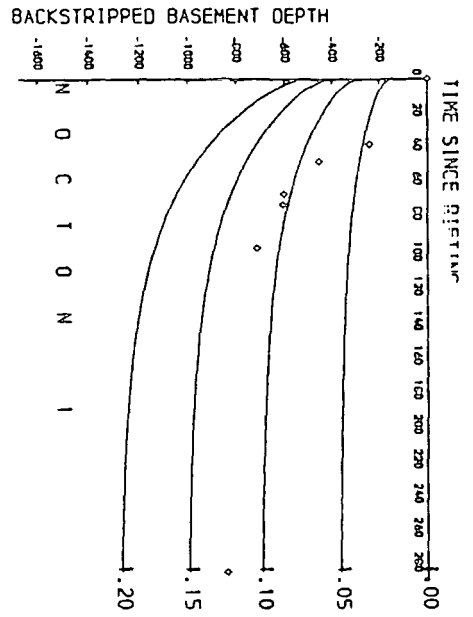


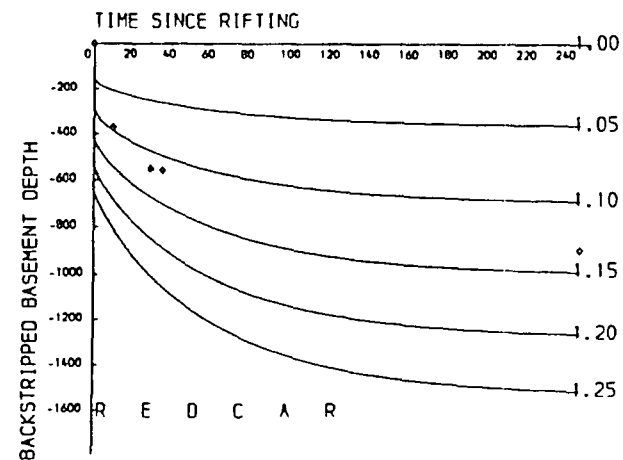
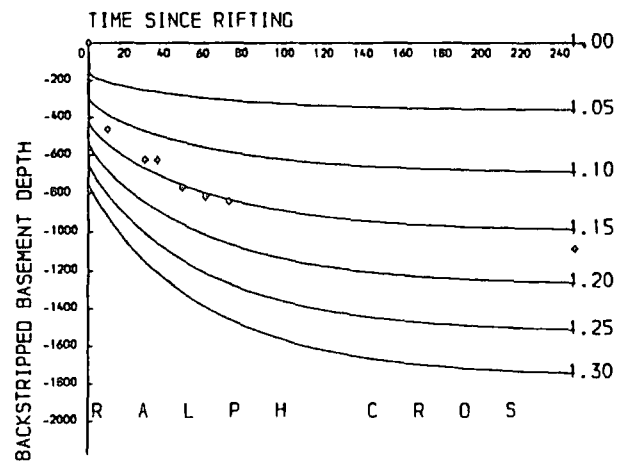
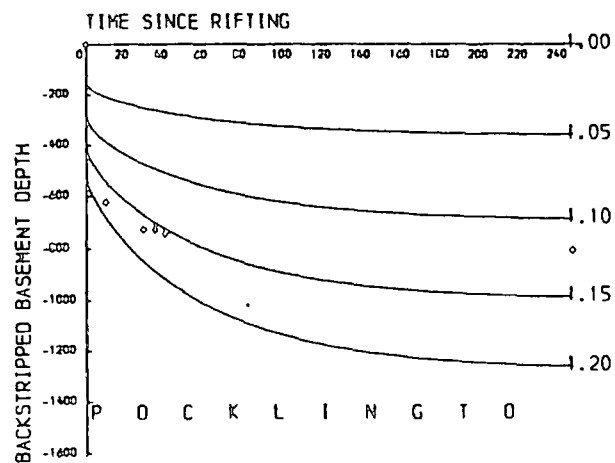
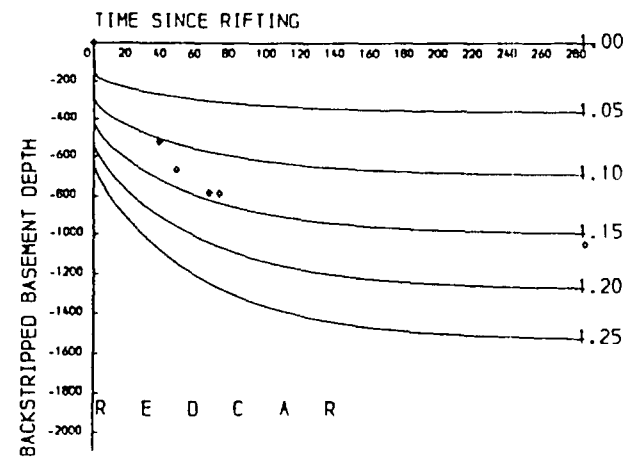
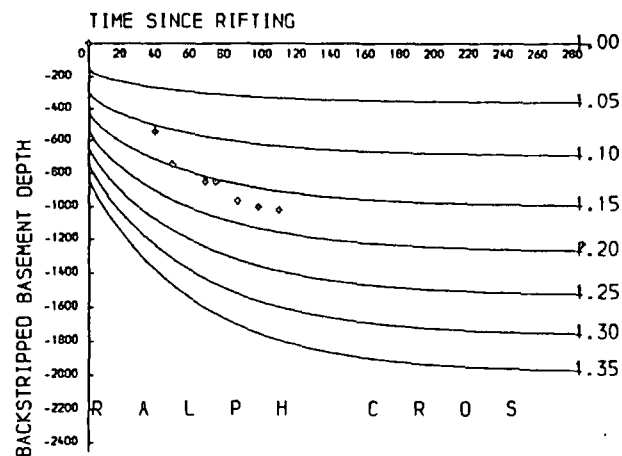
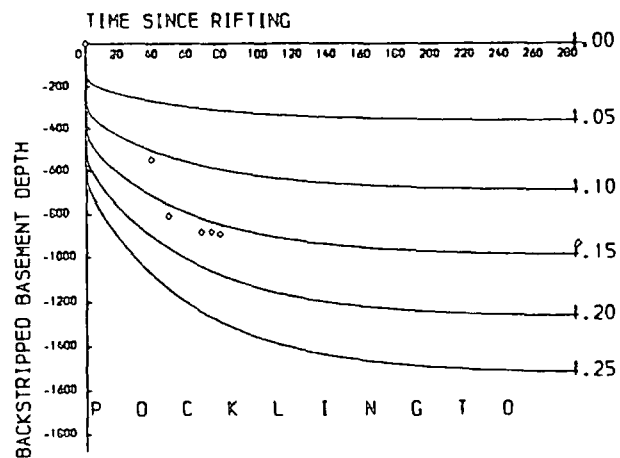


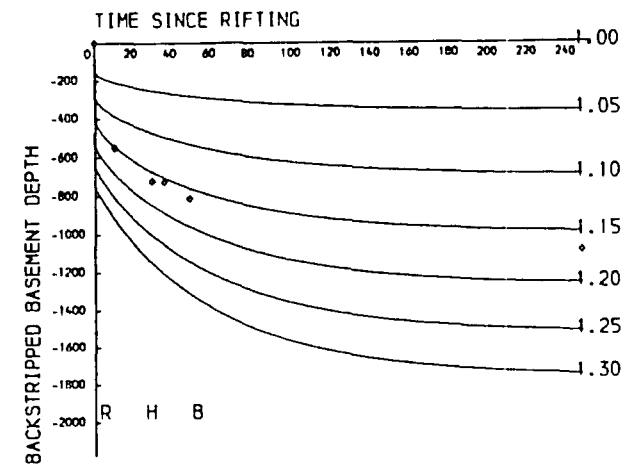
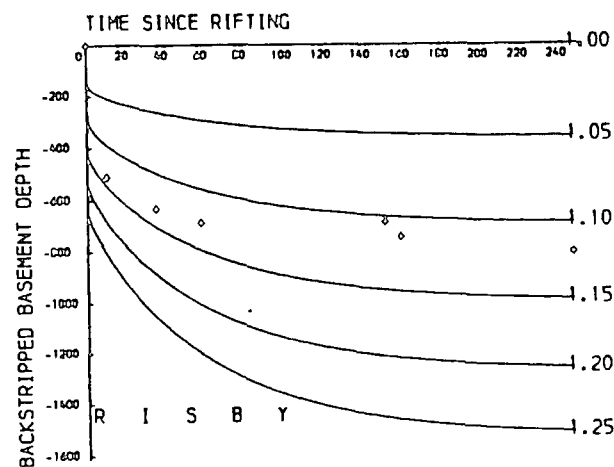
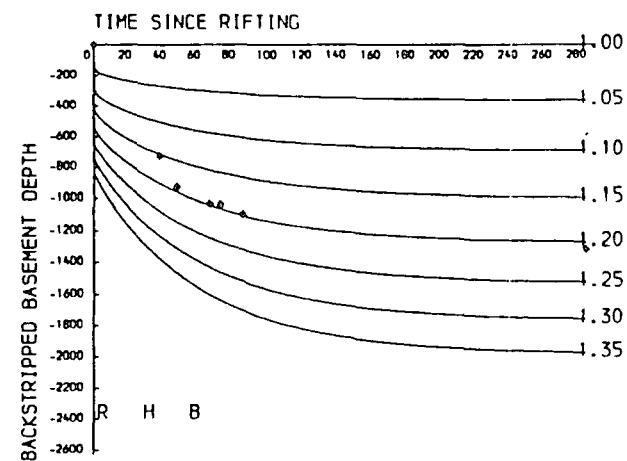
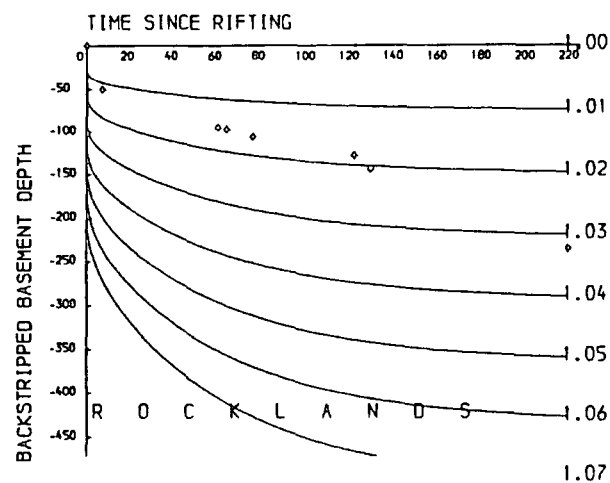
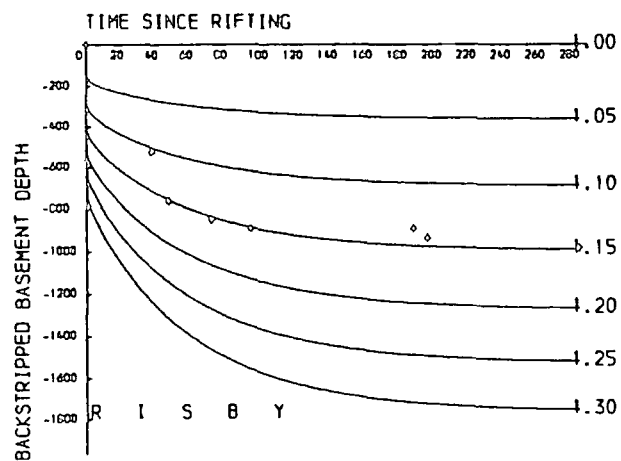


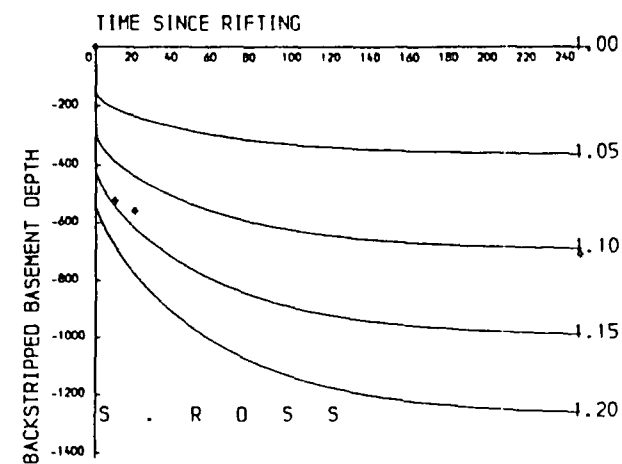
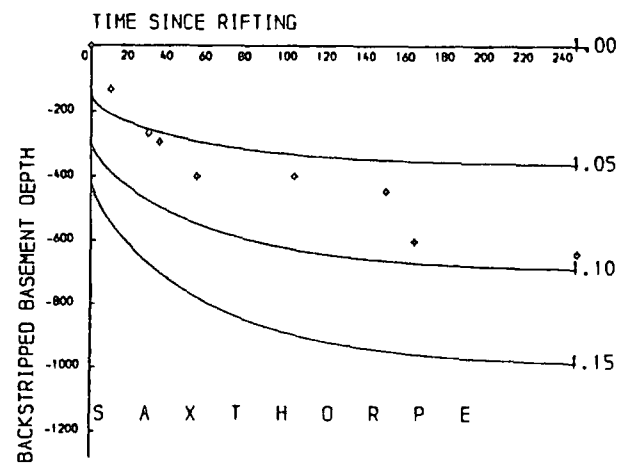
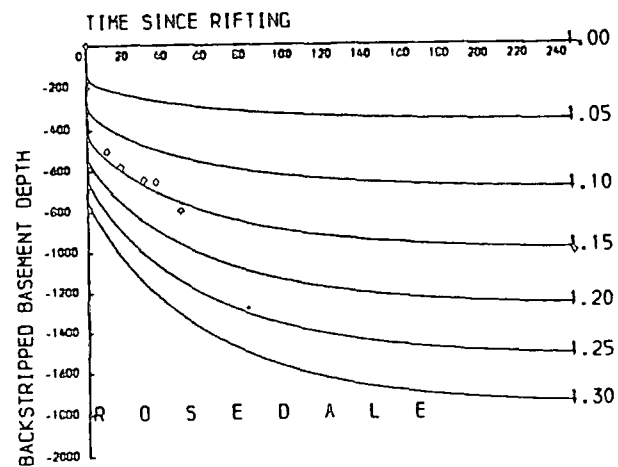
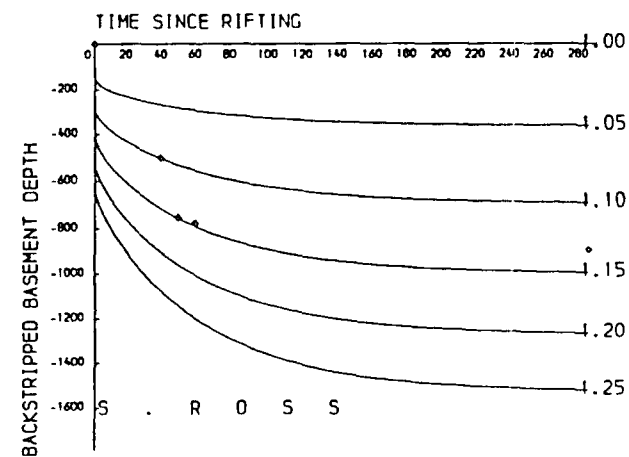
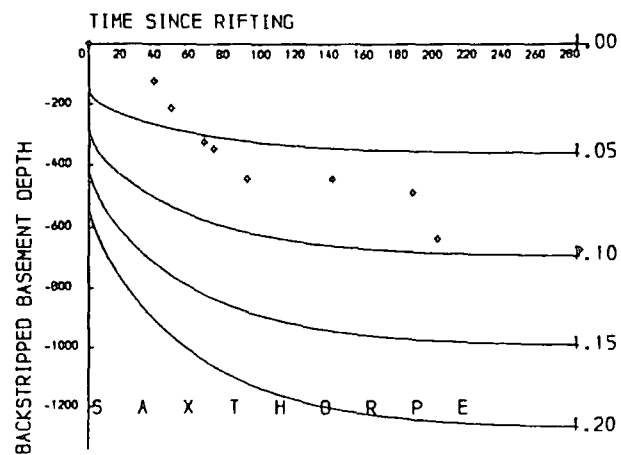
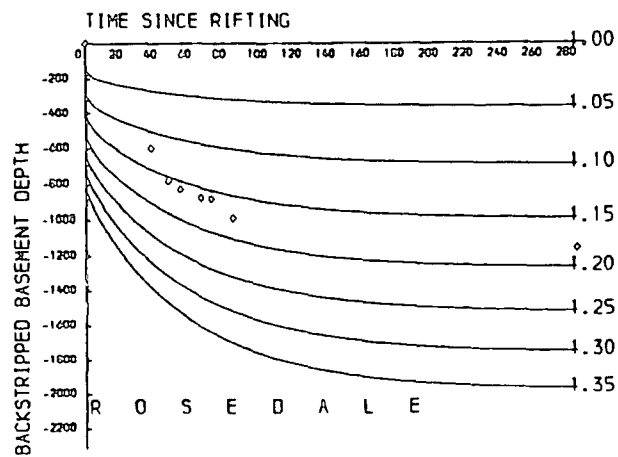


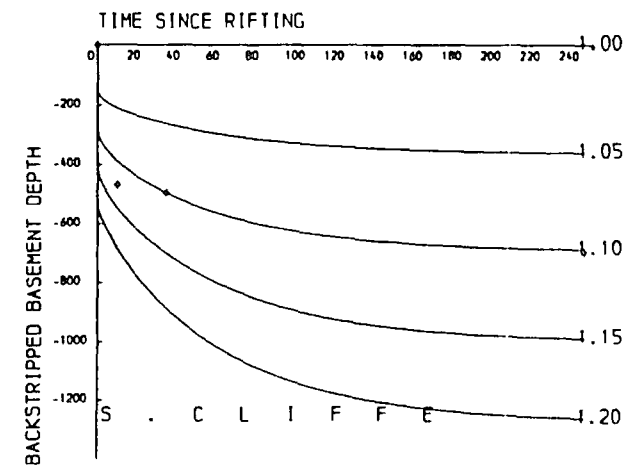
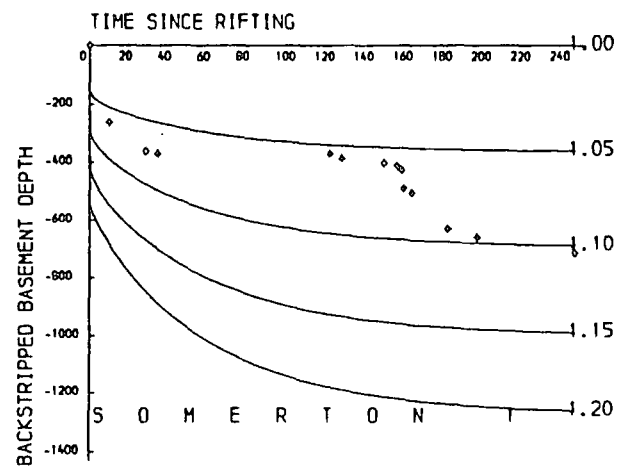
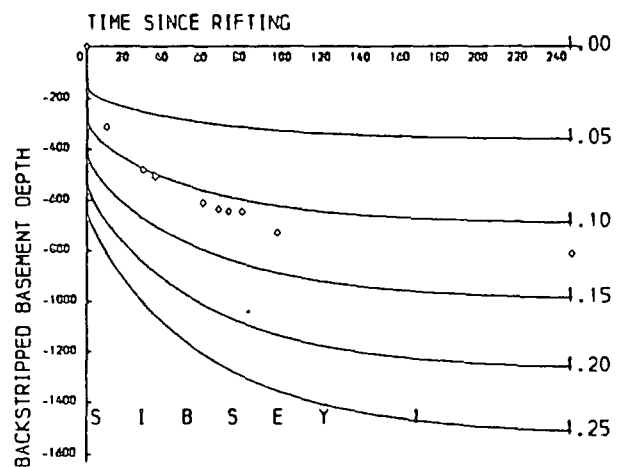
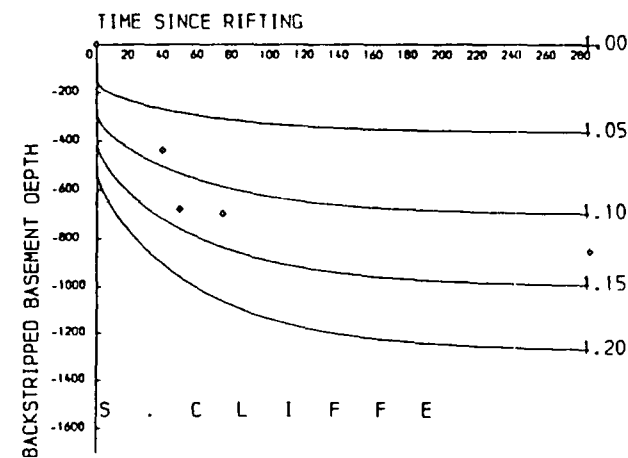
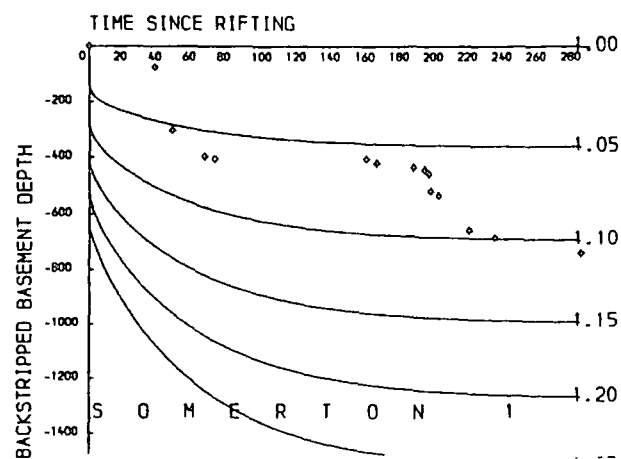
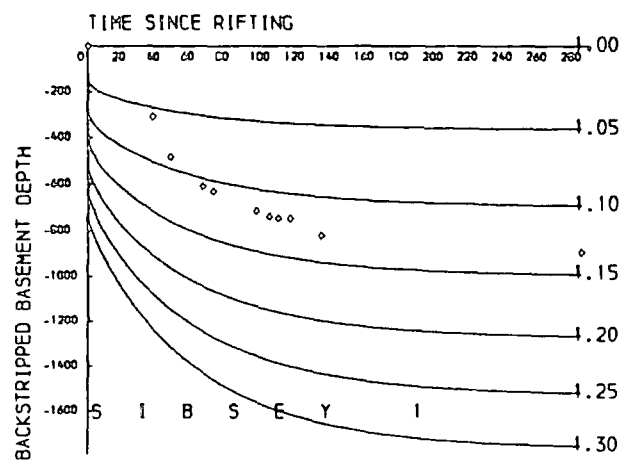


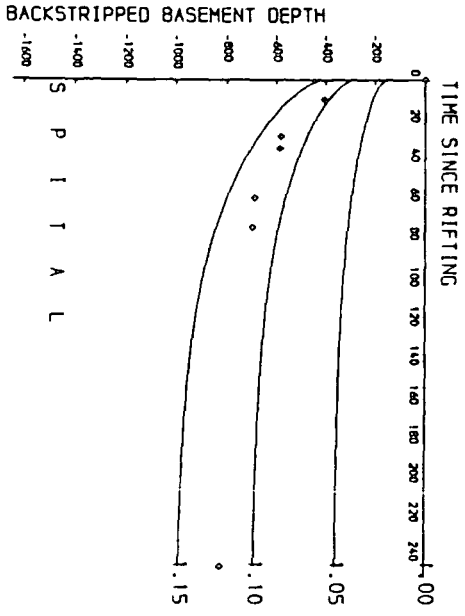
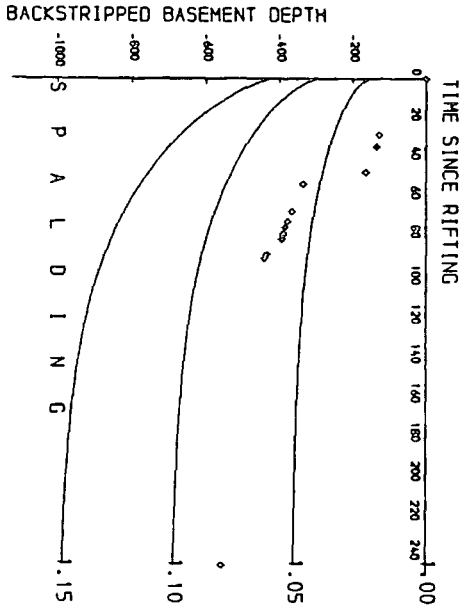
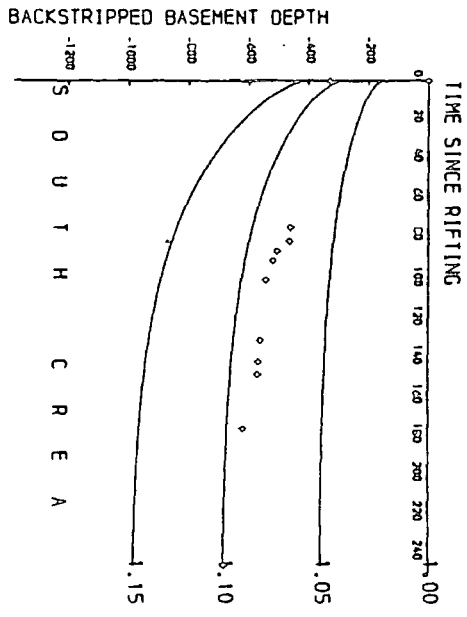
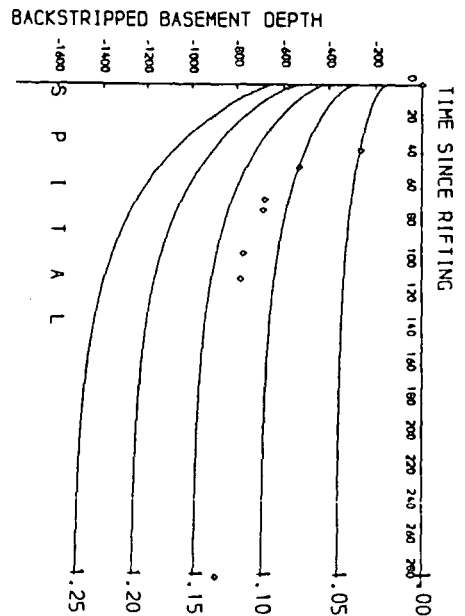
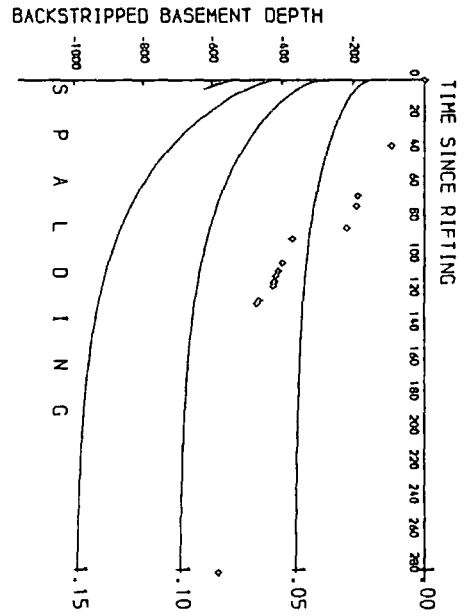
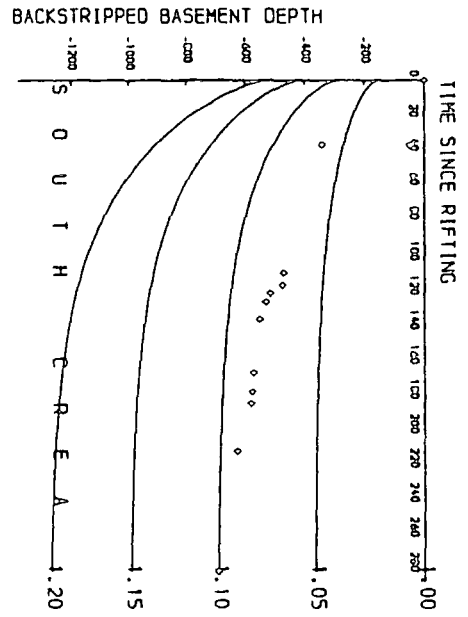


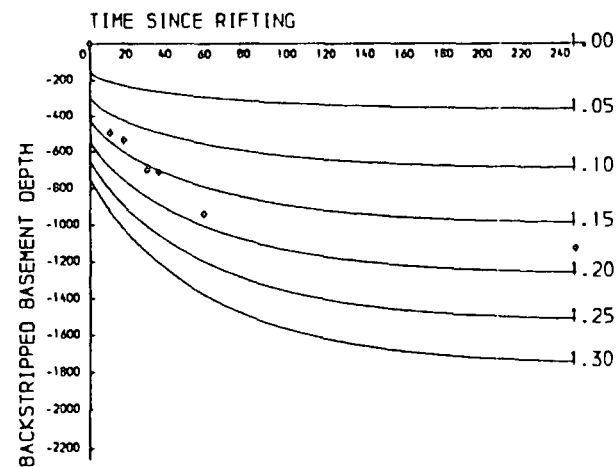
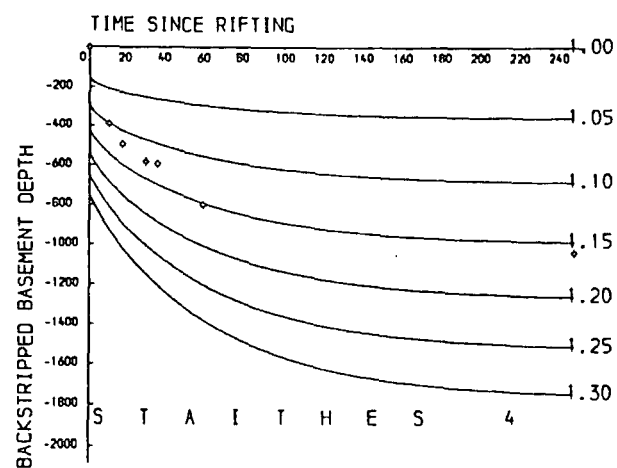
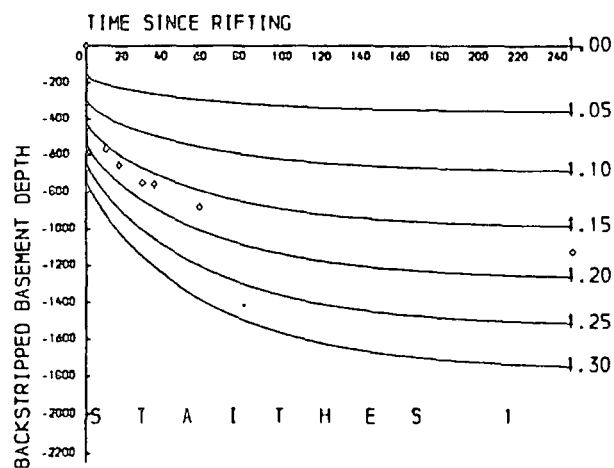
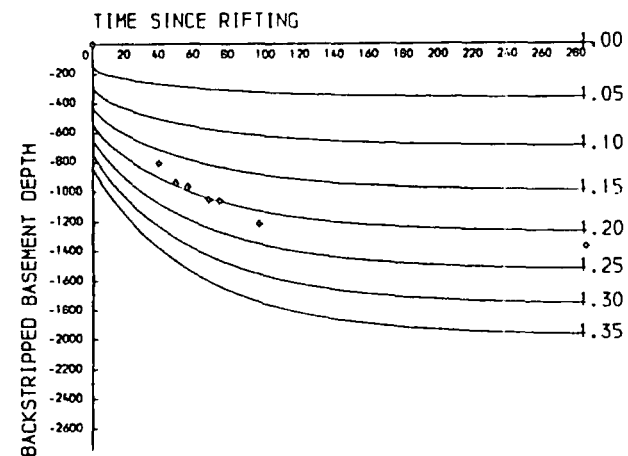
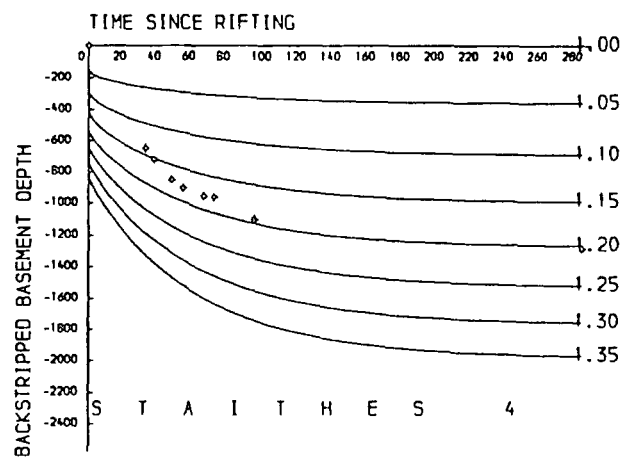
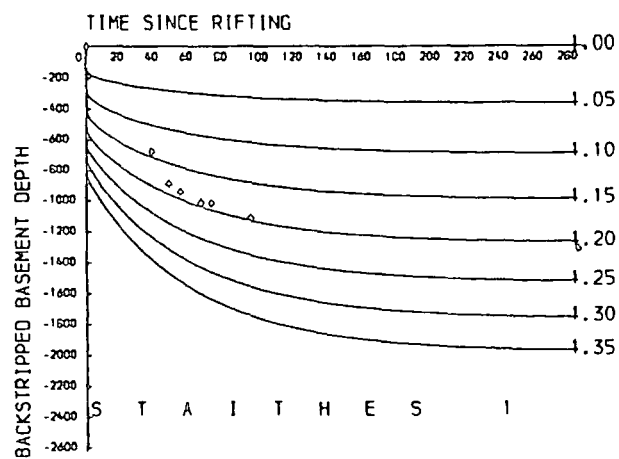


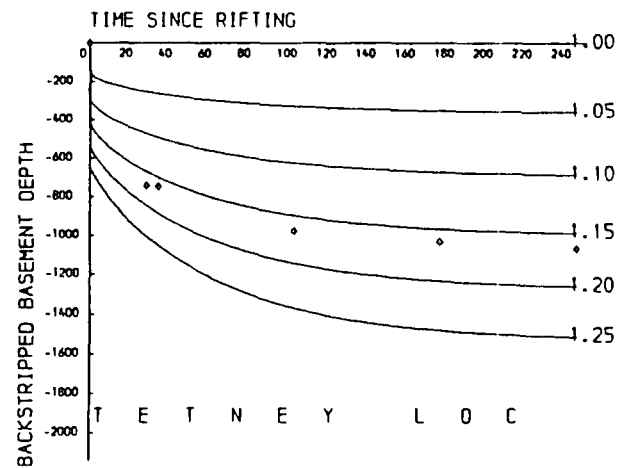
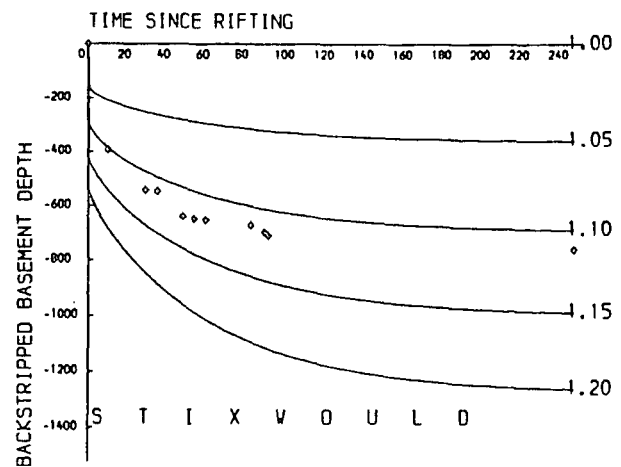
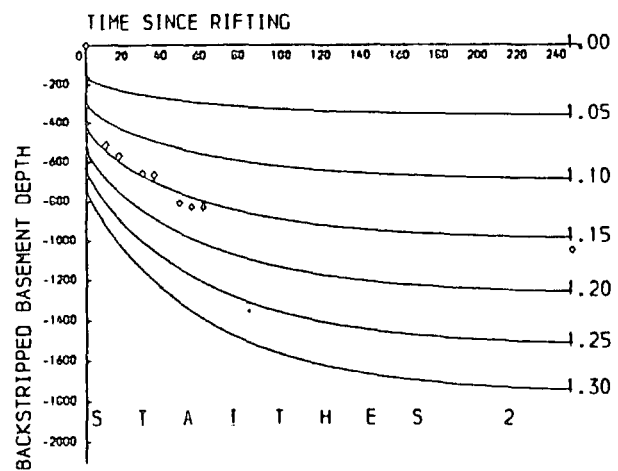
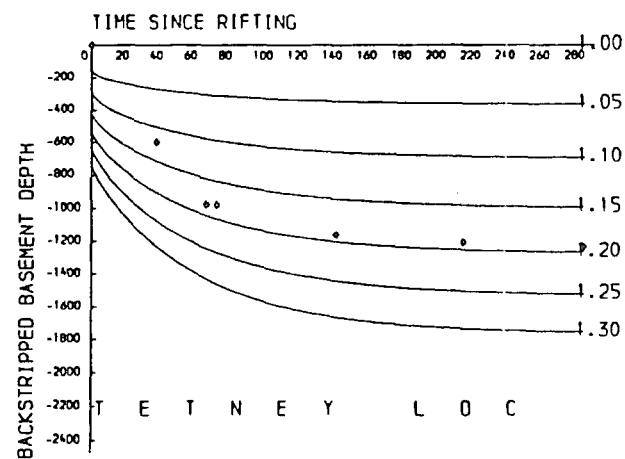
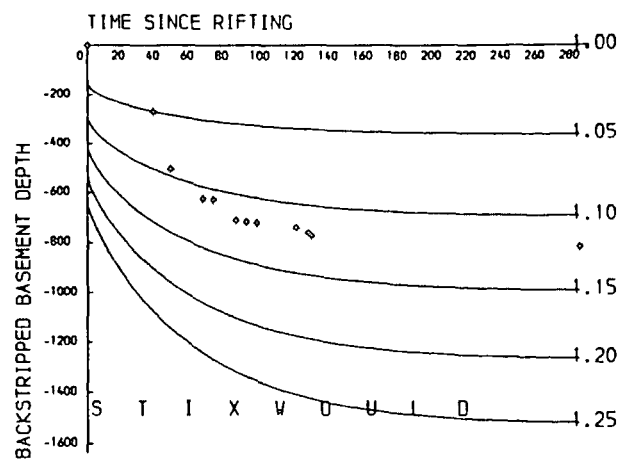
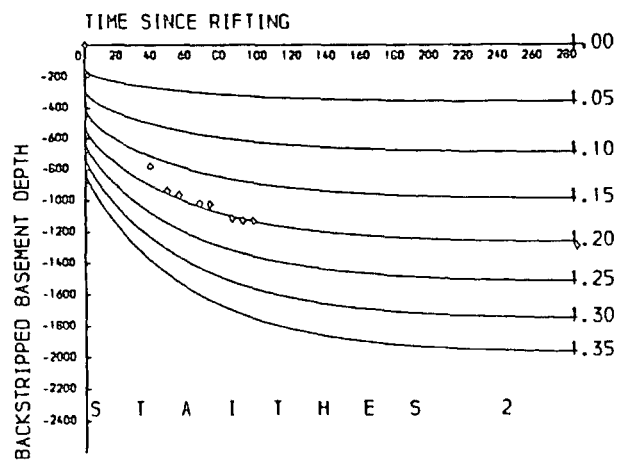


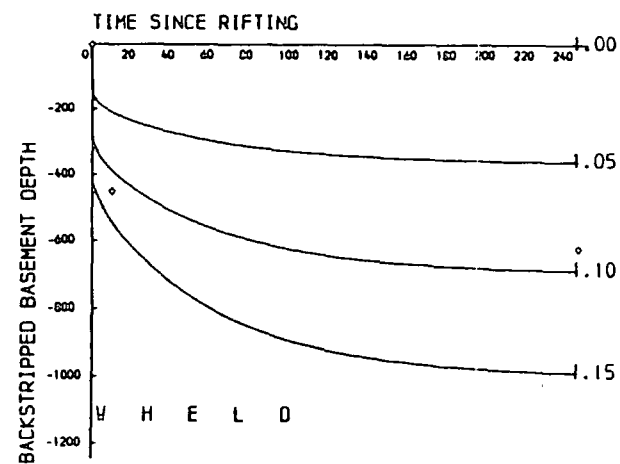
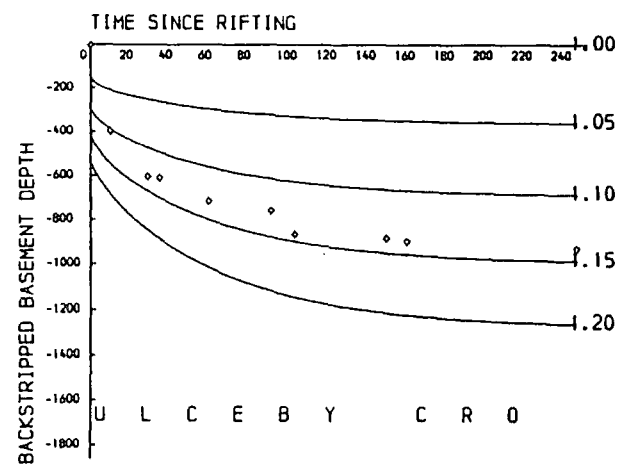
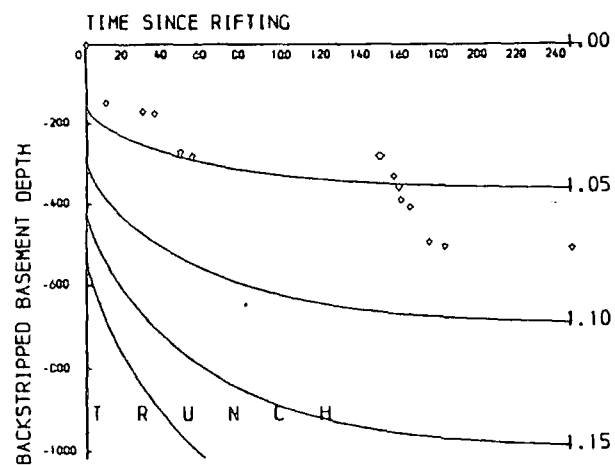
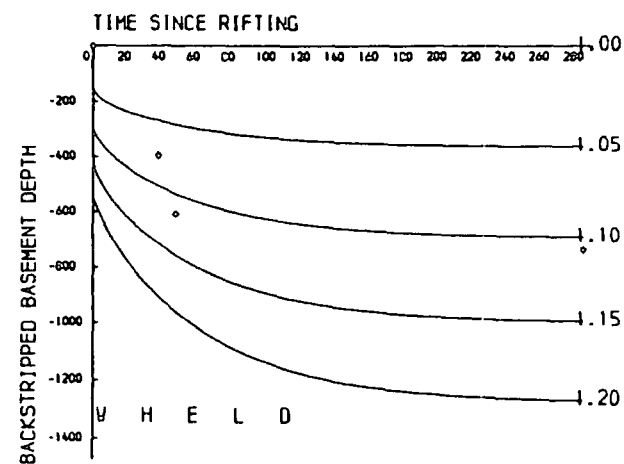
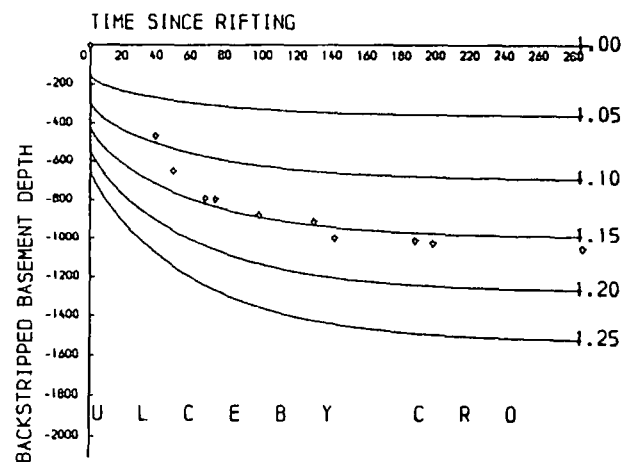
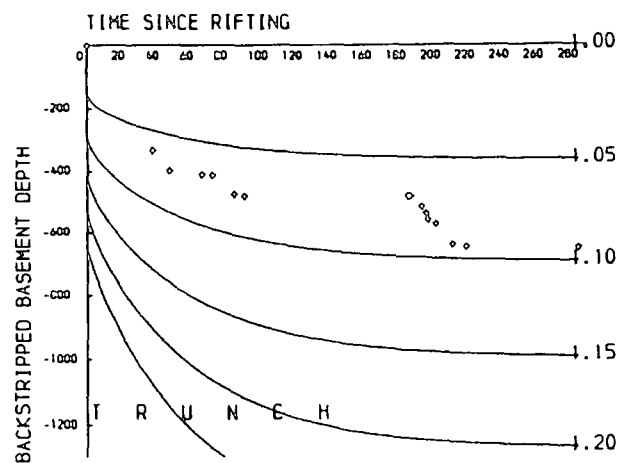


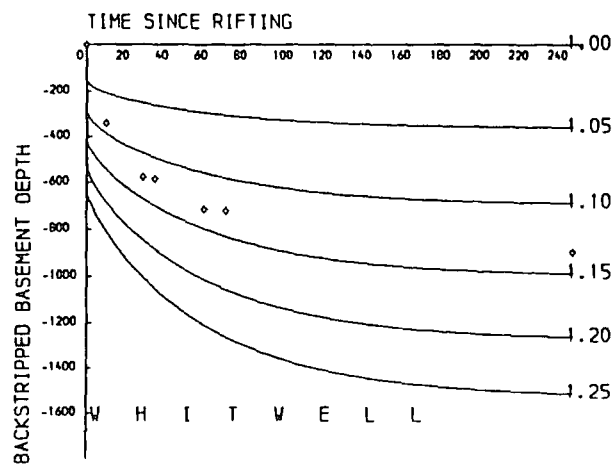
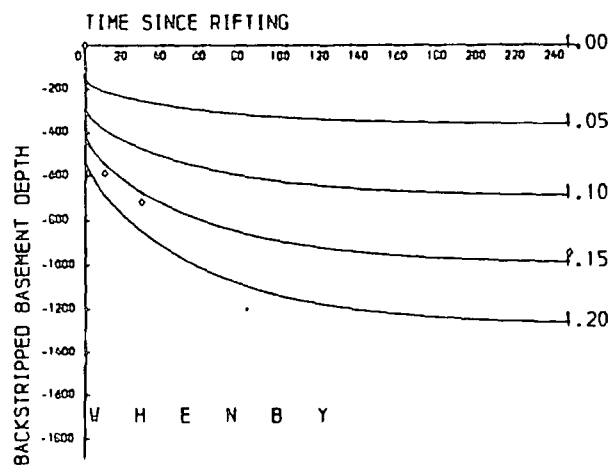
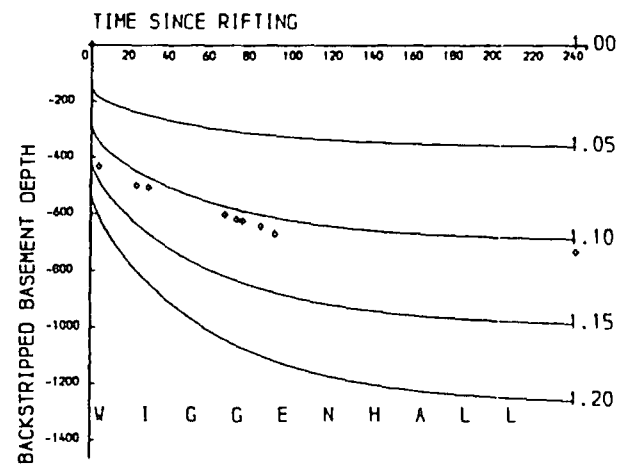
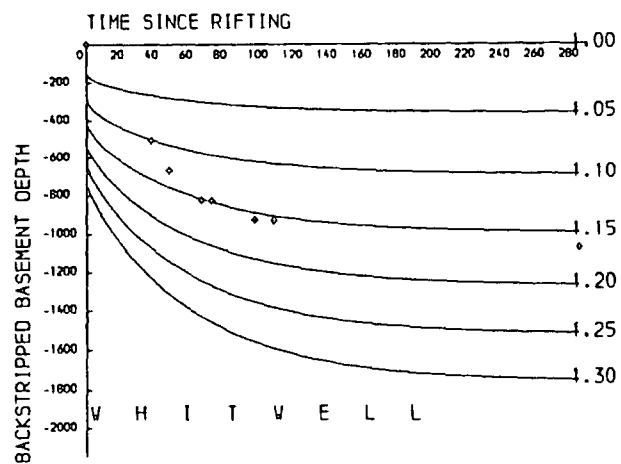
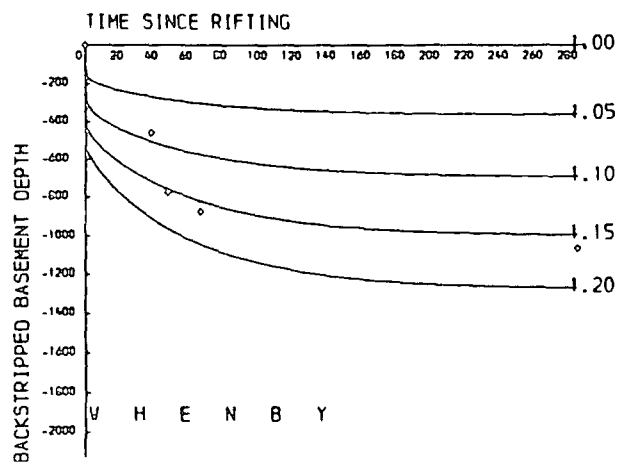


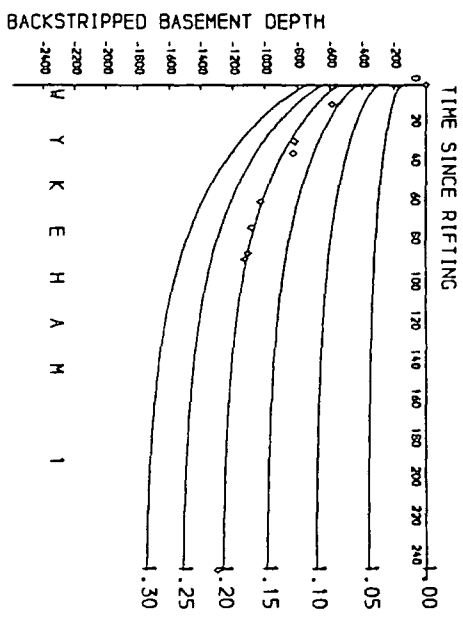
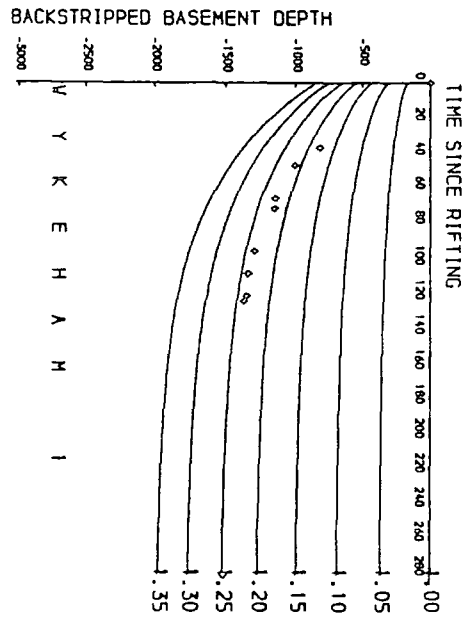
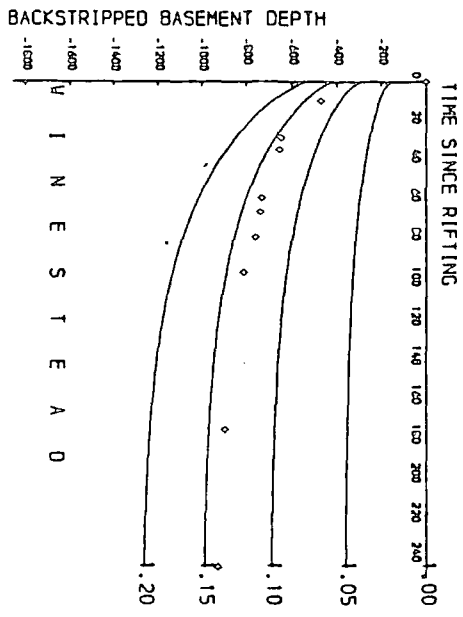
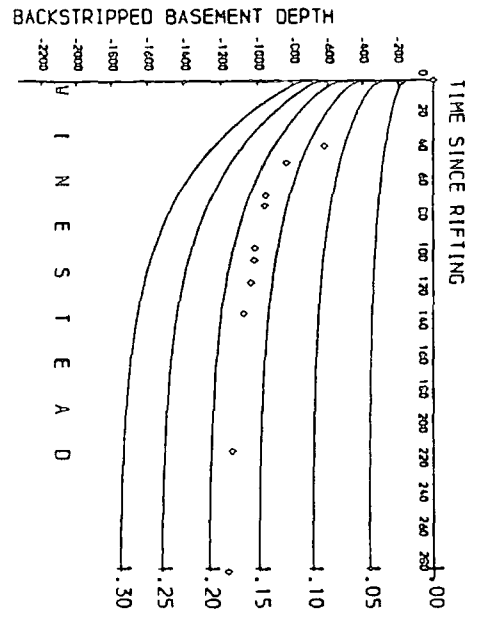


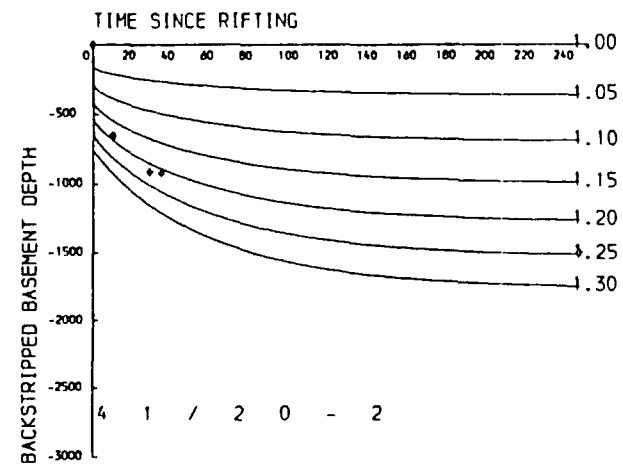
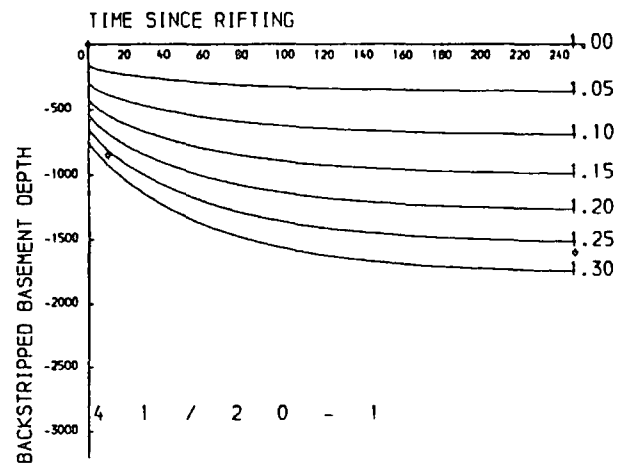
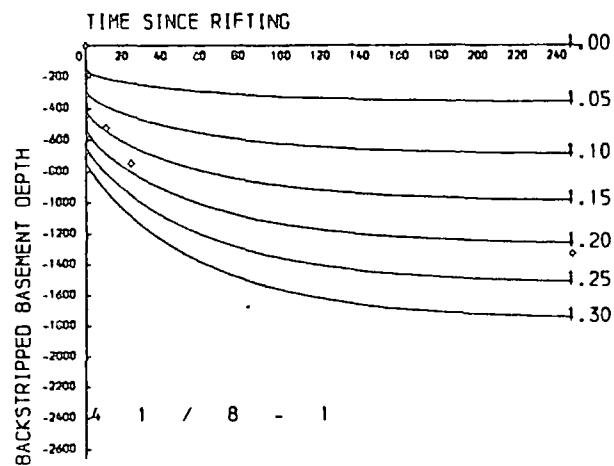
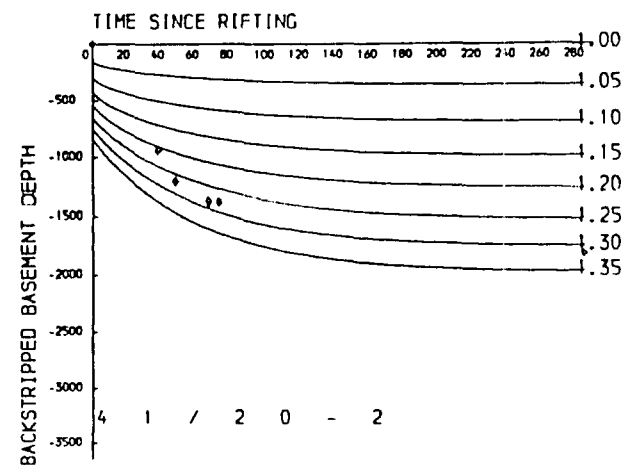
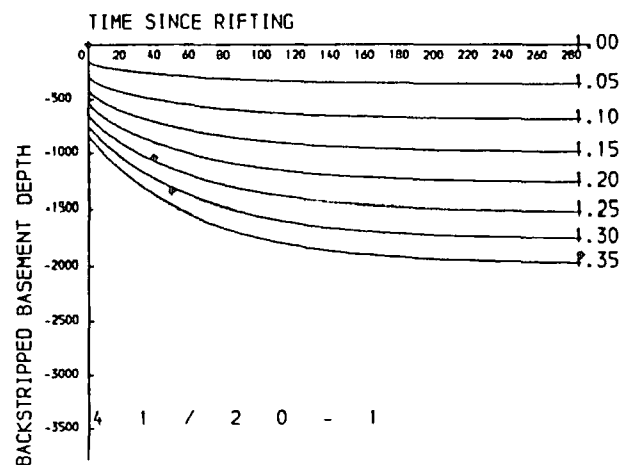
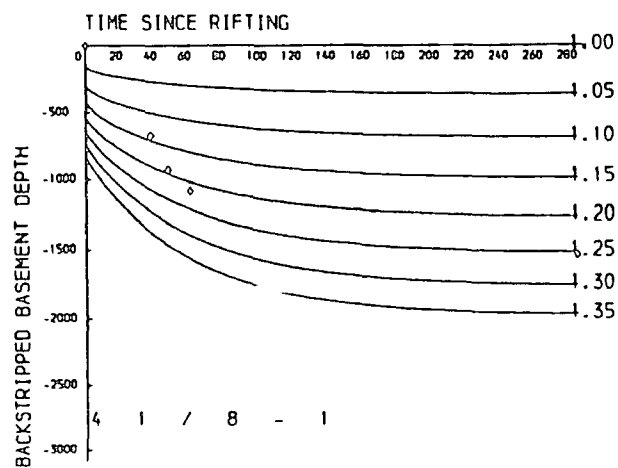


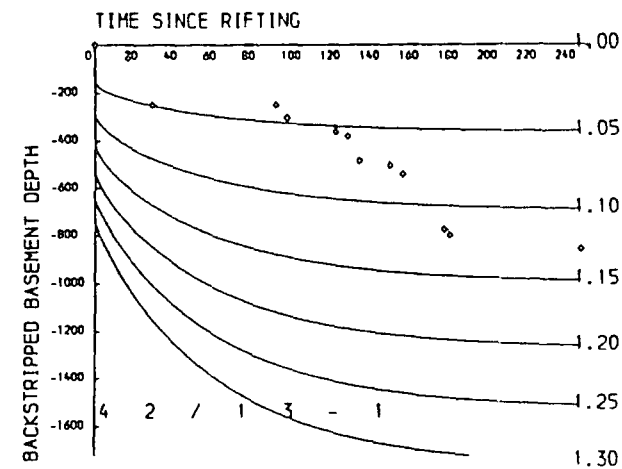
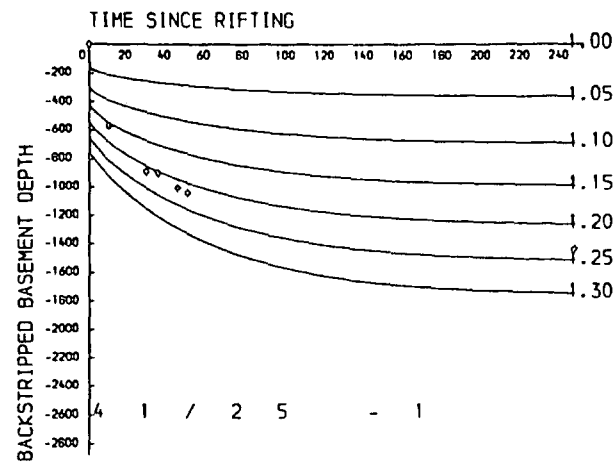
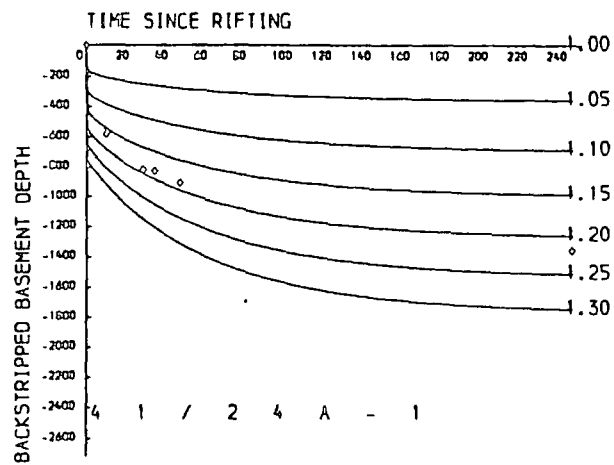
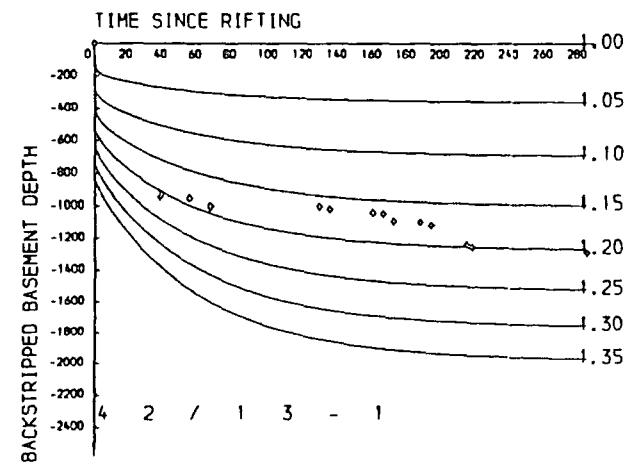
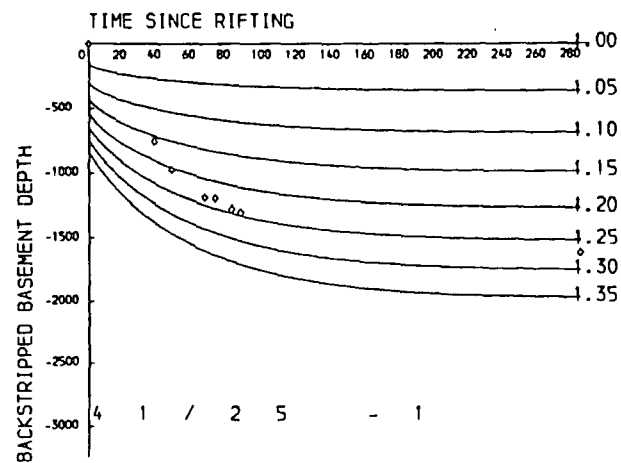
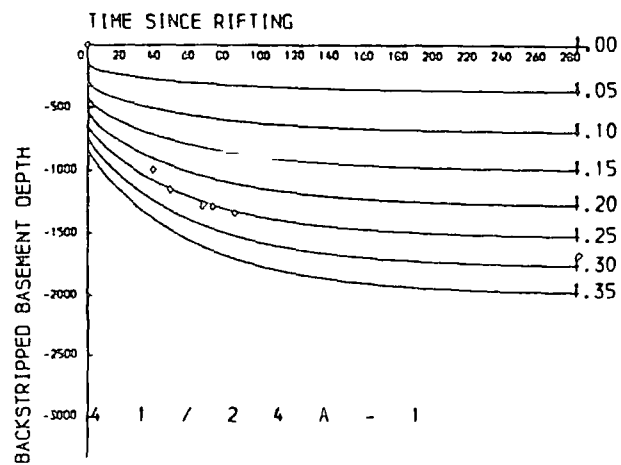


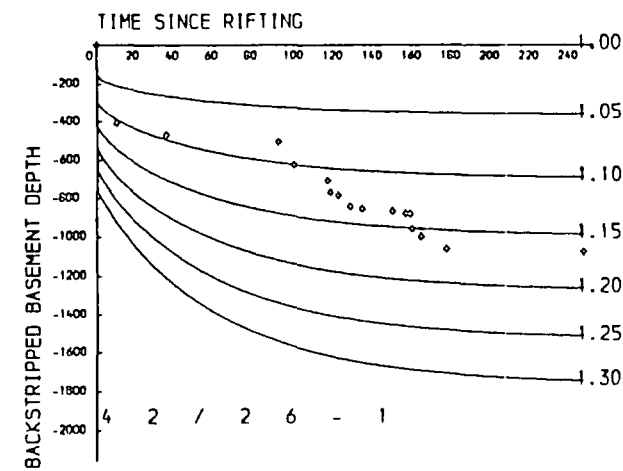
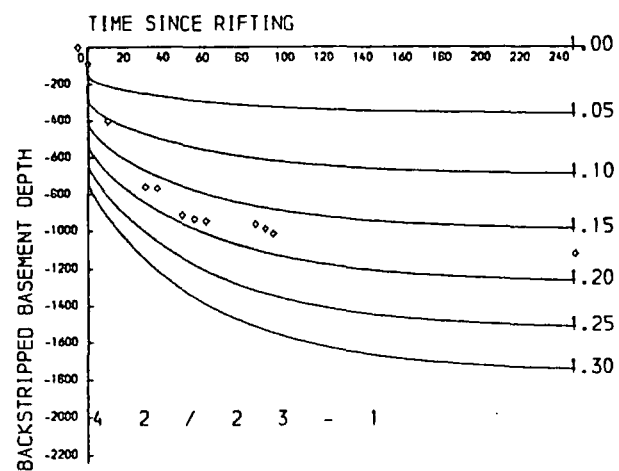
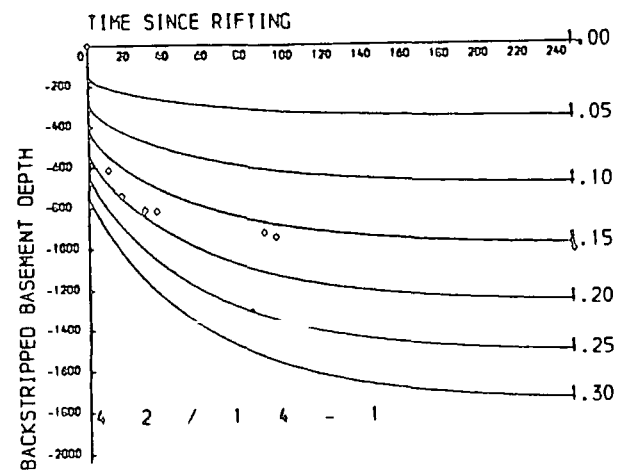
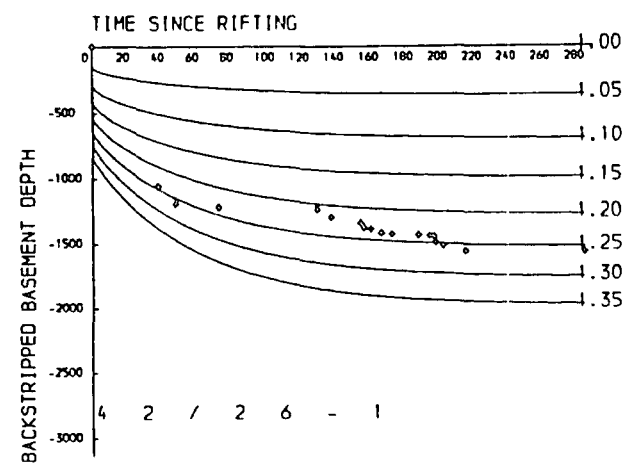
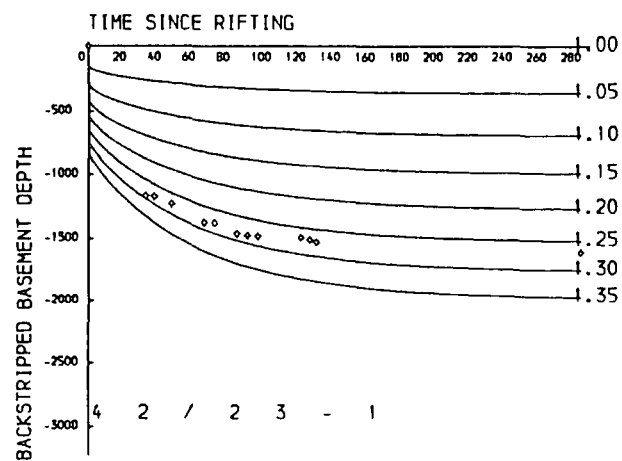
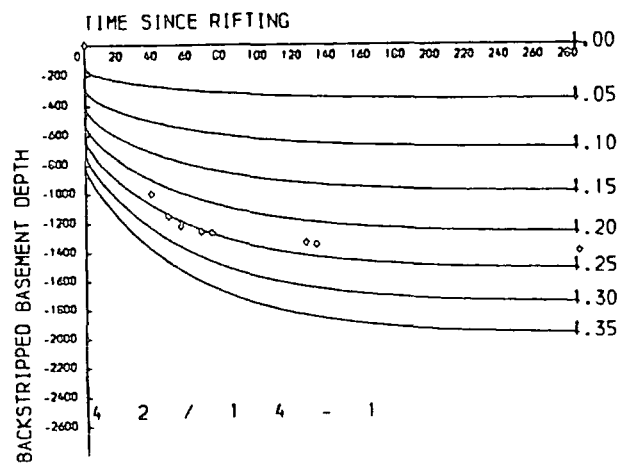


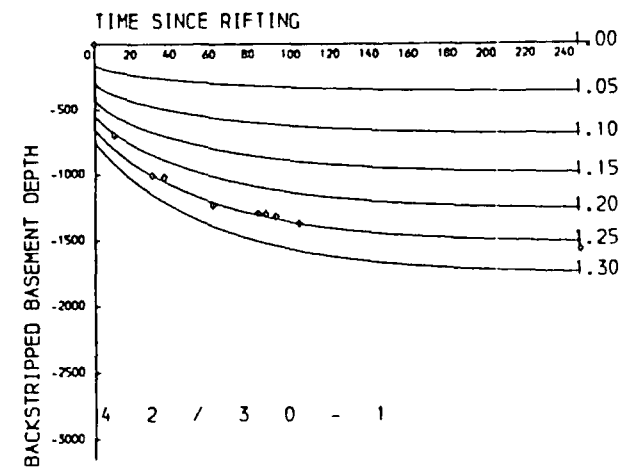
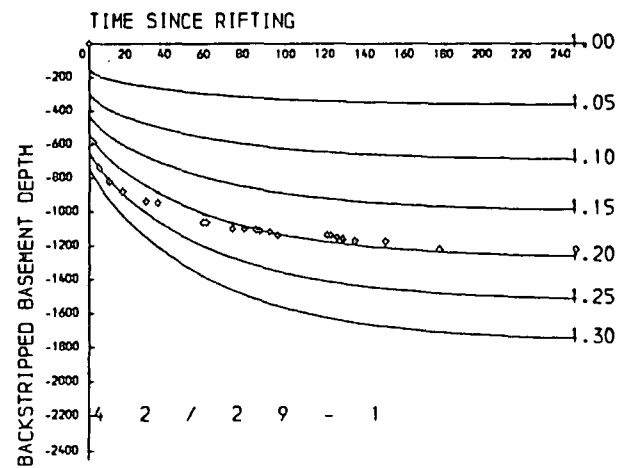
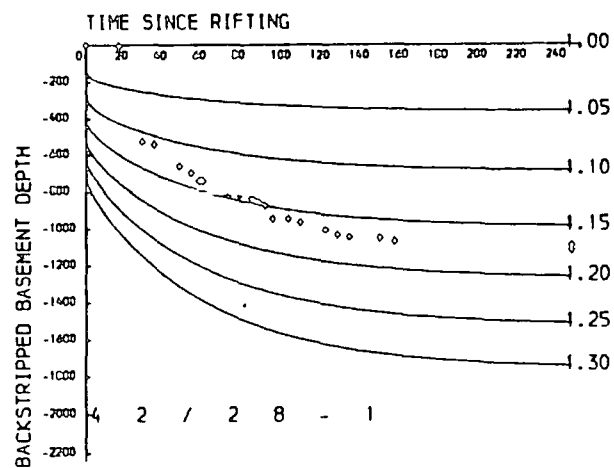
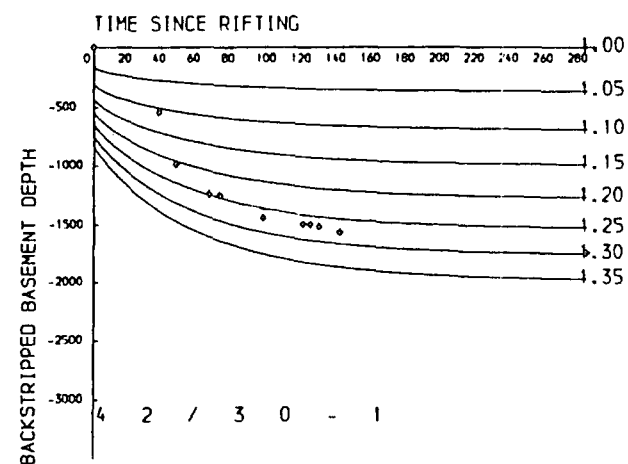
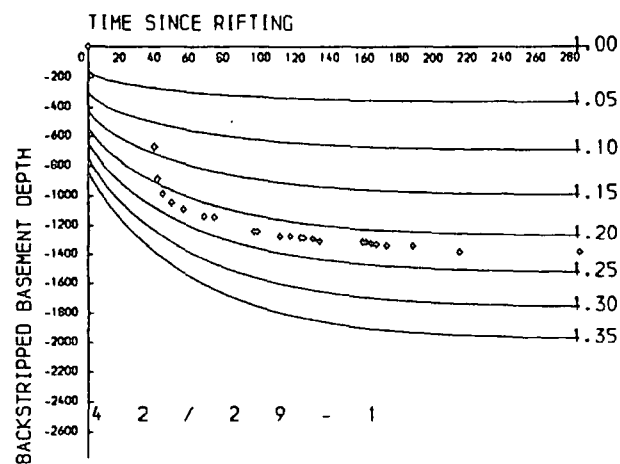
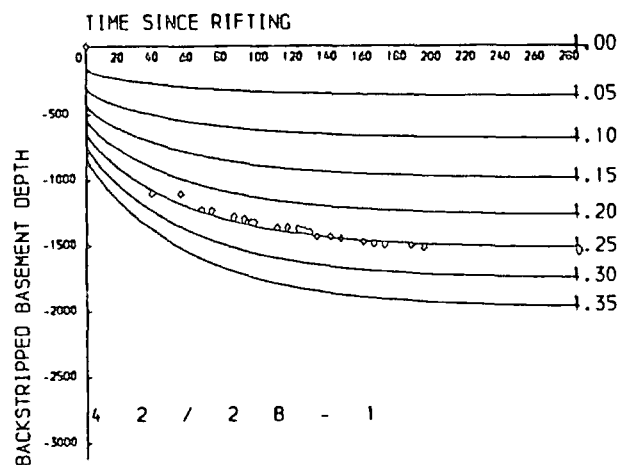


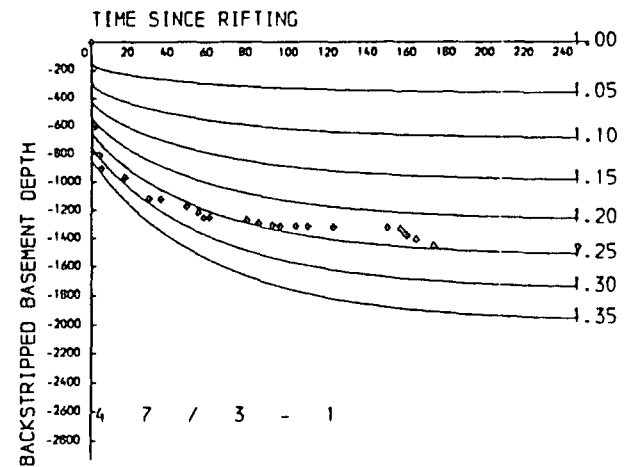
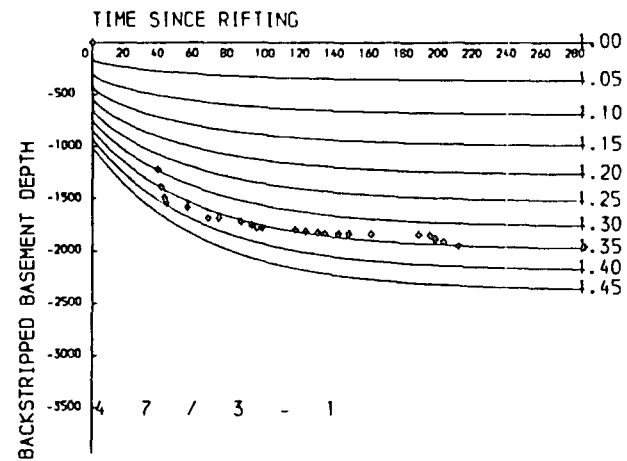
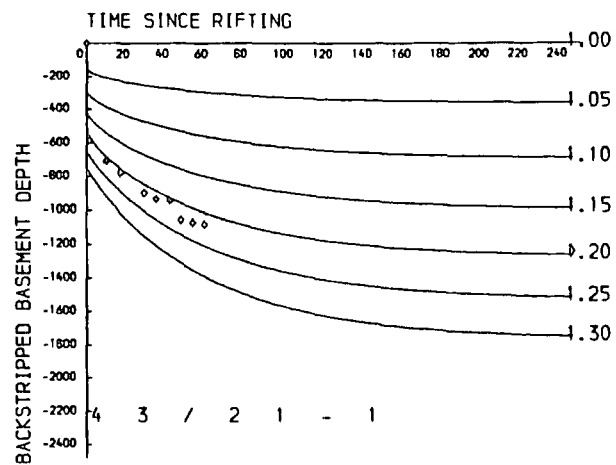
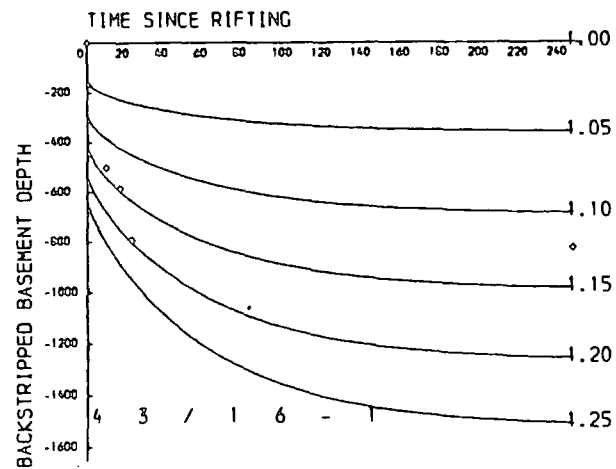
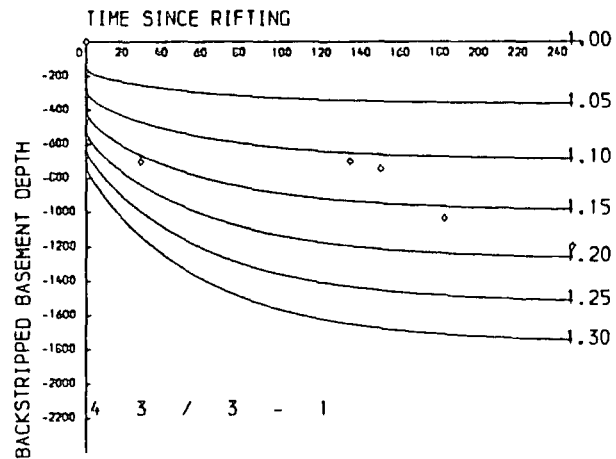


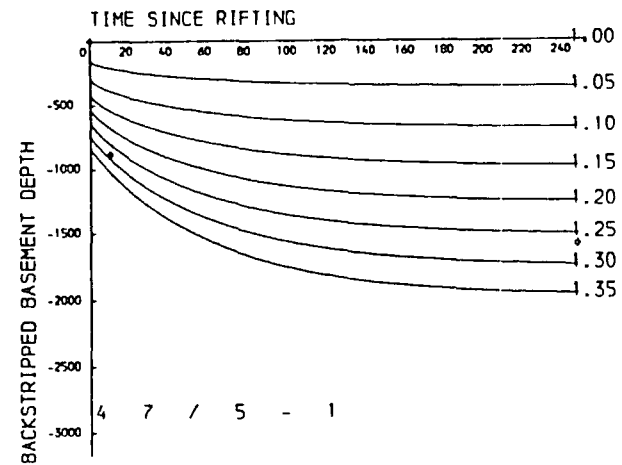
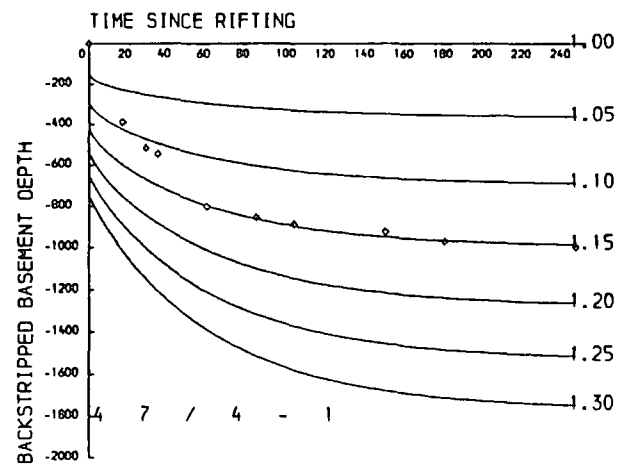
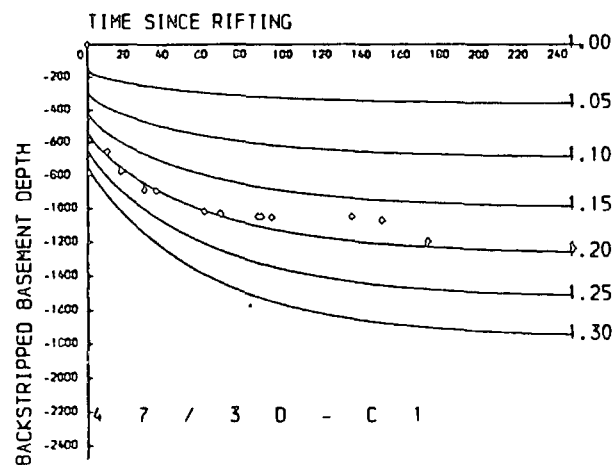
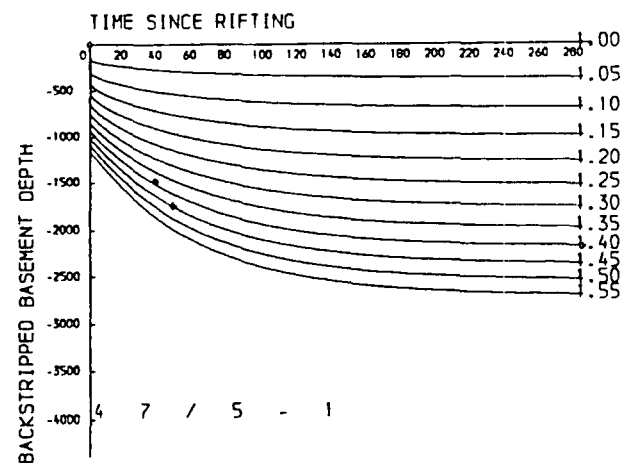
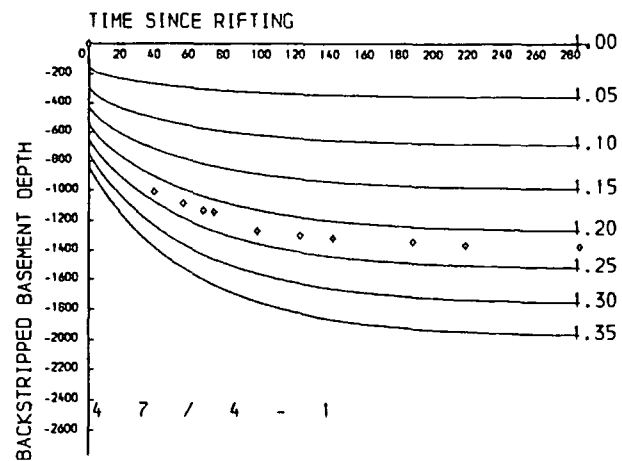
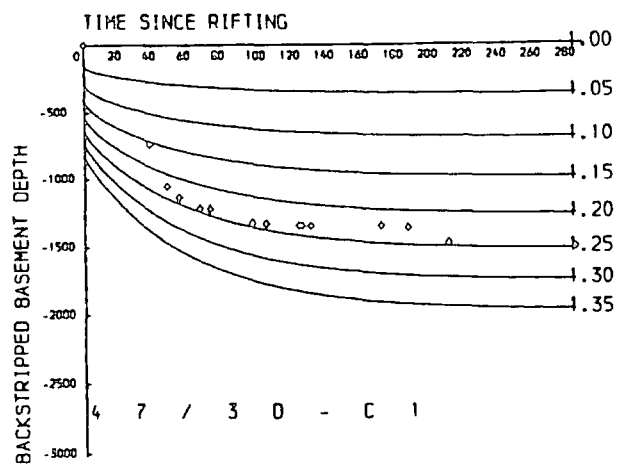


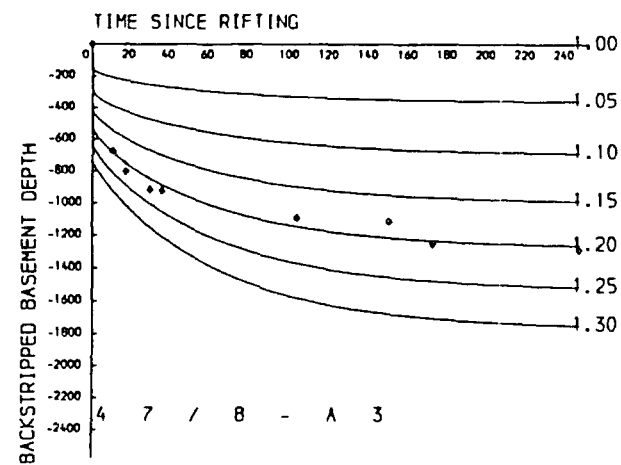
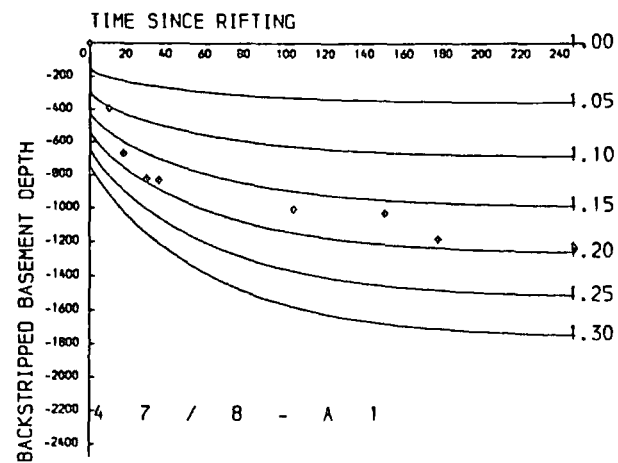
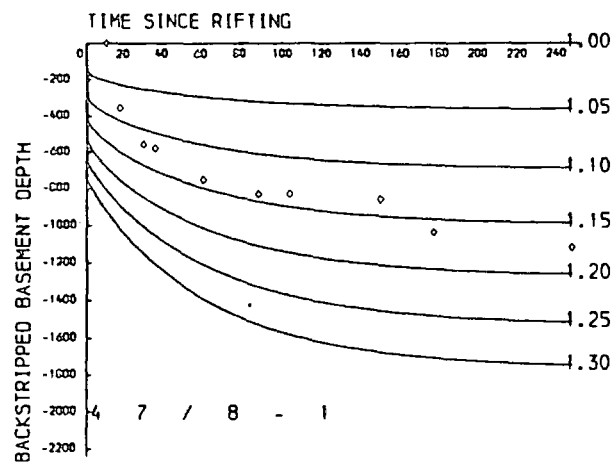
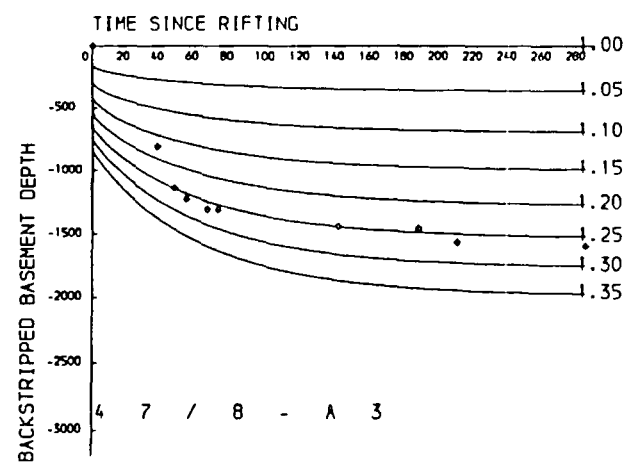
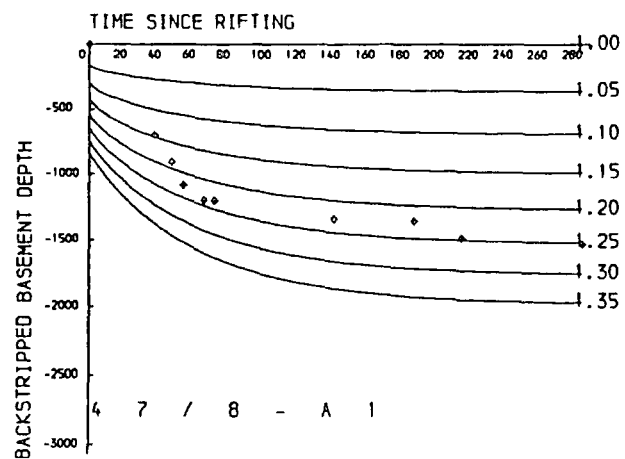
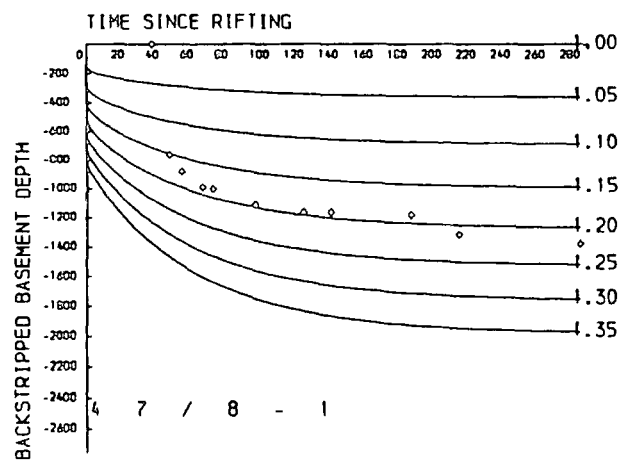


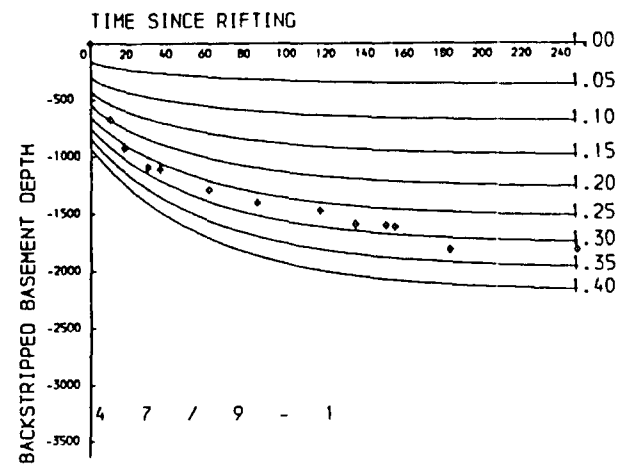
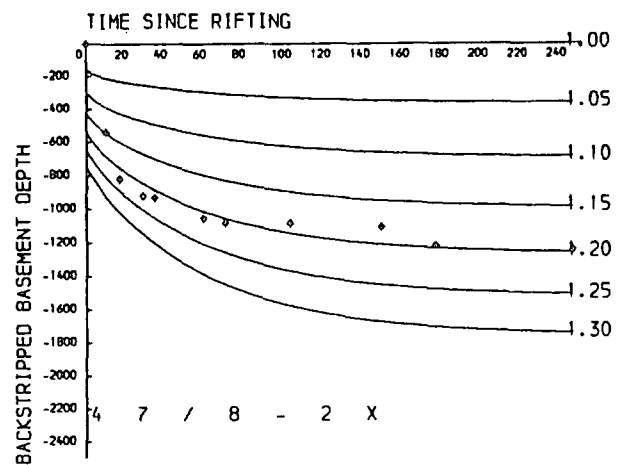
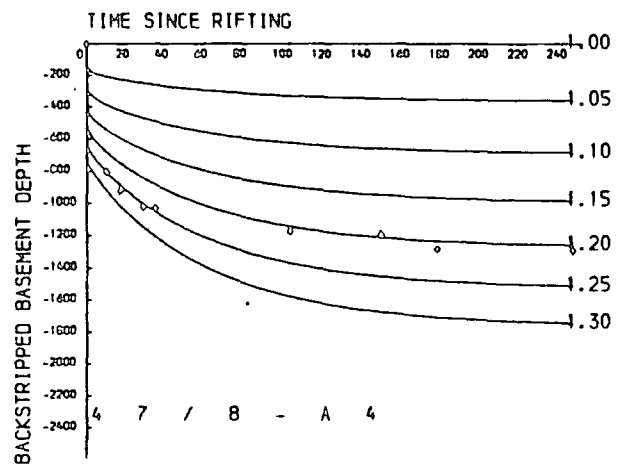
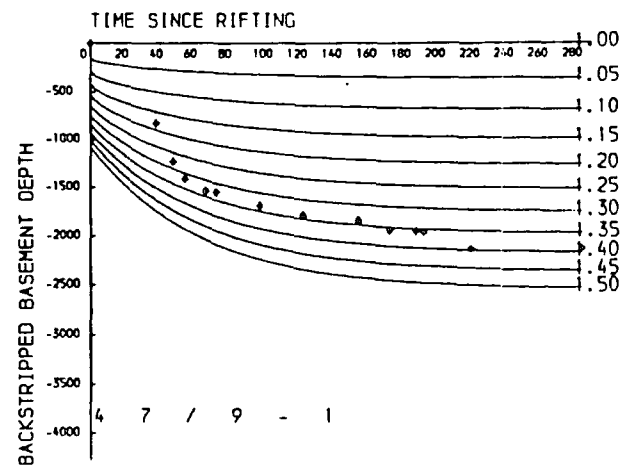
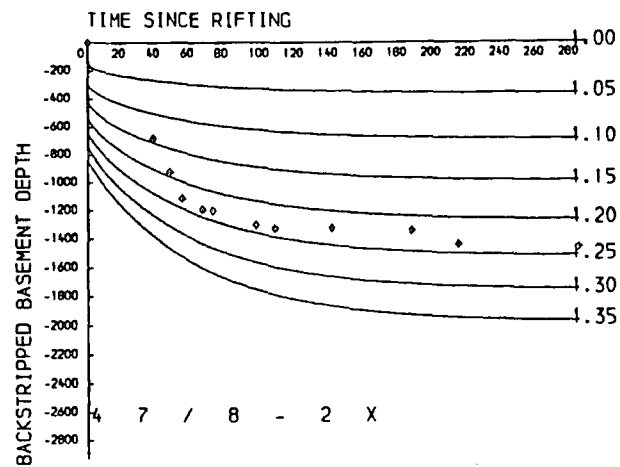
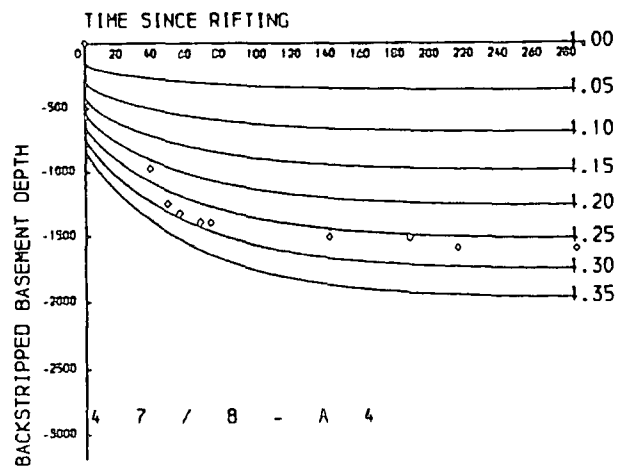


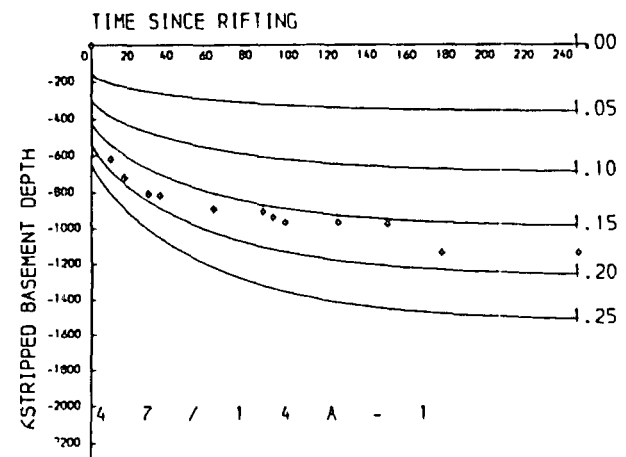
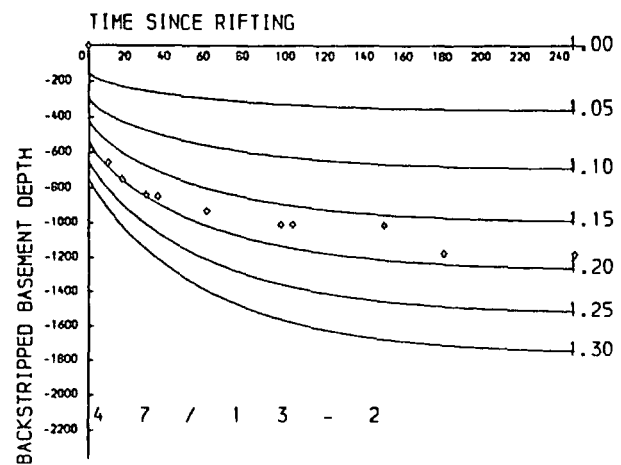
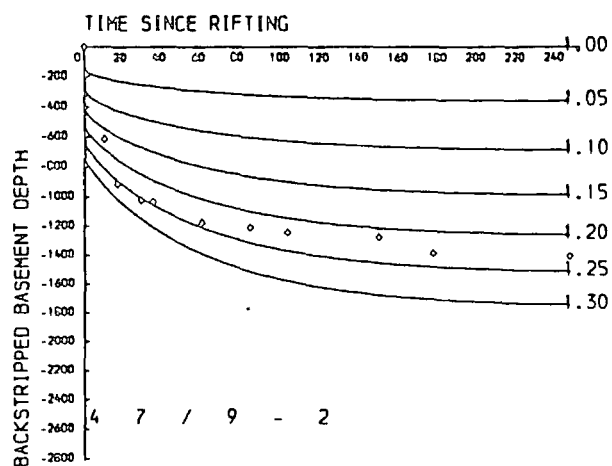
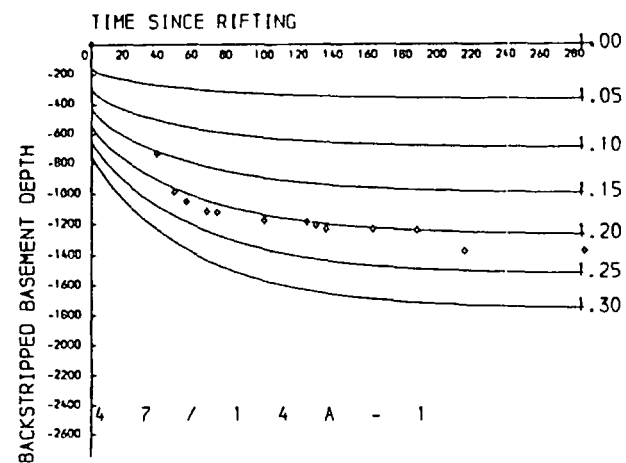
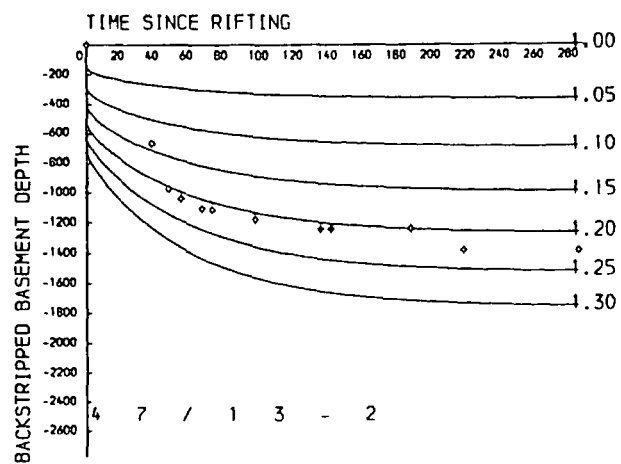
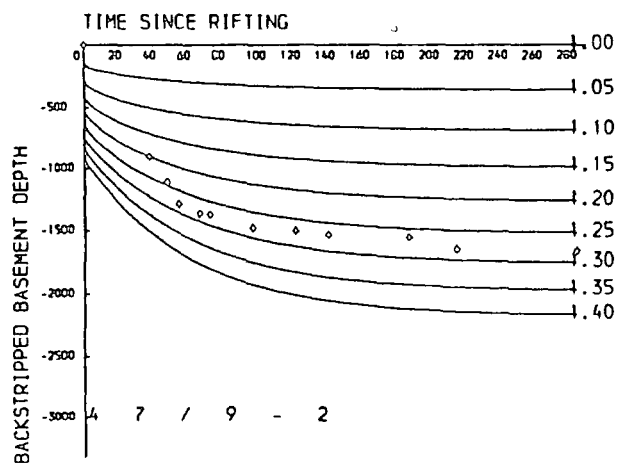


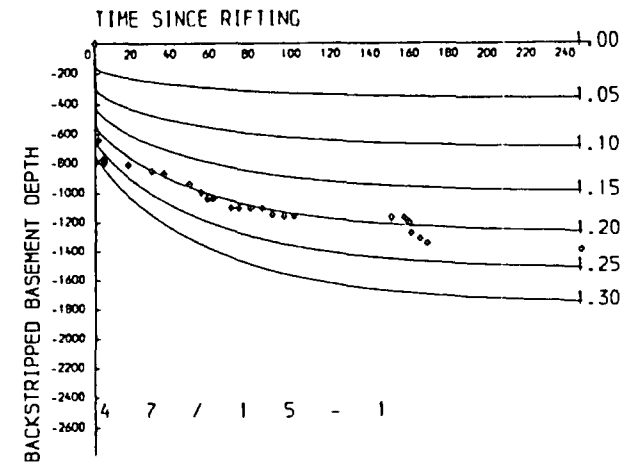
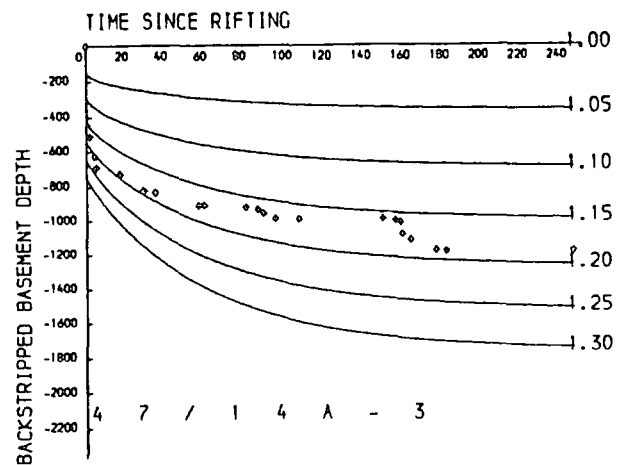
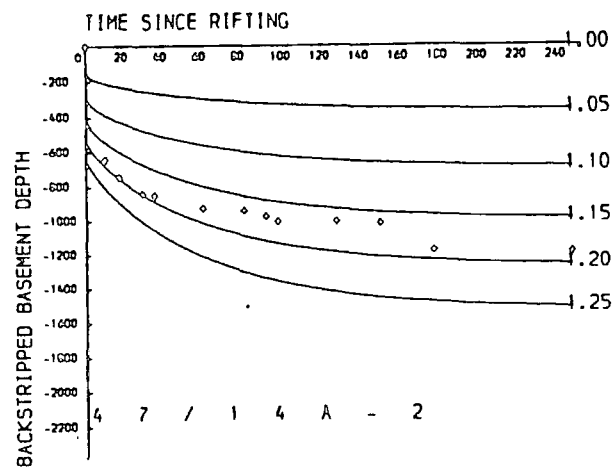
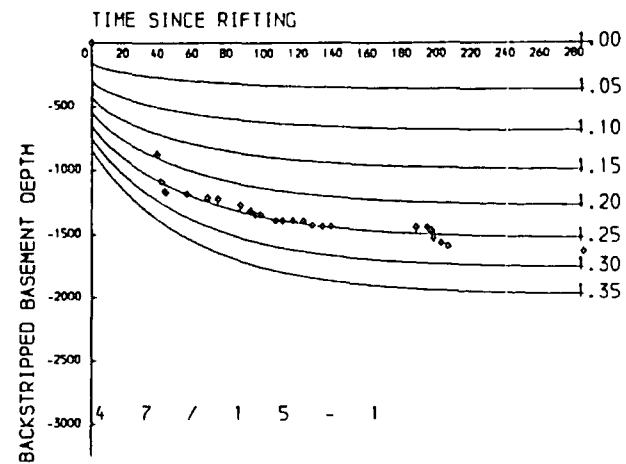
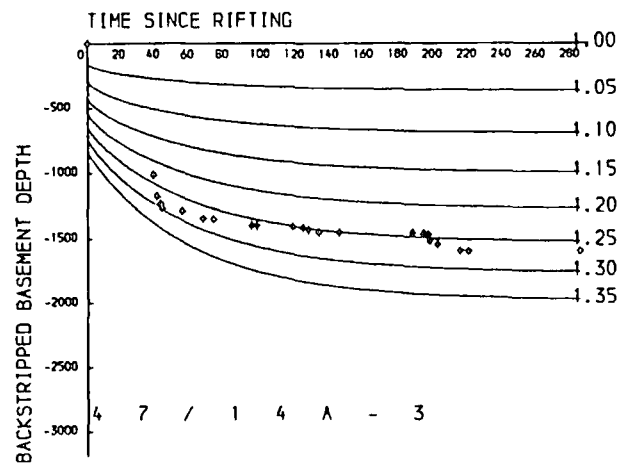
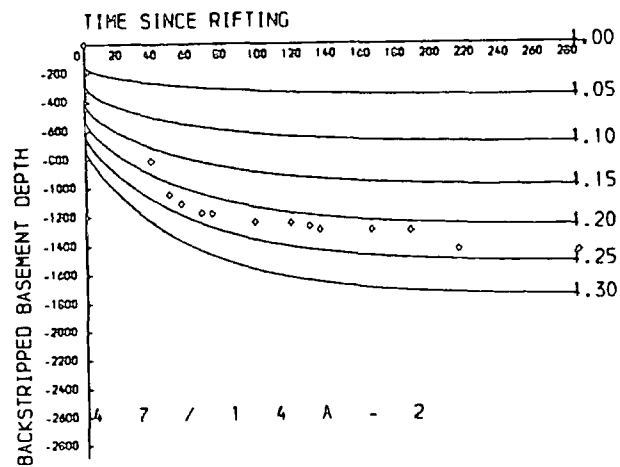


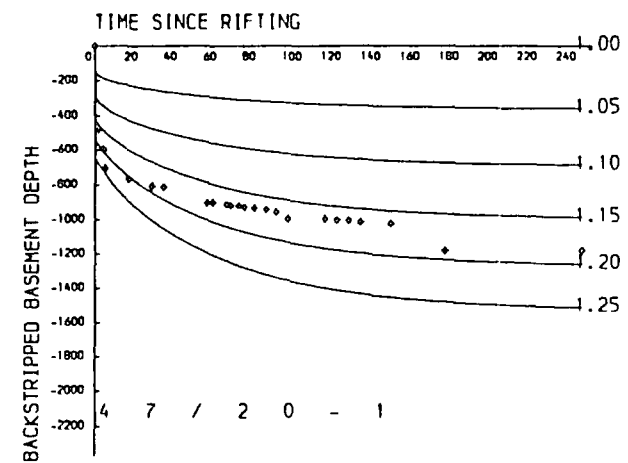
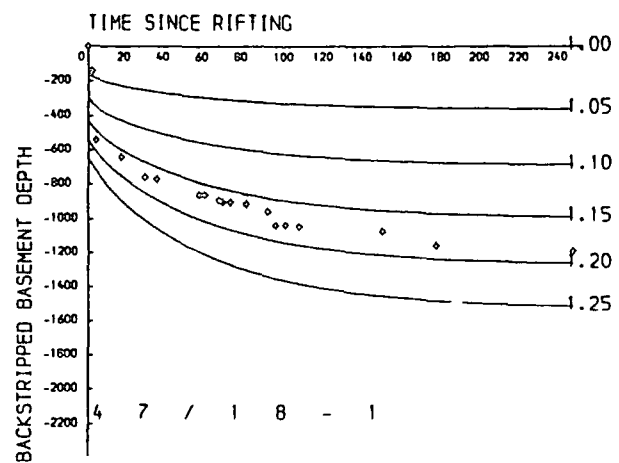
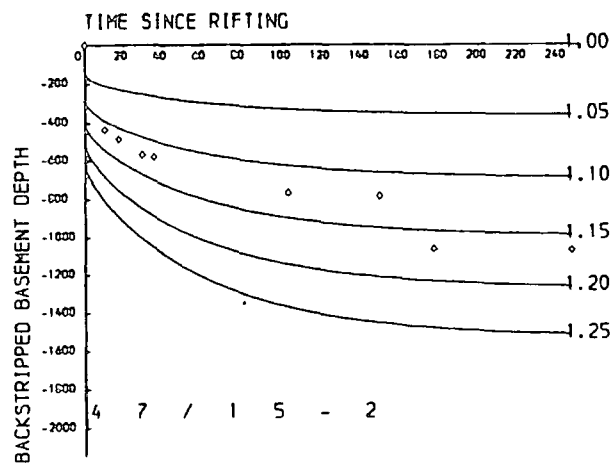
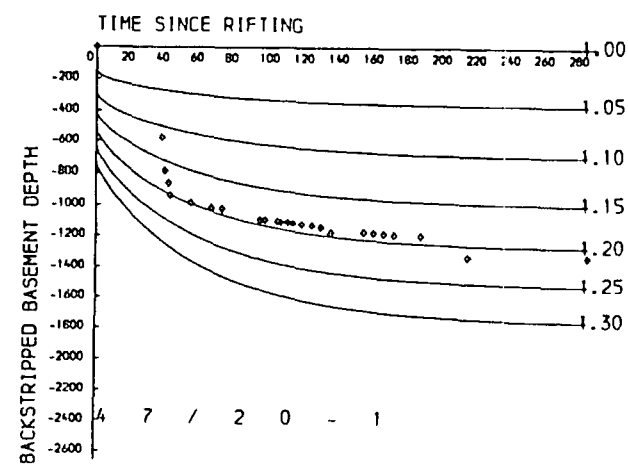
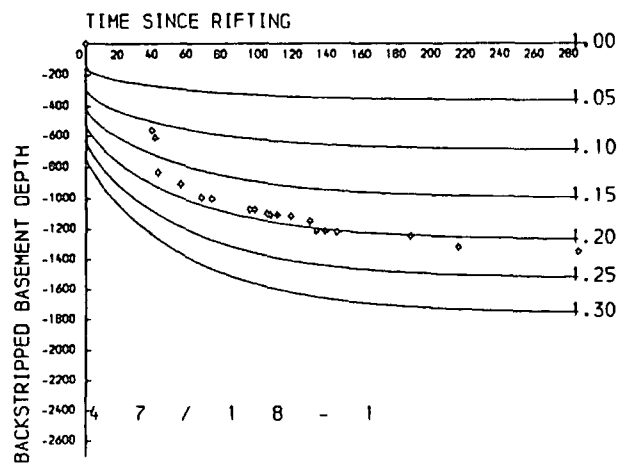
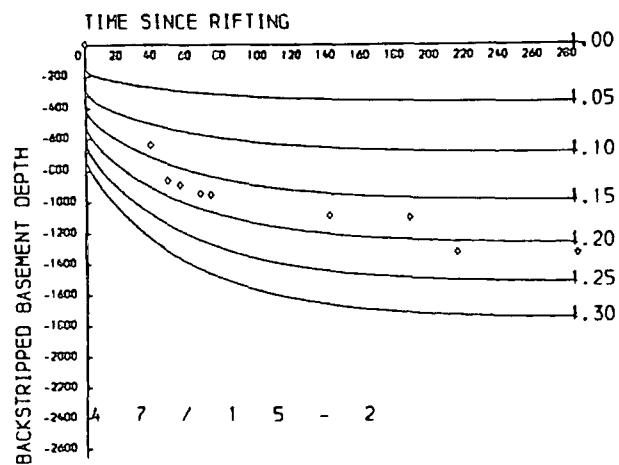


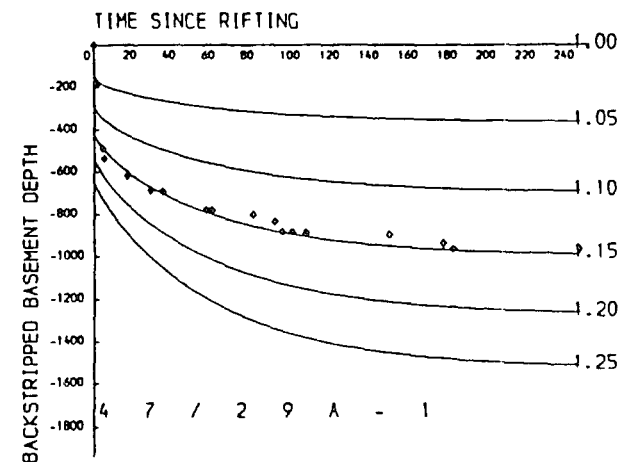
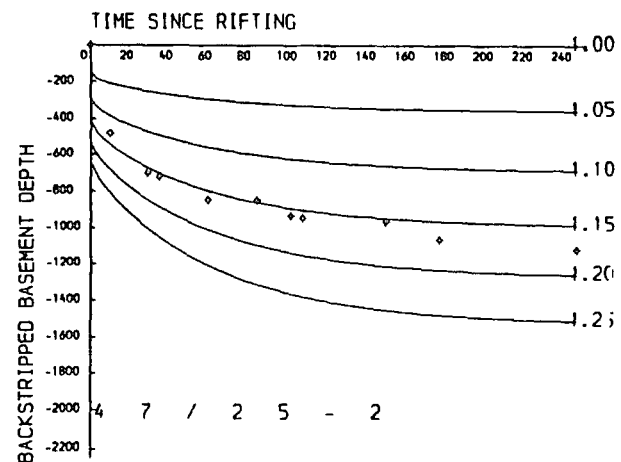
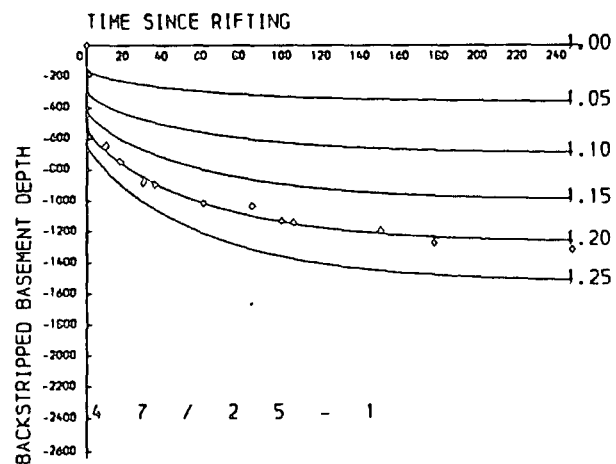
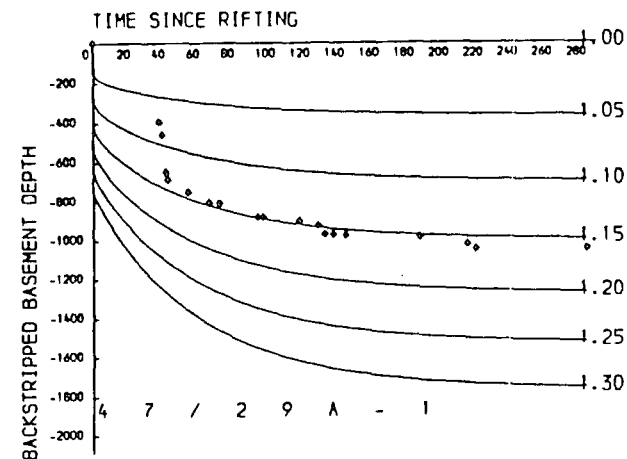
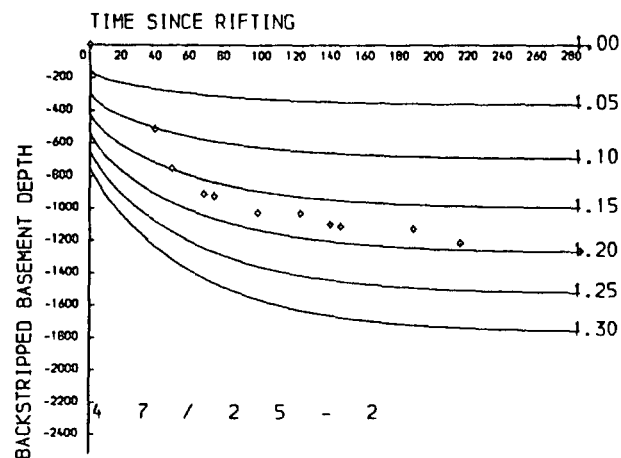
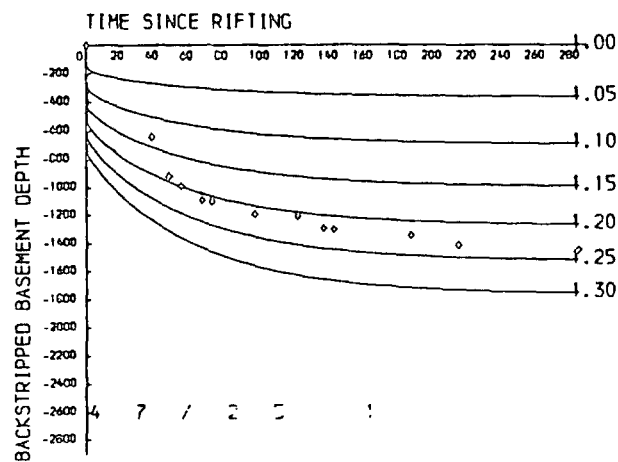


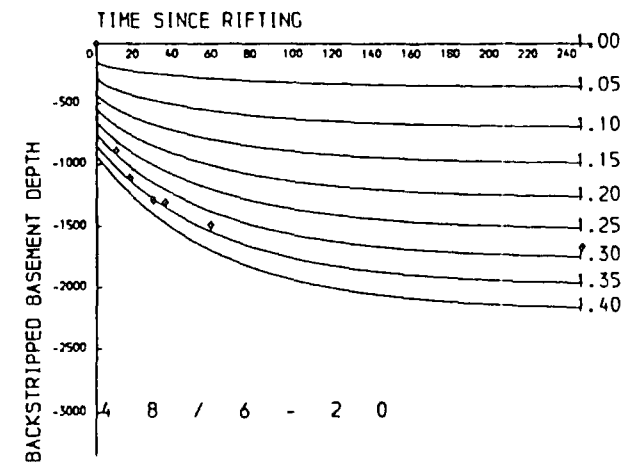
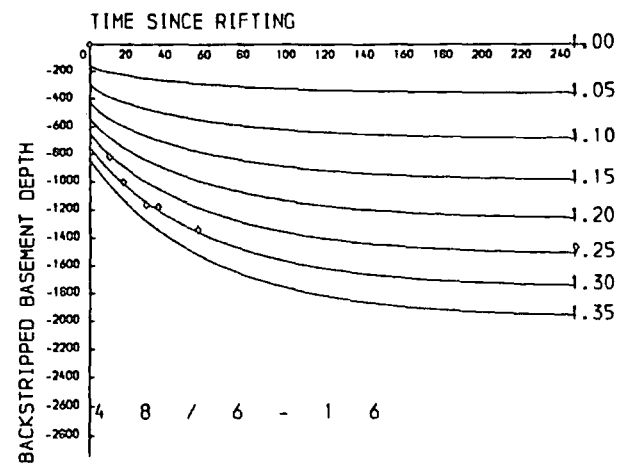
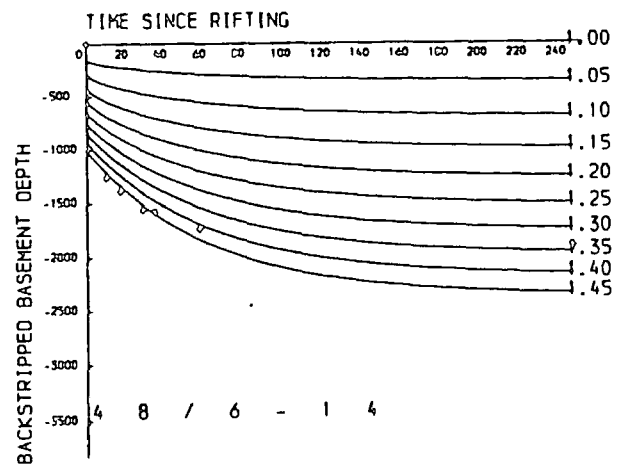
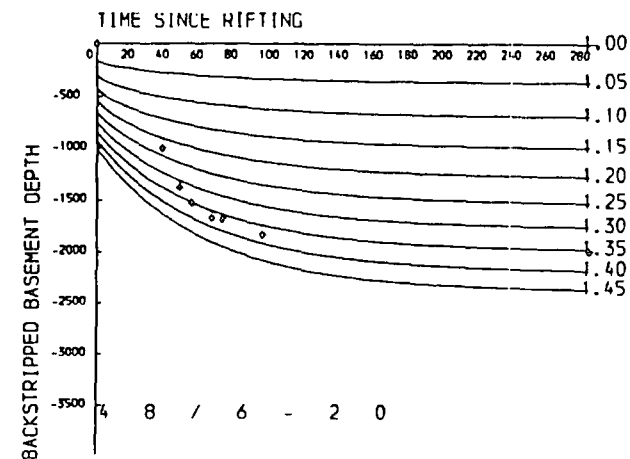
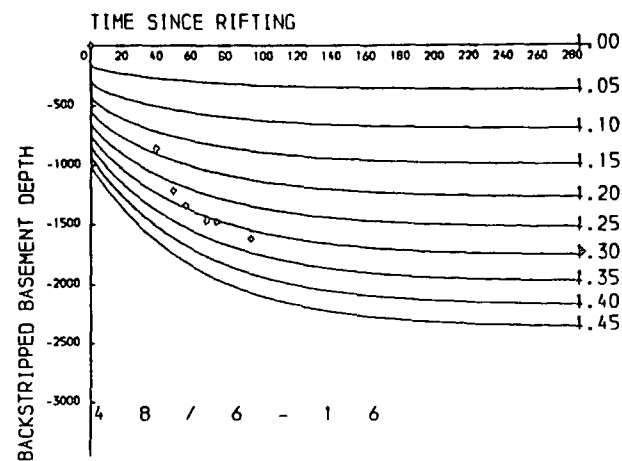
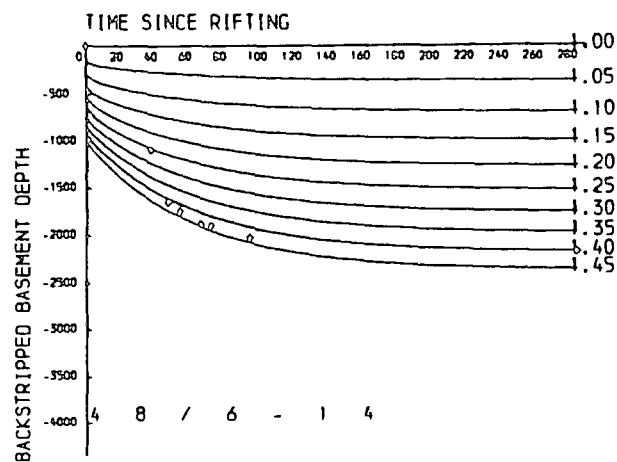


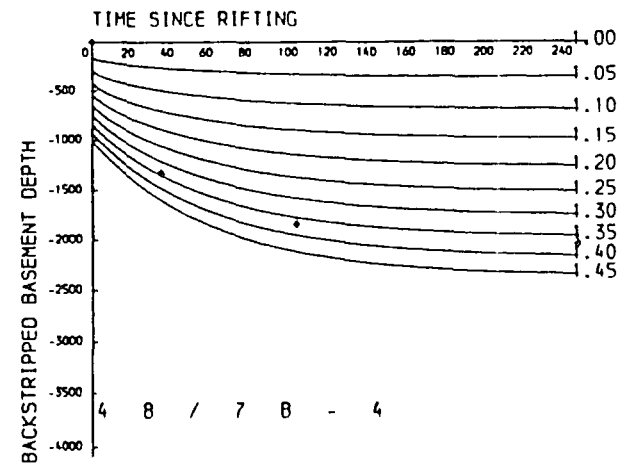
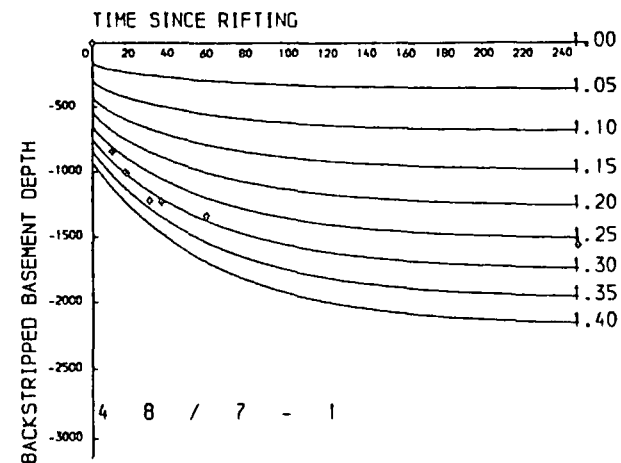
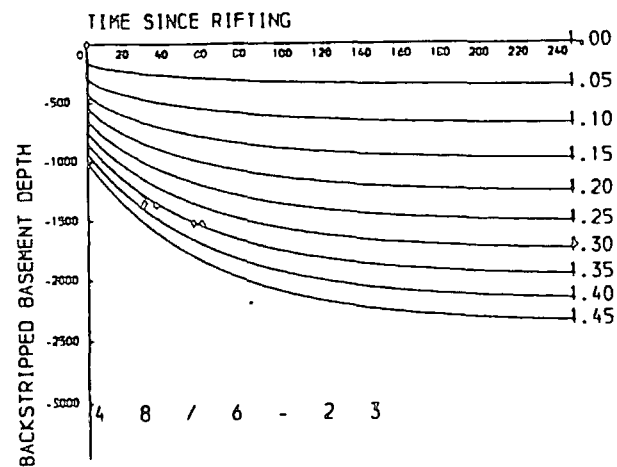
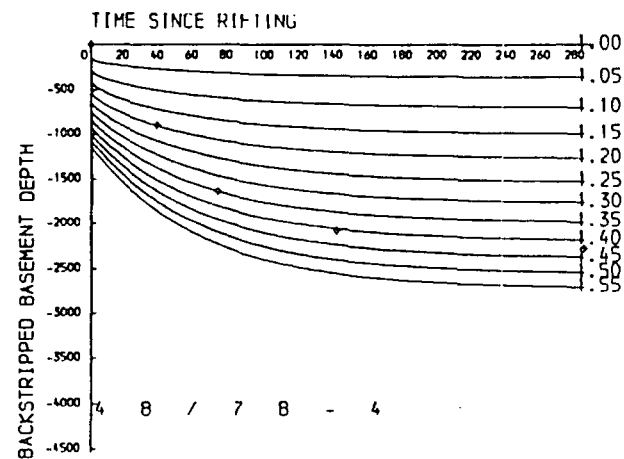
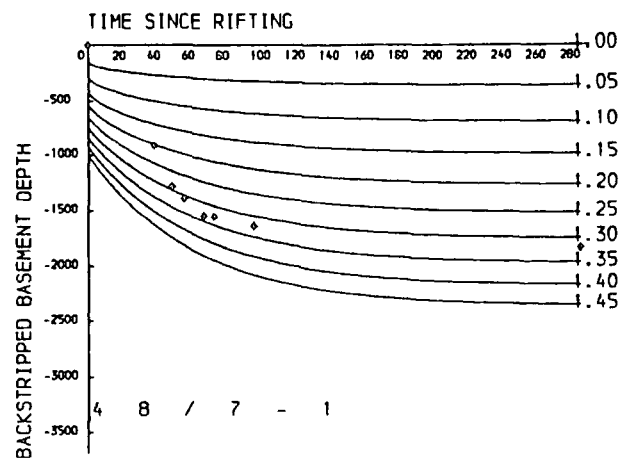
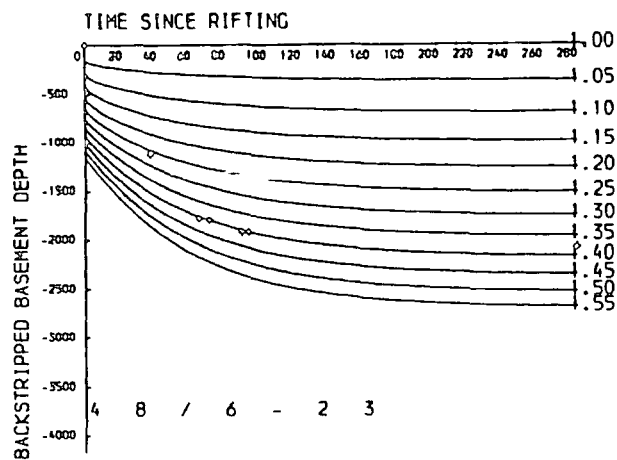


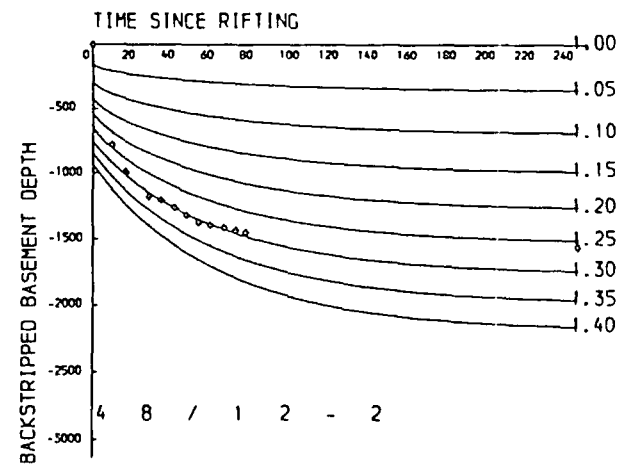
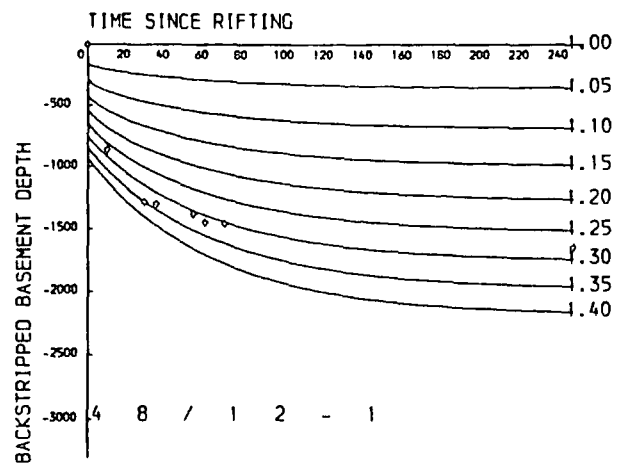
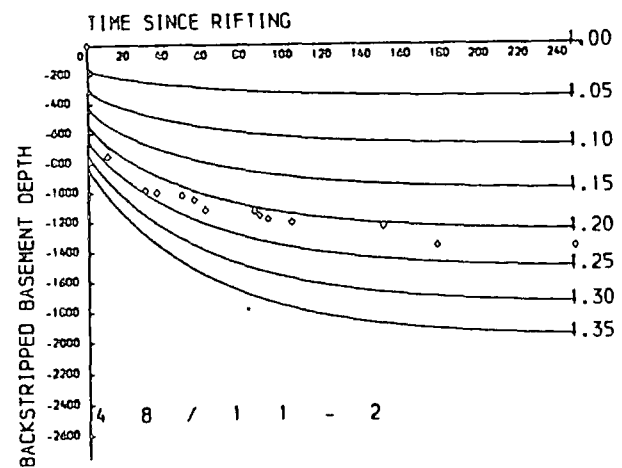
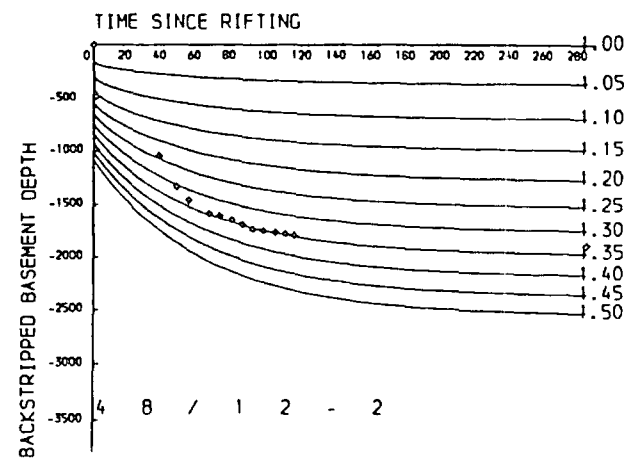
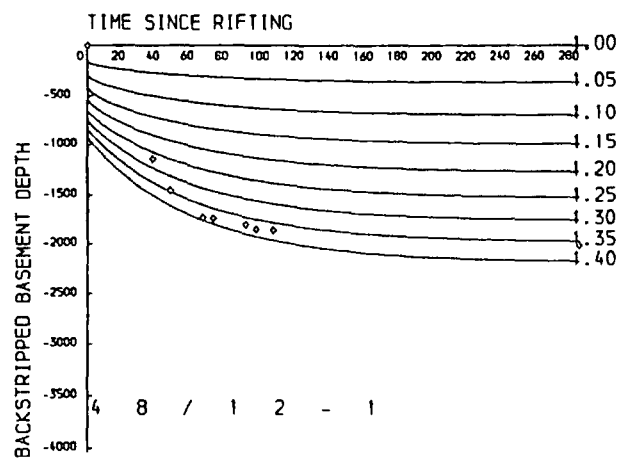
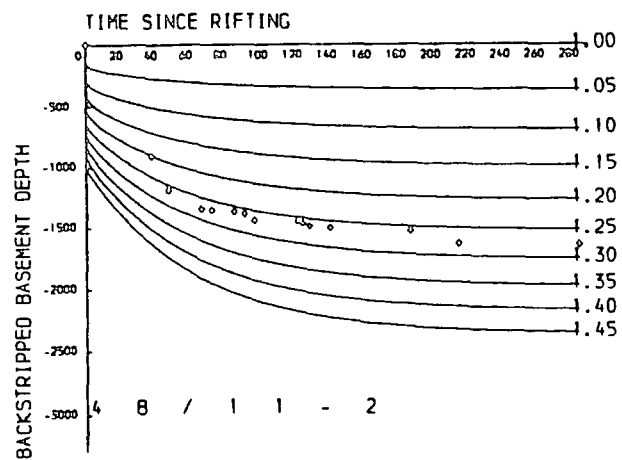


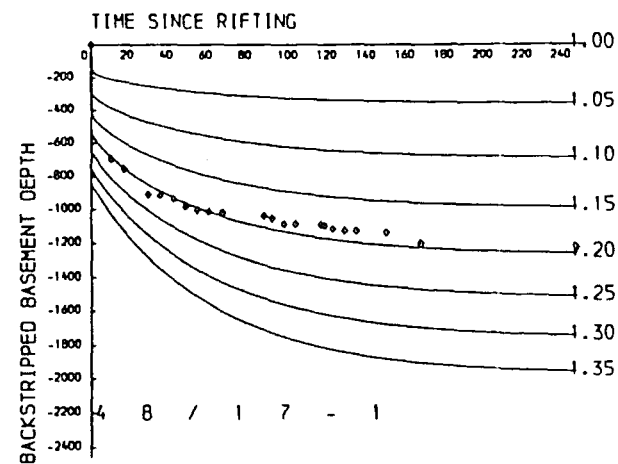
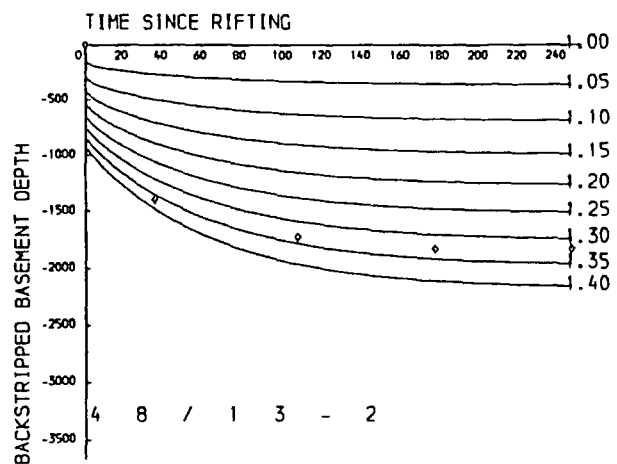
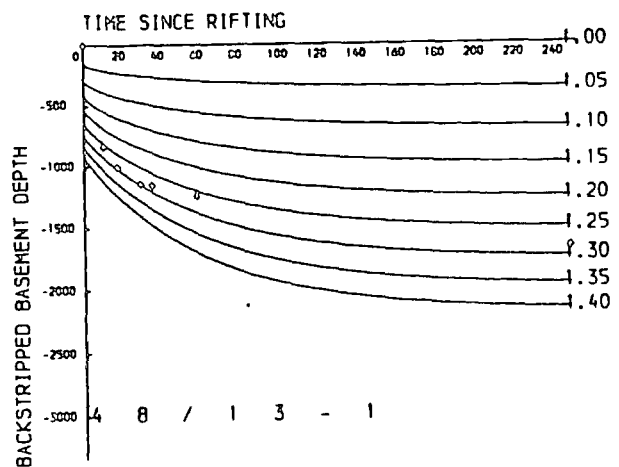
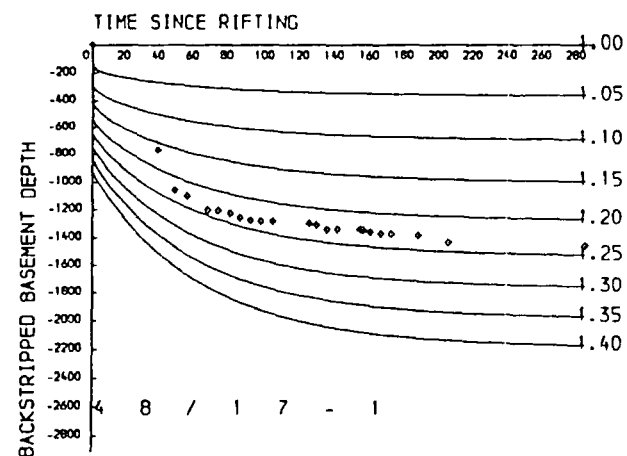
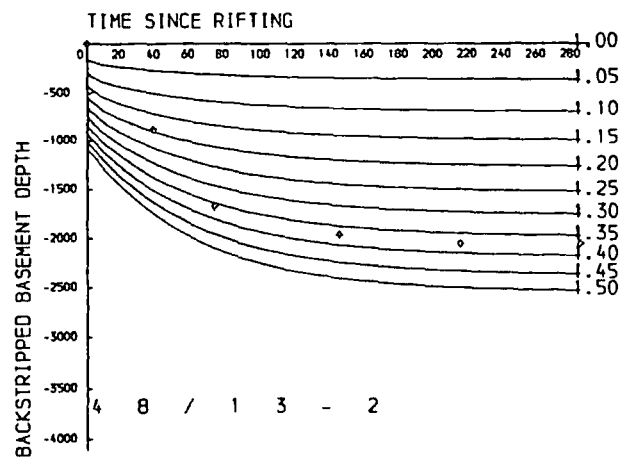
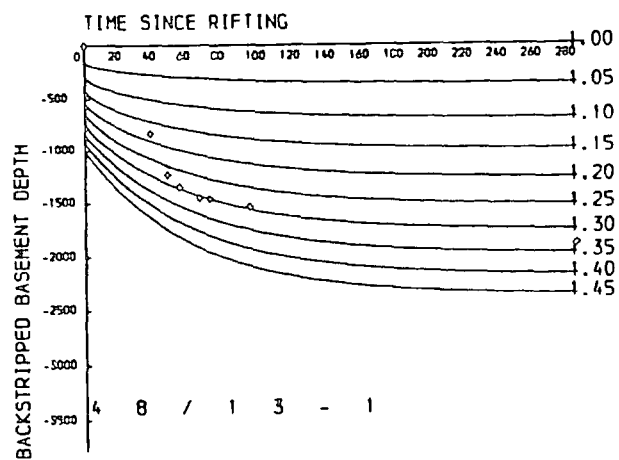


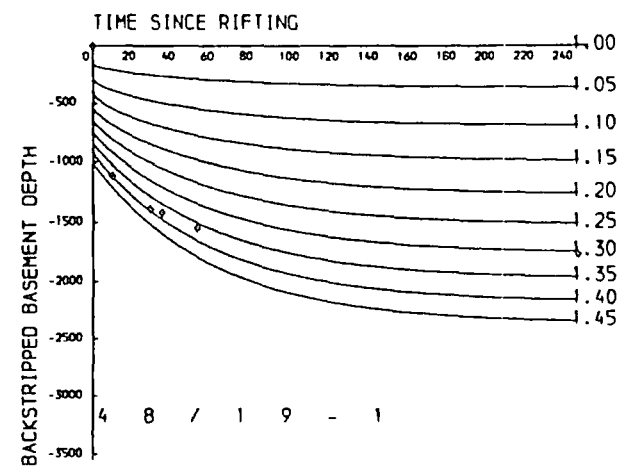
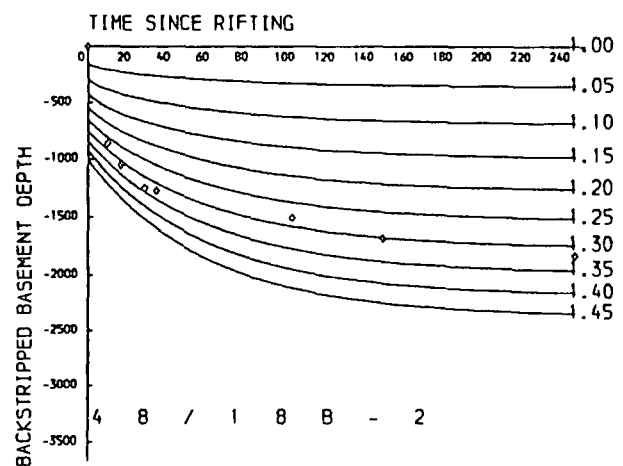
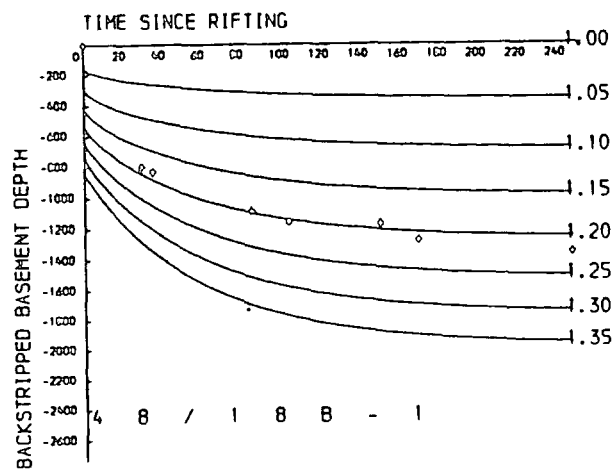
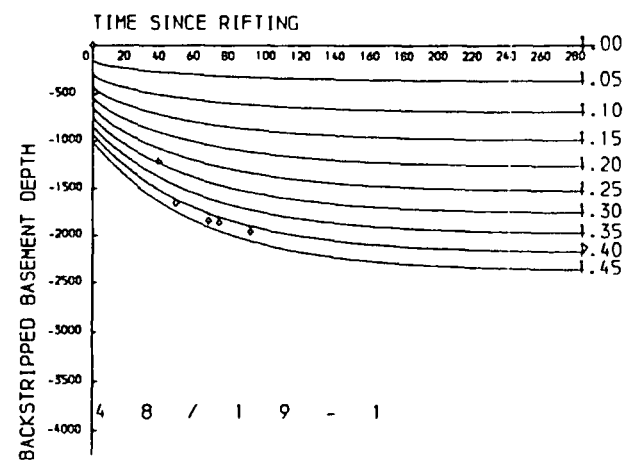
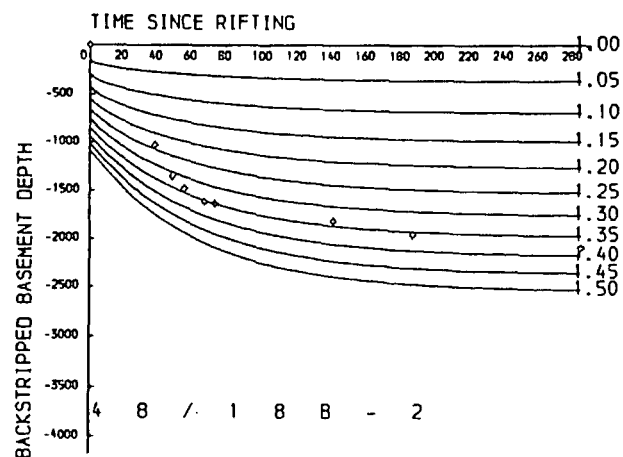
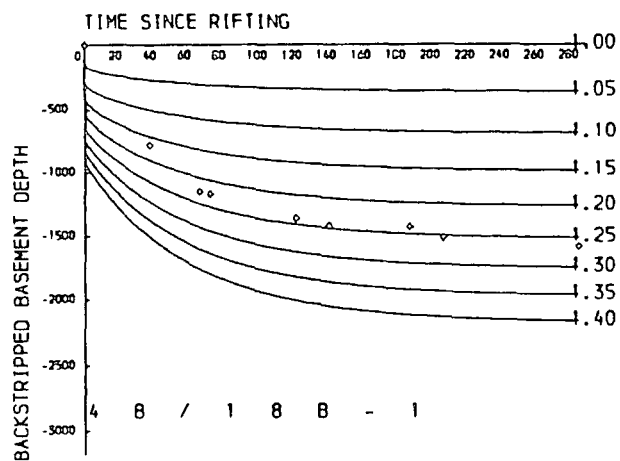


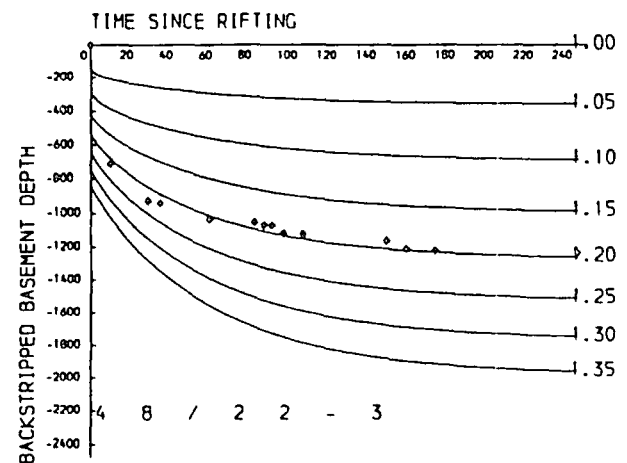
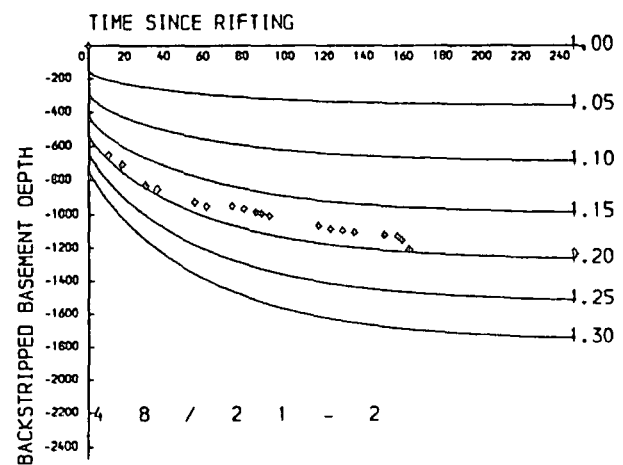
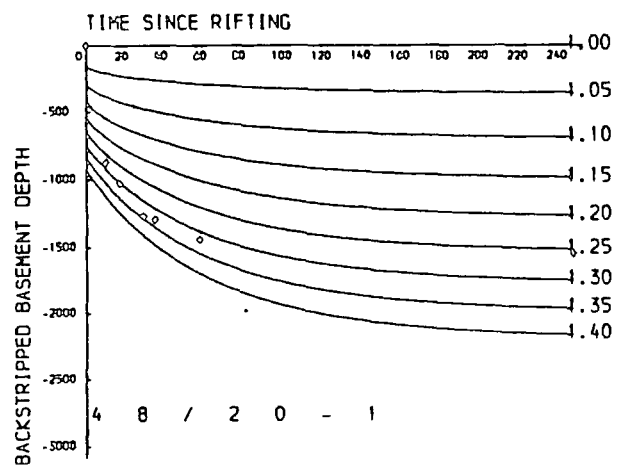
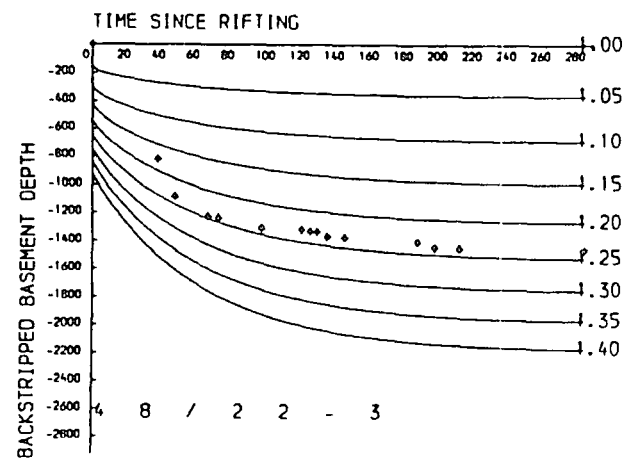
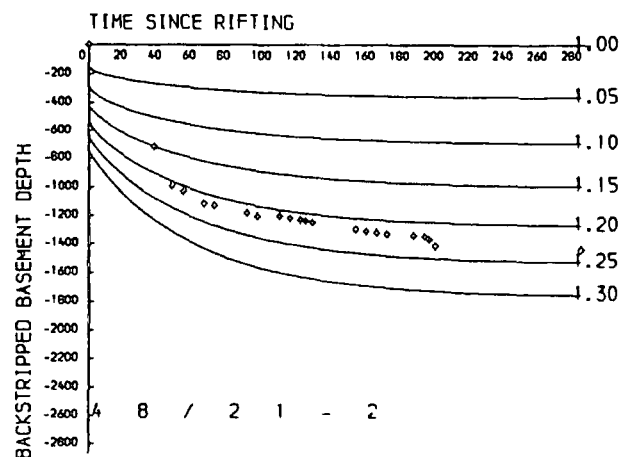
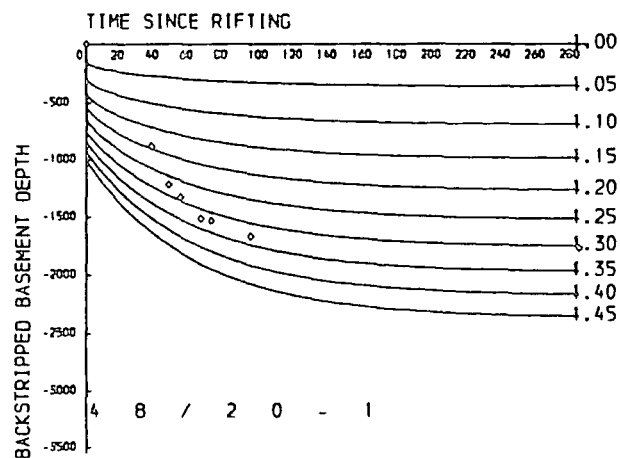


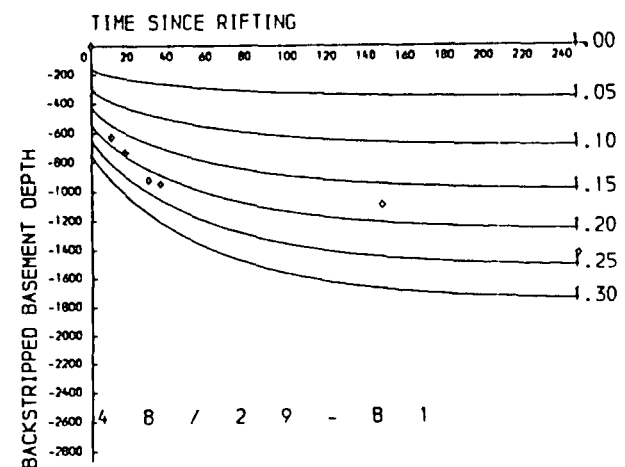
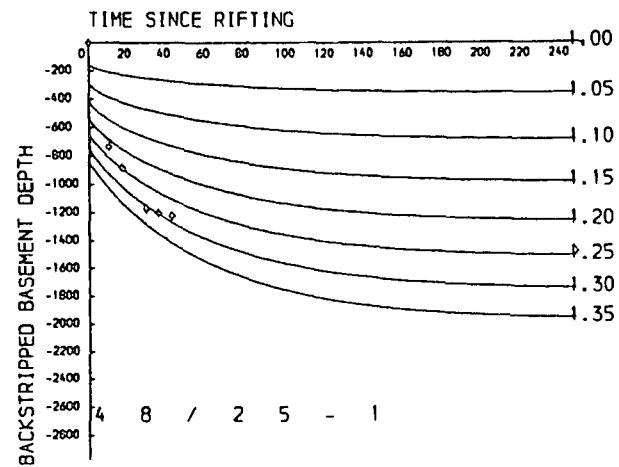
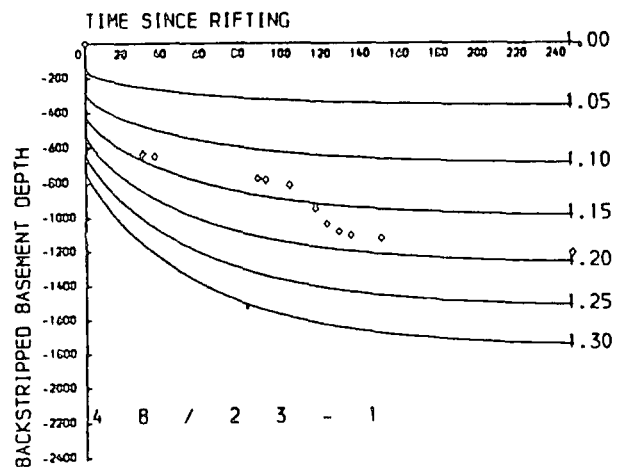
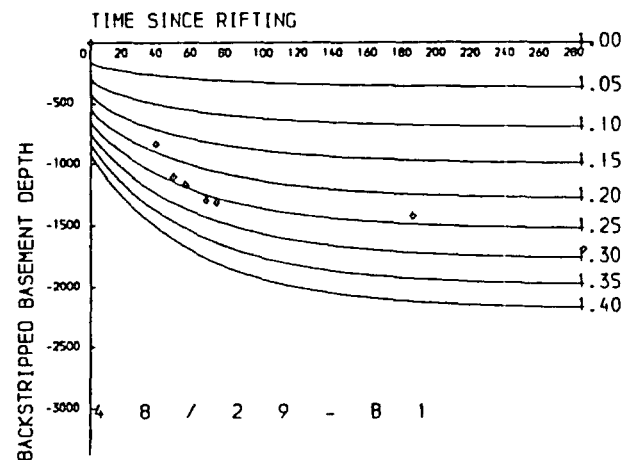
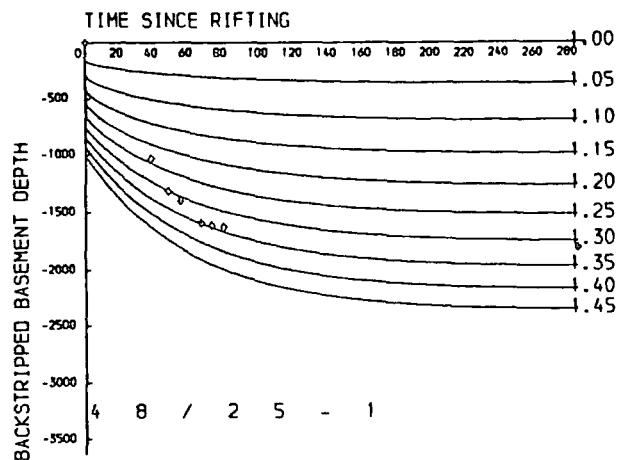
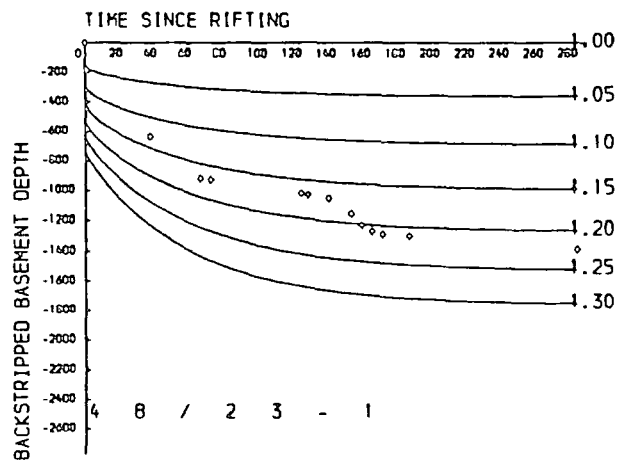


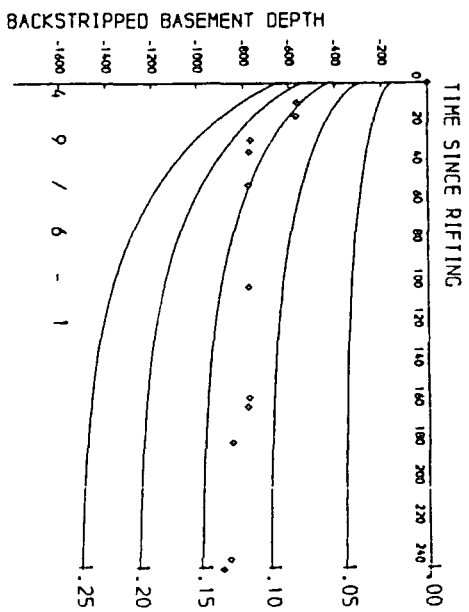
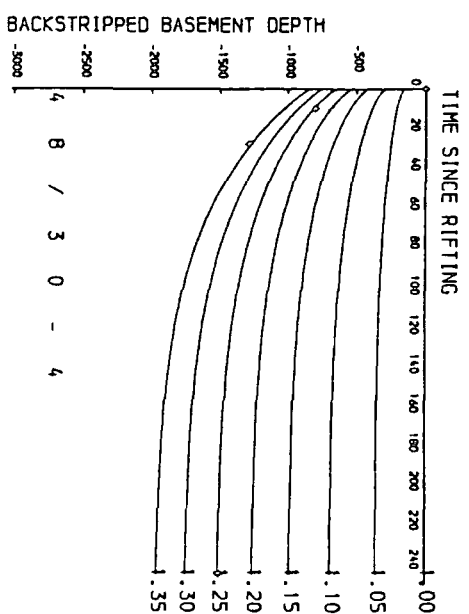
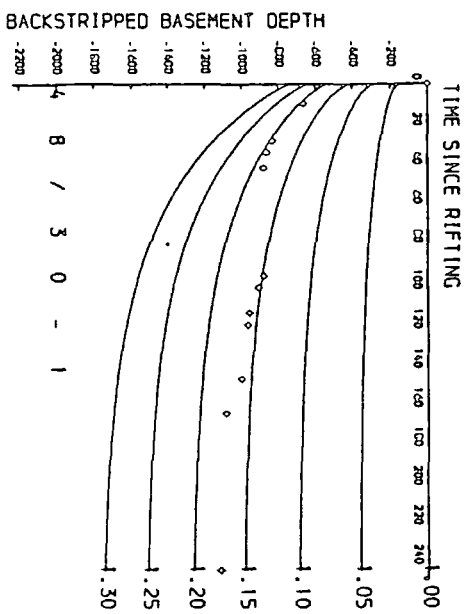
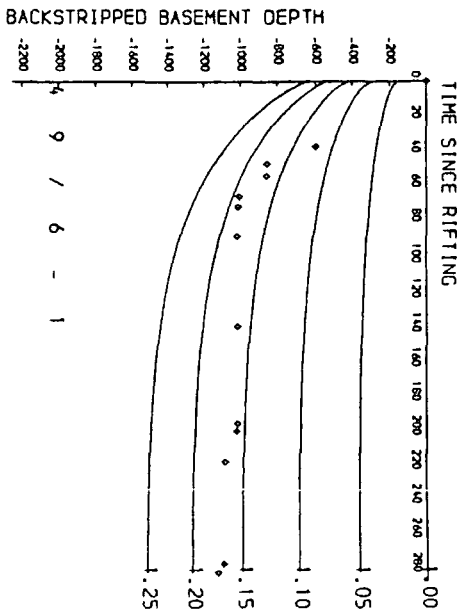
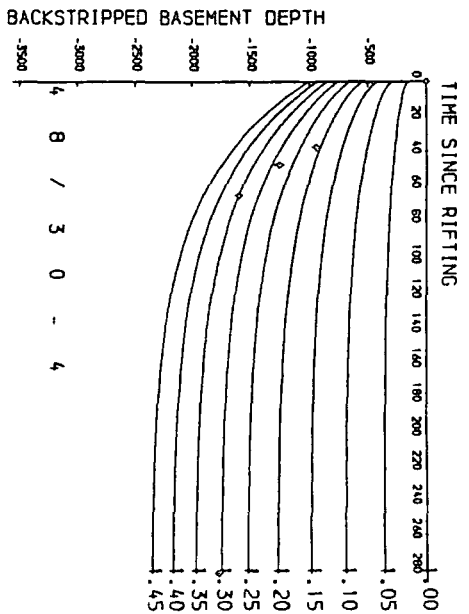
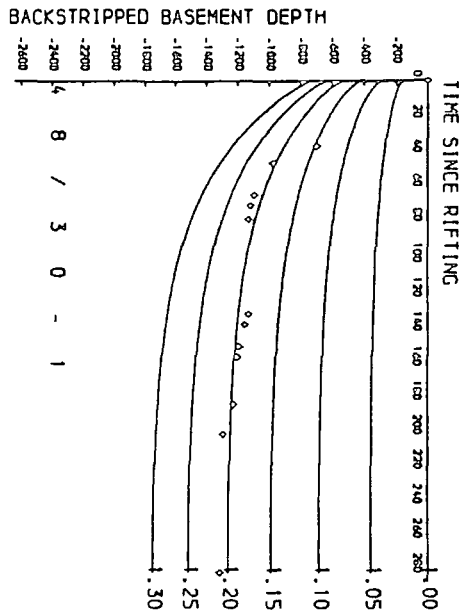


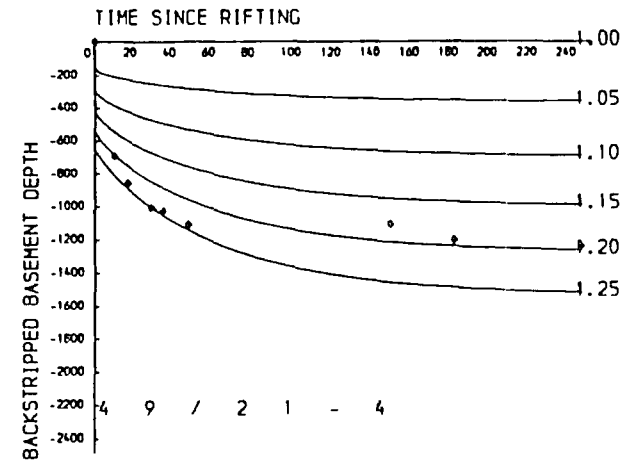
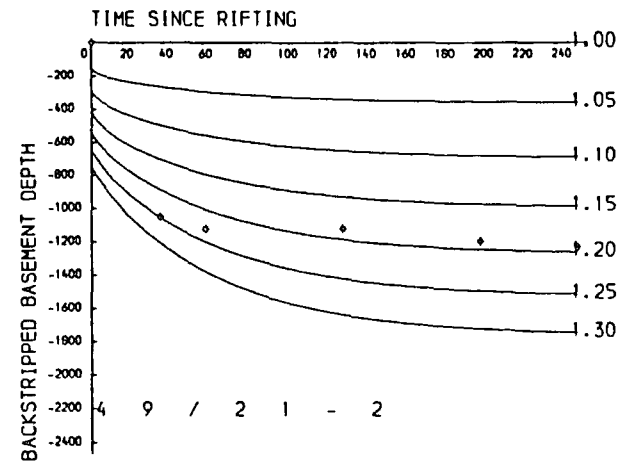
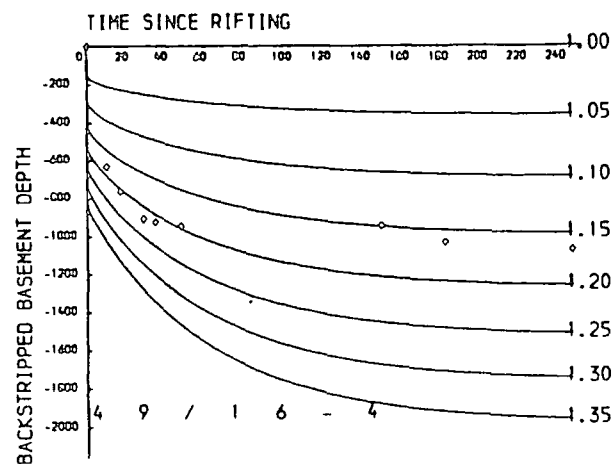
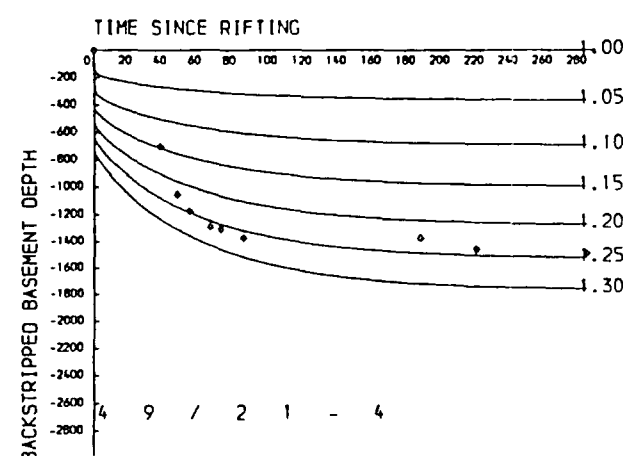
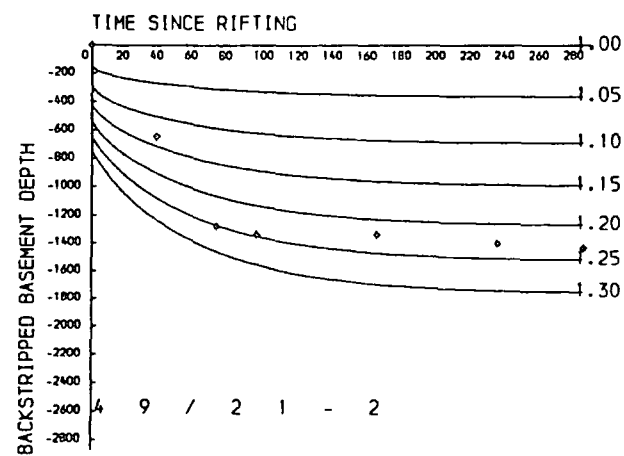
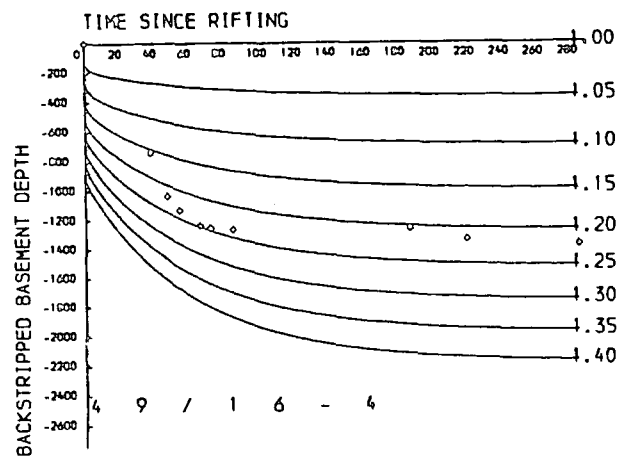


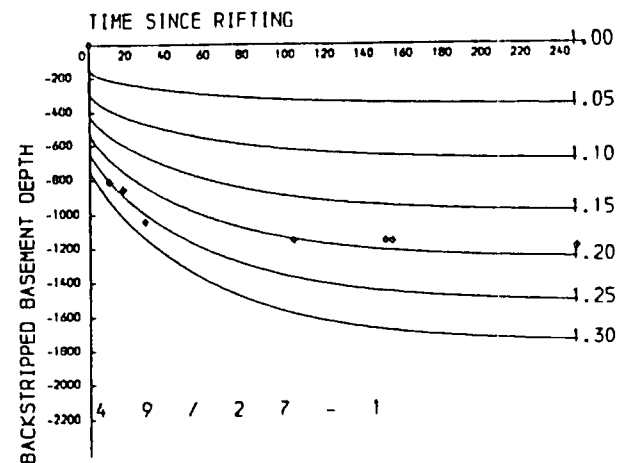
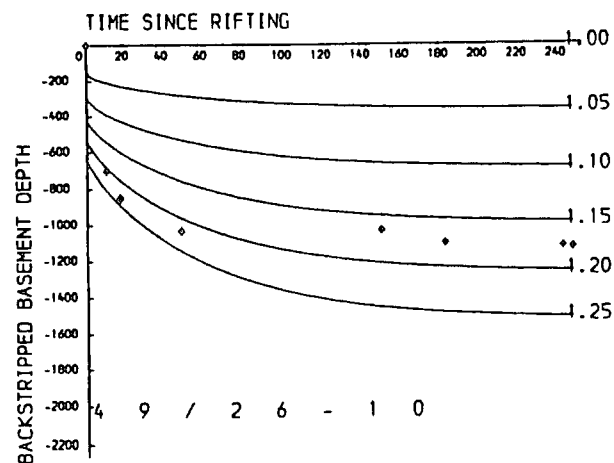
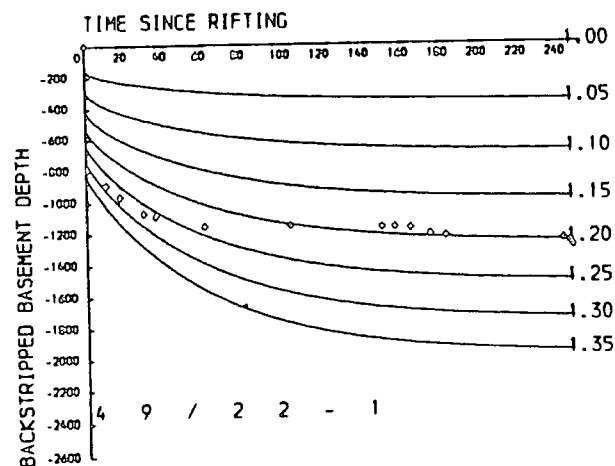
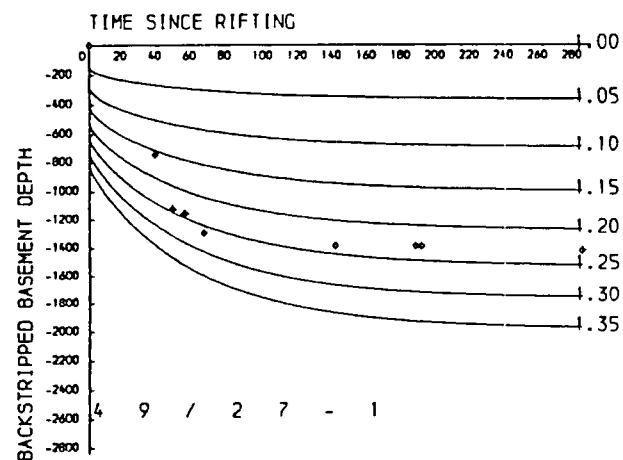
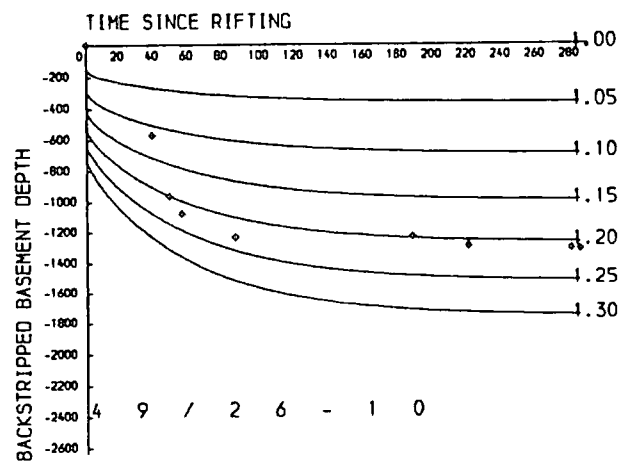
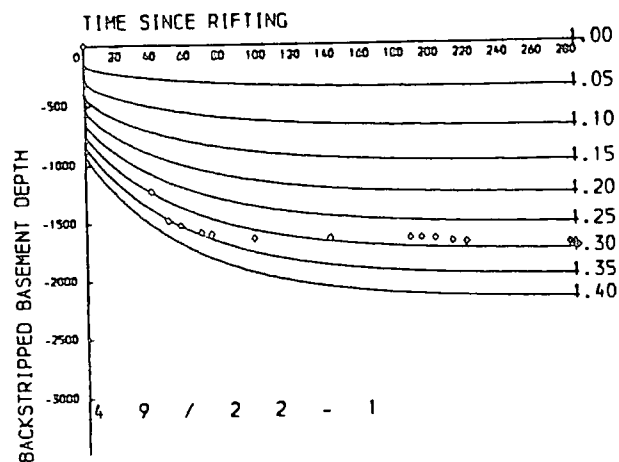


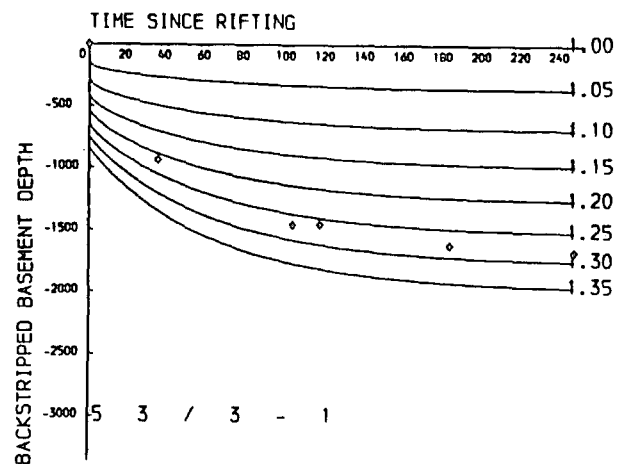
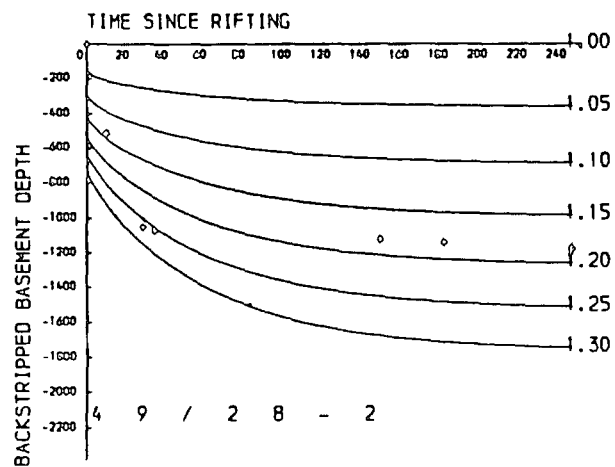
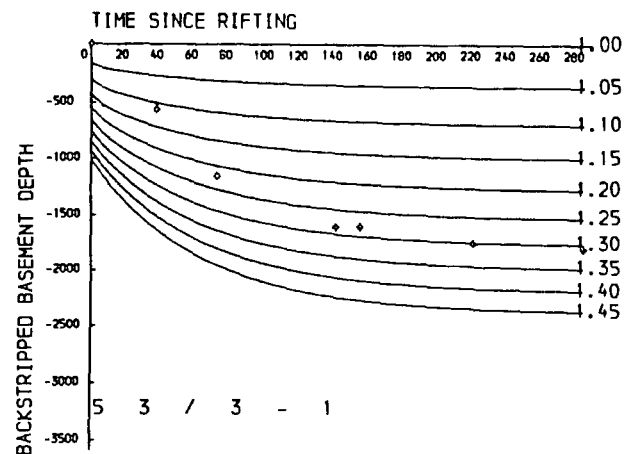
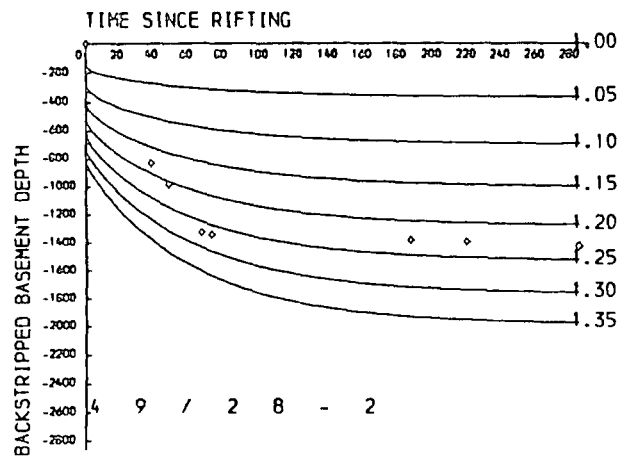












MAP 1 : BOREHOLE LOCALITY MAP

