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### *The dalradian of central Donegal: An example of polyphase mid-crustal thrusting*

Geoffrey Ian Alsop

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## ABSTRACT

The geometry and kinematic development of a major syn-metamorphic slide zone, the Central Donegal slide, is described from the Dalradian Succession of Central Donegal, Ireland. The earliest manifestation of this structure is a large scale reversal in the direction of younging and stratigraphy across the slide plane, a feature that probably developed at the lower greenschist facies of metamorphism. Kinematic indicators associated with this early deformation have been destroyed by later higher metamorphic grade overprinting, but by correlation with other early structures in Donegal, and with reference to sub-basin development in South and Central Donegal it was probably a Grampian thrust with North West directed transport. This tectonic package was then reformed at lower amphibolite facies by a kilometric scale shear zone associated with slides and large scale sheath folds. Kinematic indicators show that the sheath folds 'intrude' downwards to the south east, <sup>although</sup> originally they are regarded as having faced upwards to the south east. Following this phase of deformation the Dalradian stratigraphy of Central and South Donegal was largely uninverted and probably lay on the upper normal limb (and represents a deeper level) of the upward facing Glenelly Anticline, a major fold <sup>to the east</sup> in the Sperrin Mountains which is equated with the Tay Nappe. The zone was then reworked during another (mid-amphibolite facies) event during which large scale south facing and verging folds were formed; the Ballybofey Antiformal complex. Earlier formed sheath folds were refolded, slides reactivated and new slides formed. This phase of deformation is associated with major oblique dextral overthrusting, which with increasing metamorphic grade eventually carries the entire Dalradian cover sequence over Moine - like Proterozoic basement 30 km to the south along the Lough Derg slide. This second amphibolite facies metamorphism can be directly associated with the large scale South East directed overthrusting of the entire Dalradian stratigraphy, and related to crustal thickening and loading via the development of a nappe pile towards the south.

**THE DALRADIAN OF CENTRAL DONEGAL:  
AN EXAMPLE OF POLYPHASE  
MID-CRUSTAL THRUSTING.**

**BY**

**GEOFFREY IAN ALSOP B.Sc. (Liverpool)**

**(GRADUATE SOCIETY)**

**A thesis submitted to the University of Durham  
for the degree of Doctor of Philosophy.**

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**Department of Geological Sciences.**

**December 1987**



Algebra 101

Chapter 1

Section 1.1

Equations and Inequalities

Section 1.2

Section 1.3

Section 1.4

Thesis  
1987/ALS

## Declaration

The content of this thesis is the original work of the author and has not previously been submitted for a degree at this or any other university. Other peoples work is acknowledged by reference.

Geoffrey Ian Alsop  
Department of Geological Sciences  
University of Durham  
December 1987

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Frontispiece

“I love them, oh I love them.  
And they hold my heart in thrall.  
The heath clad hills, the cloud - capped hills.  
The hills of Donegal.”

Bridget Gallagher

(View looking North from Boultypatrick towards the Derryveagh Mountains)

## QUOTATION

“ The metamorphic rocks of Donegal and the north - west of Ireland belong to the same complex series which stretches northward into the Highlands of Scotland. They present the same difficult problems of structure, and leave, in like manner as the Scottish rocks, their true geological age still to be fixed.”

“ Much difficulty has been encountered in attempting to determine the true order of succession of these rocks, for they have been greatly plicated, fractured and inverted. Experience gained in the Geological Survey of the Highlands has shown that the apparent order may be entirely deceptive.”

ARCH. GEIKIE  
15 OCTOBER, 1890.

**CHAPTER 1**  
**INTRODUCTION,**  
**HISTORY OF PREVIOUS RESEARCH**  
**AND AIMS OF THE PRESENT STUDY.**

## CHAPTER 1

## Introduction, history of previous research and aims of the present study

The area of detailed study lies in Central Donegal, Ireland, between the three towns of Ballybofey (to the east), Fintown and Glenties (to the west) Fig. 1.1. Topographically, the area is bounded to the south by the watershed associated with the Bluestack (or Croaghgorm) Mountains, the summits of which lie at about 675 m. The western limit of mapping approximately corresponds to the watershed separating drainage to the west and directly into the Atlantic Ocean eg. Owenroe River (passing through Glenties), from that to the east and the River Foyle eg. Reelan River, River Finn Fig. 1.1. The topography of the region is dominated by the River Finn, and its major tributary the Reelan River. These two rivers separate three upland massifs, the Gaugin Mountain / Bluestack massif to the south, the Croveenananta / Boulypatrick massif in the central portion of the map, and the Three Tops massif to the north (Map 1 map box). The gross structural grain of the rocks trending NW - SE appears to only slightly influence drainage within the area. Most rock exposure is developed in the highlands in the south of the area, the northern parts having a greater cover of peat.

Geologically, the area contains a sequence of metasedimentary rocks (quartzites, psammites, pelites and limestones) belonging to the Precambrian - Cambrian Dalradian Supergroup (Harris and Pitcher 1975). These metasediments are intruded by a suite of metadolerite sheets, together with quartz diorites and felsites. The central southern portion of the mapped area is occupied by the Barnesmore Pluton, a member of the Donegal granite suite (Pitcher and Berger 1972). This adamellite body has not been mapped in detail in the present study, the contacts with the Dalradian metasediments shown on the map sheets eg. Map 1 map box, are largely based on Pitcher and Berger's review of Donegal granites (1972). The pluton appears to have no structural effects on the surrounding metasediments, the granite margins sharply cross cutting the strike

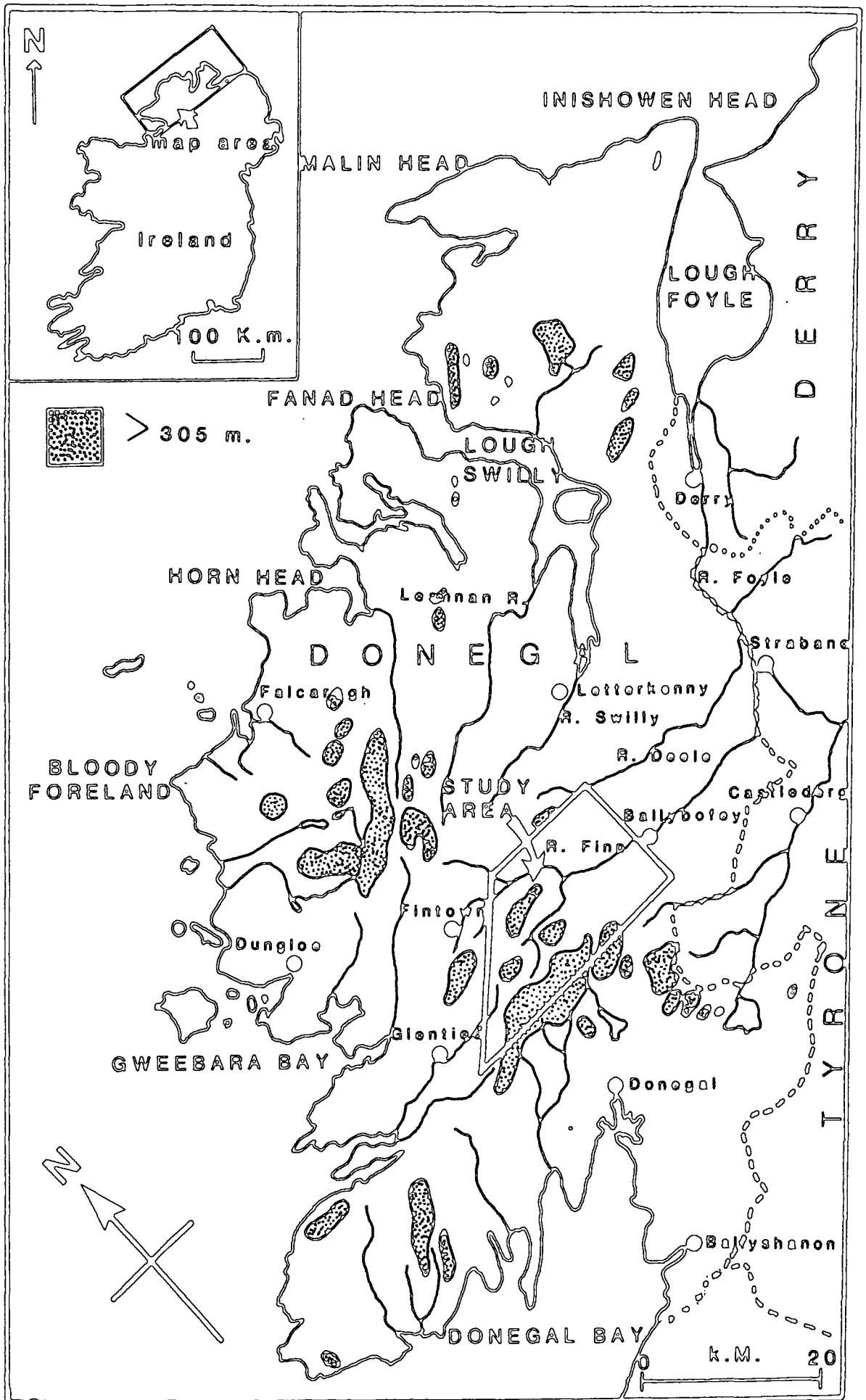


FIGURE I. I.

LOCATION MAP

of the country rocks. The thermal metamorphic effects appear limited, Smart (1962) recording a thin (less than 100m) thermal aureole. This pluton is not discussed further in the present study.

Central Donegal was first mapped by the Geological Survey in the late nineteenth century (Kilroe and Nolan 1891). A section from the memoir accompanying this mapping is shown in Fig 1.2. To date, this is the only published detailed cross section through Central Donegal. The western portion of the area was mapped by Pitcher et al. (1964), during their regional synthesis of the Leannan Fault system, and also by Cambray in his Ph.D. studies (1964). Ground to the south of the present area in southern Donegal and western Tyrone was mapped by Wood as part of his Ph.D. studies (1970). The most recent publications on the area are Pitcher, Shackleton and Wood (1971) and Pitcher and Berger (1972),\* The Dalradian stratigraphy described within these most recent papers for Central and South Donegal is as follows:

#### STRATIGRAPHIC TOP

Croaghgarrow Formation  
 Shanaghy Green beds  
 Mullyfa Formation  
 Aghyaran Formation  
 Killeter Quartzite  
 Termon Pelite / Lough Eske Psammite  
 Boulypatrick Grits  
 Croaghbrid Pelite  
 Gaugin Quartzite  
 Port Askaig Tillite  
 Owengarve Formation

#### STRATIGRAPHIC BASE

\* which provided the stratigraphic map which has been the basis of the present study (see Figure 1.3).

*Section going S 36° E over Gaugin Mountain and Brown's Hill.*

NW

SE

*Western flank of  
Boultypatrick.*

*Roelán River.*

*Gaugin Mountain*


*Owengarve River.*

*Owendoo River*

*Cronamuck River*

*Brown's Hill*



 Quartzite

 Schists

 Granite

 Basalt dykes

1 km

Cross section through Central Donegal  
(from Kilroe and Nolan 1891)

In Central Donegal early isoclinal folds cored by Appin Group Dalradian were thought to be of D1 generation, and of uncertain relationship to the Tay nappe (Pitcher, Shackleton and Wood 1971). According to these authors, these folds were refolded by the D2 Ballybofey Antiform, producing an inverted stratigraphic sequence south of its axial trace. Thus, rocks high within the Dalradian sequence were regarded as occurring at the lowest structural level, and eventually came into contact along a tectonic slide (the Lough Derg slide) with the supposedly Moinian psammites. Figure 1.3 represents a map of Central and South Donegal from Pitcher, Shackleton and Wood (1971), and shows the major Dalradian structures and stratigraphy described above. The present area of detailed study is concerned with the central and southern portions of this map (Figure 1.3) and is shown in Figure 1.4.

The most recent correlation of Dalradian stratigraphy throughout the British Isles is by Harris and Pitcher (1975). They have placed the Dalradian succession of Central Donegal in the Blair Atholl subgroup (Appin Group), and the Islay, Easdale, Crinan subgroups of the Argyll Group.

There were a number of aims embodied in the present study. A major objective was to ascertain the origin, nature and kinematic significance of Pitcher, Shackleton and Woods D1 fold in Central Donegal (Chapter 3). Also its relationship with, and the kinematics of the refolding by their D2 Ballybofey Antiform (Chapter 4). A third aim was to examine the basin opening extensional history of the Dalradian, via observations of thickness and facies variations, together with gross stratigraphic considerations and correlations (Chapters 2 and 6). A final objective was to study the nature of orthogonal refolding by 'late', North - South trending folds of regional significance (Chapter 5).

Thus, this project has been undertaken on a structural / stratigraphic 'field' oriented basis. Mapping of the area (approximately 200 km<sup>2</sup>) took place over 17 months during 1984-87, and involved the collection and analysis of over 22,000

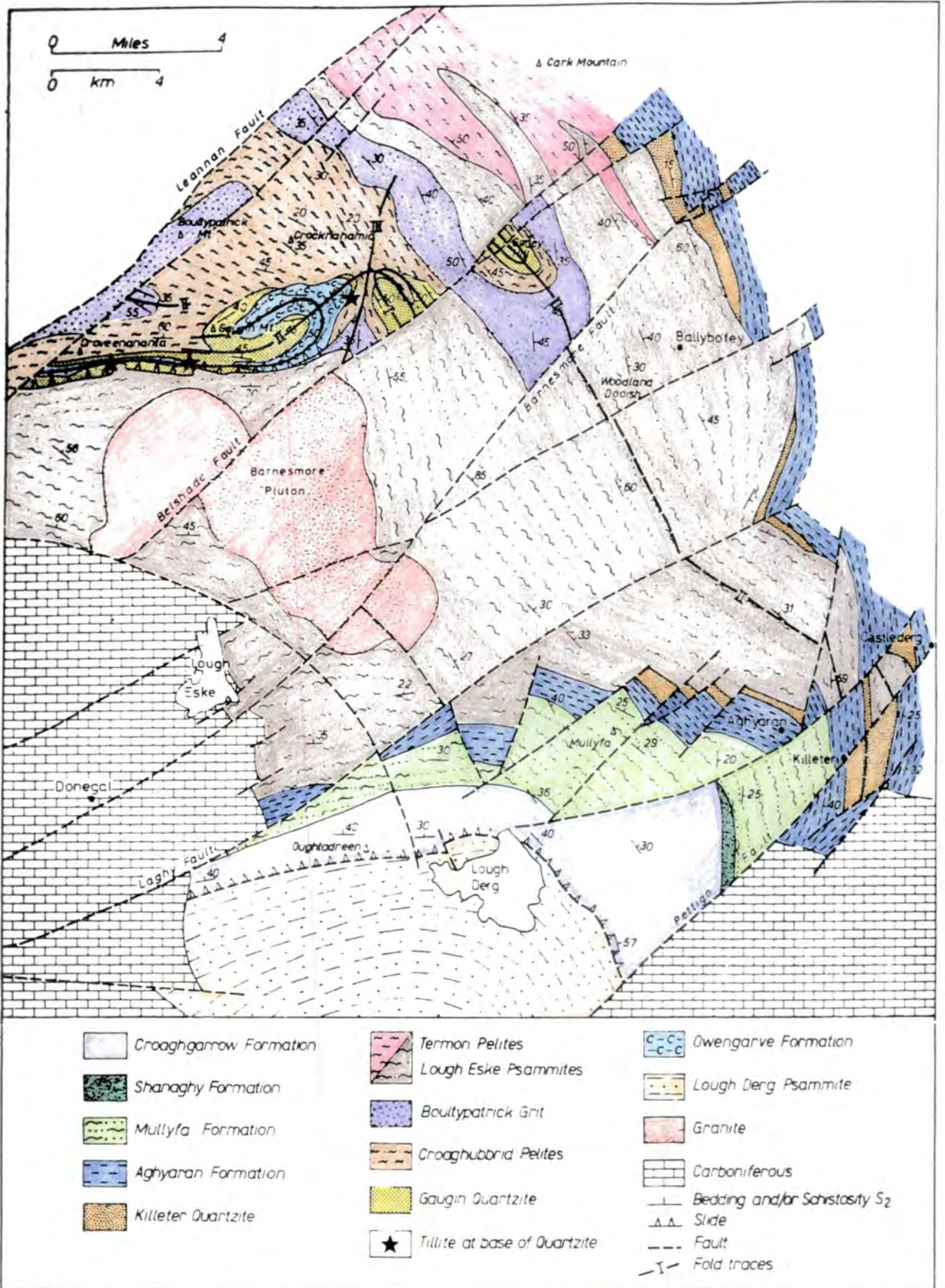


FIGURE I.3.  
GEOLOGICAL MAP  
FROM PITCHER,  
SHACKLETON AND  
WOOD (1971)

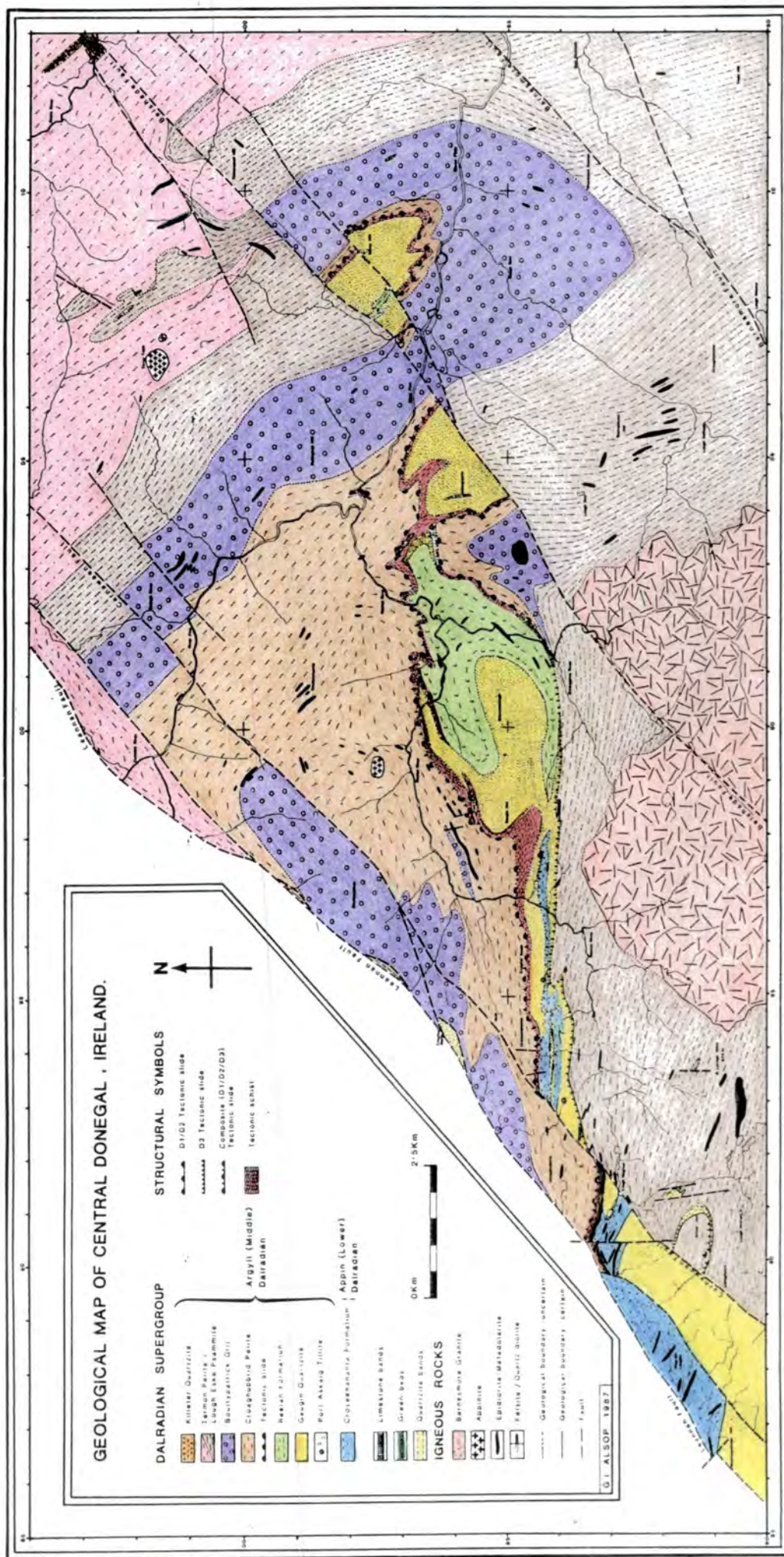


FIGURE I.4.

structural measurements from 6,500 localities. Base sheets used for the exercise are at a scale of 6 inches to 1 mile, the following Ordnance Survey sheet numbers being used for detailed mapping: sheets 67, 68, 75, 76, 77 and 84 (second edition 1906). Synoptic map sheets of the various deformation phases are produced at a scale of 1 : 25,000 and included in Volume 2 (map box). The Irish grid is divided into lettered squares with 100 km sides. The mapped area includes portions of squares B, C, G and H. Grid references are given with the appropriate letter preceding the six figure coordinates. The mapped area was divided into three basic sub-areas, a deformation phase being described from all three sub-areas prior to a synopsis. The same procedure is then followed for the next deformation (Chapter 5). A map showing the position of the various structural domains is shown in Figure 1.5. A regional overview relating to correlations of structure, stratigraphy and metamorphism for Donegal and the Sperrin Mountains of County Tyrone is given in Chapter 6. Chapter 7 gives a brief summary of the major conclusions of this work.

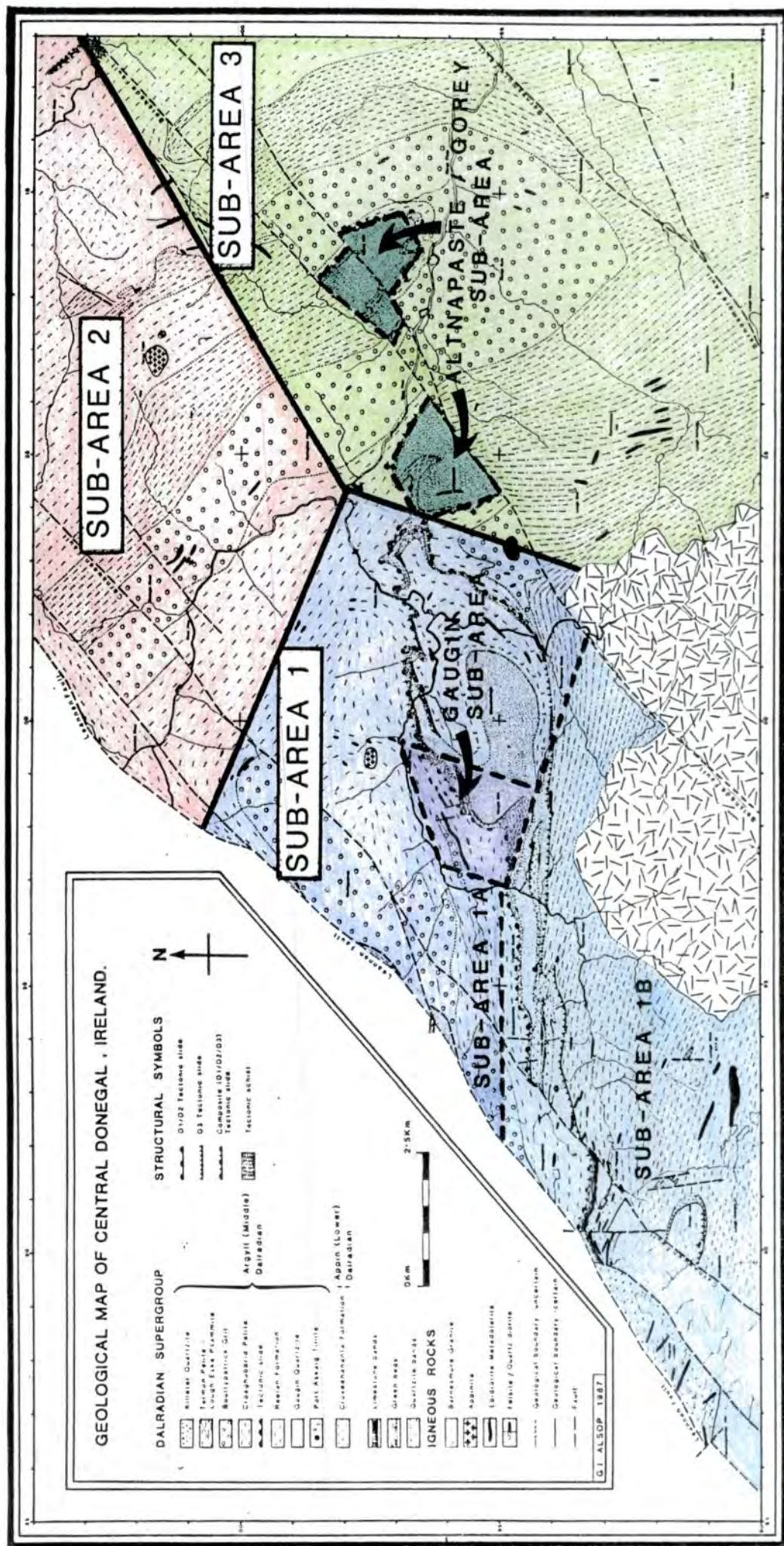


FIGURE I.5.  
 SUB-AREA MAP  
 SHOWING STRUCTURAL  
 DOMAINS

**CHAPTER 2**  
**DALRADIAN STRATIGRAPHY**  
**AND SEDIMENTOLOGY.**

## CHAPTER 2

## DALRADIAN STRATIGRAPHY AND SEDIMENTOLOGY

## 2.1) Introduction

The Dalradian stratigraphy of the study area has for convenience been divided into two successions. These successions are separated by a major tectonic dislocation, the Central Donegal slide (see 3.2). This tectonic slide everywhere separates the two stratigraphic packages which ubiquitously young away from the slide zone. All stratigraphic thicknesses given are post-tectonic approximations. Tectonic package A (containing the Port Askaig Tillite Formation) is regarded as being the older of the two sequences, and comprises the following formations.

## 2.2) Tectonic Package A.

## 2.2a) Croveenananta Formation

The Croveenananta Formation are the oldest Dalradian rocks observed in the present study. They are confined to the core of a D2 fold (see 3.3b) in the south western portion of the mapped area (Map 1 -map box). The base of the formation is nowhere exposed, so the thickness variation of approximately 1.5 Km. adjacent to the Leannan Fault, reducing to approximately 150m on Croveenananta (G 943943) are obviously minimums. The formation is best exposed in the townland of Croaghubrid (G 935937), where a highly attenuated sequence of pelites (some calcareous), psammites, quartzites and dolomitic limestones can be seen. The pelites of the formation weather to a grey-brown (occasionally green), attract patches of thin white lichen and generally contain quartz segregations parallel to the main fabric of the rock. They tend to be found in slightly lower lying bog-covered ground and may contain more psammitic bands (less than 5 cm thick) which aid in the definition of bedding. Pyrite cubes (up to 5 mm) are common, with large chlorite and biotite crystals (up to 4mm) also occurring. In addition muscovite, albite, opaques as well as quartz

are visible in thin section.

Psammitic rocks in the formation are found in close association with the pelites with interbanding on a small scale (less than 30 cm) being common. The psammite weathers to a dark grey with a greenish tinge and contains quartz segregations as well as occasional detrital feldspar grains. More quartzitic bands up to 40 cm in width have been noted from within the psammites.

Quartzite members up to 25m thick commonly produce small ridges supporting longer grasses than the adjacent psammites and pelites. The pure, white orthoquartzite attracts patches of thin brown lichen and is commonly well jointed at right angles to bedding. In general the quartzite is thinly bedded (less than 20 cm), with dark heavy mineral bands (less than 1 mm) aiding in the definition of trough cross lamination (Plates 1a. and 2b.). Quartzite may be interbanded on a 50 cm scale with the pelites previously described.

Dolomitic limestone is most commonly developed adjacent to the quartzite members (G 940943). The units are generally less than 10m. thick, but can attain thicknesses of 20m. adjacent to the Leannan Fault (G 899929). It is generally buff weathering with outcrops of upstanding blocks supporting a slightly more lush vegetation. Pale blue pure limestone members, up to 25m. thick with bedding at 30 cm intervals are more commonly developed adjacent to the Leannan Fault at the Magrath Loughs (G 873916). Tracing of such calcareous members along strike is hindered by poor exposure. This association of pelites (some calcareous), psammites, quartzites and limestones young towards and passes via sedimentary transition into the Port Askaig Tillite Formation.

### 2.2b) Port Askaig Tillite Formation

This most important of Dalradian marker horizons ( Kilburn et al. 1965 , Spencer, 1971.) has been identified at a number of localities in the present area of study (Map 1, map box). In Central Donegal the formation has been strongly deformed and attenuated due to tectonic sliding and it occurs as a

zone of tectonic lenses each no more than 20 m long (see 3.3f). Despite the degree of deformation and paucity of exposure, the localities shown on Map 1 (map box) are undoubtedly representatives of the Port Askaig Tillite Formation in Central Donegal. Representatives of the lower more calcareous tillite (Howarth et al., 1966) are found as loose blocks at Priestown (H 028964). They contain recrystallised calcite clasts up to 10 cm long, in a calcareous pelite matrix. The more common form of tillite in central Donegal is that of the upper more psammitic type (op. cit.).

In areas of lower strain such as the hinge of the Ballybofey Antiform (H 037965) (see 4.1), this formation is represented by well bedded (approximately 25 cm intervals) pale green psammitic rocks with thinner (less than 5 cm) pelitic interbeds. The tillite in this state may give rise to rounded hillocks supporting slightly more lush vegetation and gorse. There are few joints and lichen is relatively sparse. The psammite contains green/brown biotite in abundance, together with quartz, opaques and detrital feldspar fragments. In the psammite units clasts of leucogranite (quartz, K-feldspar, biotite, muscovite) up to 50 cm (but more commonly less than 3 cm) are observed (Plates 1b., 21a., 35b.). Granite pebbles tend to be flattened in the plane of the main fabric (see 3.3f). Such clasts become extremely deformed adjacent to the Central Donegal slide, and are best observed in areas where vegetation has recently been removed. Pockets of tillite with leucogranite up to 10 cm in length have been found in the lower 100 m of the overlying Gaugin Quartzite (G 930939).

### 2.2c) Gaugin Quartzite

The Gaugin Quartzite is a well exposed unit forming the central upland portion of the mapped area. The thickness variation is extreme, outcropping over a width of 8.75 km. to the west of the Carnaween Fault, whilst in some of the central portions of the map it is totally absent (Map 1 -map box). The Gaugin Quartzite can be traced as far south as Binbane (G 848870) beyond the south west corner of the mapped area, where it is in tectonic contact with the

Lough Eske Psammities (see 4.5).

The Gaugin Quartzite is typically a massively bedded orthoquartzite, with jointing orthogonal to bedding and a tendency to attract a thin brown lichen. Flat surfaces formerly covered by acidic peat are bleached white and present an opportunity to study trough cross bedding (Plates 2a., 3a., 3b., 4b.). In all cases such structures suggest younging away from the Port Askaig Tillite Formation, and towards the overlying Reelan Formation. Cross bedding appears to be more common towards the stratigraphic top of the quartzite. Coarse graded beds approximately 20 cm thick and containing feldspar grains up to 5 mm in diameter are observed in the lower portions of the quartzite (H 043958) (Plate 4a.). Grading is in agreement with the younging direction suggested by cross bedding.

The Gaugin Quartzite passes via a 10 m thick sedimentary transition in to the overlying Reelan Formation. Within this transition the quartzite contains 1 cm thick pelitic partings every 10 cm, the pelitic content increasing towards the Reelan Formation until eventually only thin (less than 5 cm) sugary quartzite bands remain. There is clearly no major depositional break at this juncture, the transition being best exposed on the southern side of Slievemullagh (H 007944).

#### 2.2d) Reelan Formation

The calcareous pelites, limestones, psammities and quartzites of the Reelan Formation are the youngest rocks observed in tectonic package A. The major exposure of these rocks is in the core of a D2 fold (see 3.3e.) in the central portion of the map (see Map 1 -map box). The base of the formation is clearly a transition (see 2.2c), whilst the top has since been eroded. The thickness estimate of 750 m is thus a minimum. The Reelan Formation is best exposed to the South of Slievemullagh (H 008943), and in the Owengarve and Reelan rivers. The formation tends to form low-lying poorly exposed ground covered with lush vegetation. Indeed the position of the formation on Altnapaste (H 042958) is

clearly marked by a topographic hollow with greener vegetation.

The Reelan Formation calcareous pelites are commonly pale green, contain large chlorite crystals (up to 3mm) with quartz, calcite and biotite as well as opaques. Occasionally within more psammitic bands adjacent to the Gaugin Quartzite, rounded quartz grains up to 2 mm in diameter have been identified (H 014945). Thin orthoquartzite bands (less than 25 cm) tend to be found within 100 m of the contact with the Gaugin Quartzite, as do pelites containing albite porphyroblasts.\* Beds of impure limestone up to 20 m in width and traceable for 500 m are found at distances greater than 100 m from the Gaugin Quartzite. This pale cream limestone is largely composed of calcite, with bands of muscovite and quartz standing proud on weathered surfaces and defining the main fabric of the rock. Typical aspects of calcareous weathering are shown, with hollows up to 15 cm in length and jagged edges being common. Rounded, matrix-supported clasts of recrystallised pink calcite up to 5 cm in length, together with dolomitic clasts of similar dimensions are wrapped by the main fabric. They represent original detrital carbonate material (H005964) (Plates 5a., 5b.). Such clastic carbonates appear to be restricted to the upper portions of the exposed Reelan Formation.

The Reelan Formation is in all cases bounded by the Gaugin Quartzite or tectonic sliding, the effect of which will be described in 3.3e. Overall stratigraphic relationships of tectonic package A are summarised on a sedimentary log (Fig. 2.1.).

### 2.3) Tectonic package B.

Tectonic package B has been brought in to juxtaposition with tectonic package A along the dislocation named the Central Donegal slide (see 3.2). Nowhere are beds of the two tectonic packages found interbedded.

\* The quartzite bands are not as thick as those developed in the Croveenanba Fm. (quartzite units up to 30m thick), the Reelan Formation and the Croveenanba Formation originally thought to be equivalent by Pitcher, Shackleton and Wood (1971).

Hypothetical sedimentary log through tectonic package A

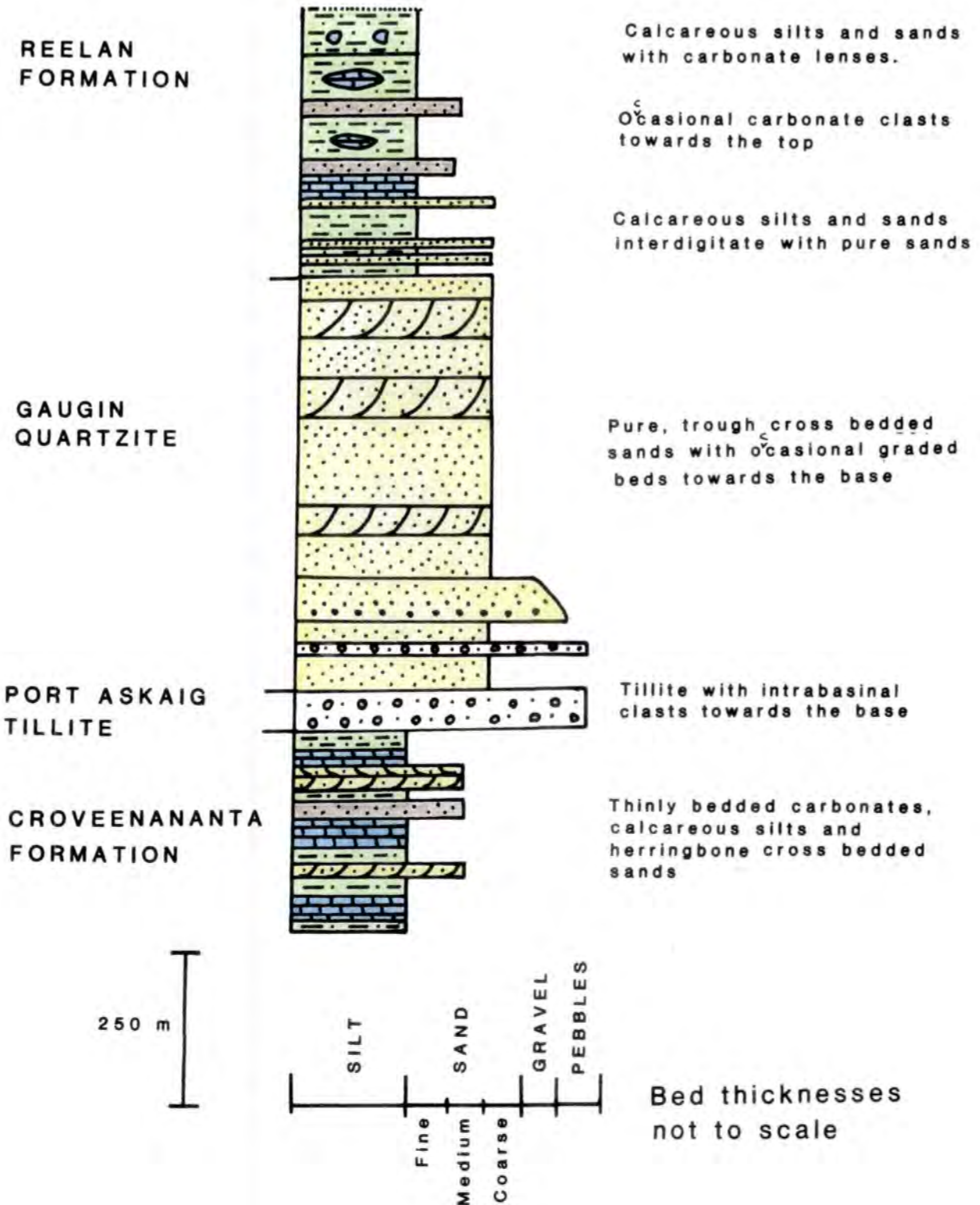


FIGURE 2.I.

### 2.3a) Croaghubbrid Pelite

The Croaghubbrid graphitic pelites are the oldest rocks of tectonic package B, everywhere being found adjacent to the Central Donegal slide. They undergo rapid tectonic thickness variations from approximately 1500 m thick on Crocknahamid (H 005988), reducing to 70 m on Gorey Hill (H 090980). The upper boundary of the Croaghubbrid Pelite<sup>a</sup> is difficult to define precisely due to it being an extended sedimentary transition with the overlying Boultypatrick Grits. The contact has been drawn at the base of the lowest laterally continuous grit band (Map 1 -map box).

The Croaghubbrid Pelites are best exposed on Croaghubbrid (G 915936) and Croaghugagh (G 917942). The upper sedimentary transition is most clearly observed in the River Finn West of Annagh bridge (H 041984). Typical rocks of this unit are soft (although hardening towards the Central Donegal slide, see 3.2), black, highly graphitic fissile pelites. They commonly develop a rusty patina, with a bright yellow sulphurous powder occasionally visible on internal cleavage surfaces. Thin psammitic bands (less than 25 cm) are common throughout the pelites. In general these pyritiferous graphitic pelites are poorly bedded (20 -30 cm intervals), contain quartz stringers and produce higher, agriculturally poorer ground than the Reelan or Croveenananta formations.

Within the Croaghubbrid Pelites, lenses of buff weathering dolomitic limestone up to 30 m in length have been found on the northern flank of Gaugin Mountain (G 985963), and the River Finn (C 012009). Dolomitic limestones react with cold dilute hydrochloric acid, are moderately bedded (25 cm intervals), and contain calcite, quartz, biotite and opaques as well as stellate tremolite clusters up to 3 cm in diameter (G 990967). The extended sedimentary transition with the overlying Boultypatrick Grits takes place over an interval of approximately 500 m. It is marked by the increasing frequency of psammitic bands up to 1 m thick (more commonly 40 - 50 cm thick) towards the outcrop of the grits. Eventually the graphitic pelite intercalations become rare, with only thin

(less than 2 cm) wisps of pelite remaining in the grit.

Within the transition, the presence of trough cross bedding (H 041984) (Plate 6b.) and 15 cm graded units (C 020011) (Plate 6a.) suggest younging towards the Boulypatrick Grits. Also present are channeling structures (C 034005) where gritty (grains up to 4 mm) sandstone channels are clearly seen to have cut down in to underlying graphitic pelites. Interleaving at the cm scale takes place at the margin of the channels (Fig. 2.2.). In the upper portions of the transition, thicker (50 cm) graded sequences become more common, sandstone units having sharp bases and transitional tops with graphitic pelite (Plates 7a., 7b.). This could be interpreted as A and B units of the Bouma sequence.

As the psammitic intercalations become more frequent up the succession they become coarser, with thin (less than 15 cm) grit bands (grains up to 5 mm) being observed at the top of the transition. Such rocks exhibit palaeochannel features with coarse sub-rounded feldspars being found in the centre of the ancient channel, and fining towards the edges (Plate 8a.). Thus, the transition is a coarsening up sequence of psammitic intercalations into the overlying Boulypatrick Grits.

### 2.3b) Boulypatrick Grits

Passing upwards from the Croaghubbrid Pelites via a sedimentary transition, the Boulypatrick Grits are a relatively thick sequence of massive gritty rocks with occasional thin (15 cm) intercalations of graphitic pelite. In the north western portion of the mapped area the grits are approximately 550 m thick. They thicken towards the south east around the hinge of the Ballybofey Antiform (see 4.4), reaching a maximum thickness of 1500 m prior to being thinned and cut out against the Ballybofey slide (see 4.6). (Map 1 - map box)

The upper contact of the Boulypatrick grits is not always easy to define due to its transitional nature with the overlying Lough Eske Psammities (see 2.3 c). Typically the Boulypatrick Grits contain a much greater abundance of sub-rounded blue quartz grains than the Lough Eske Psammite, and as such can

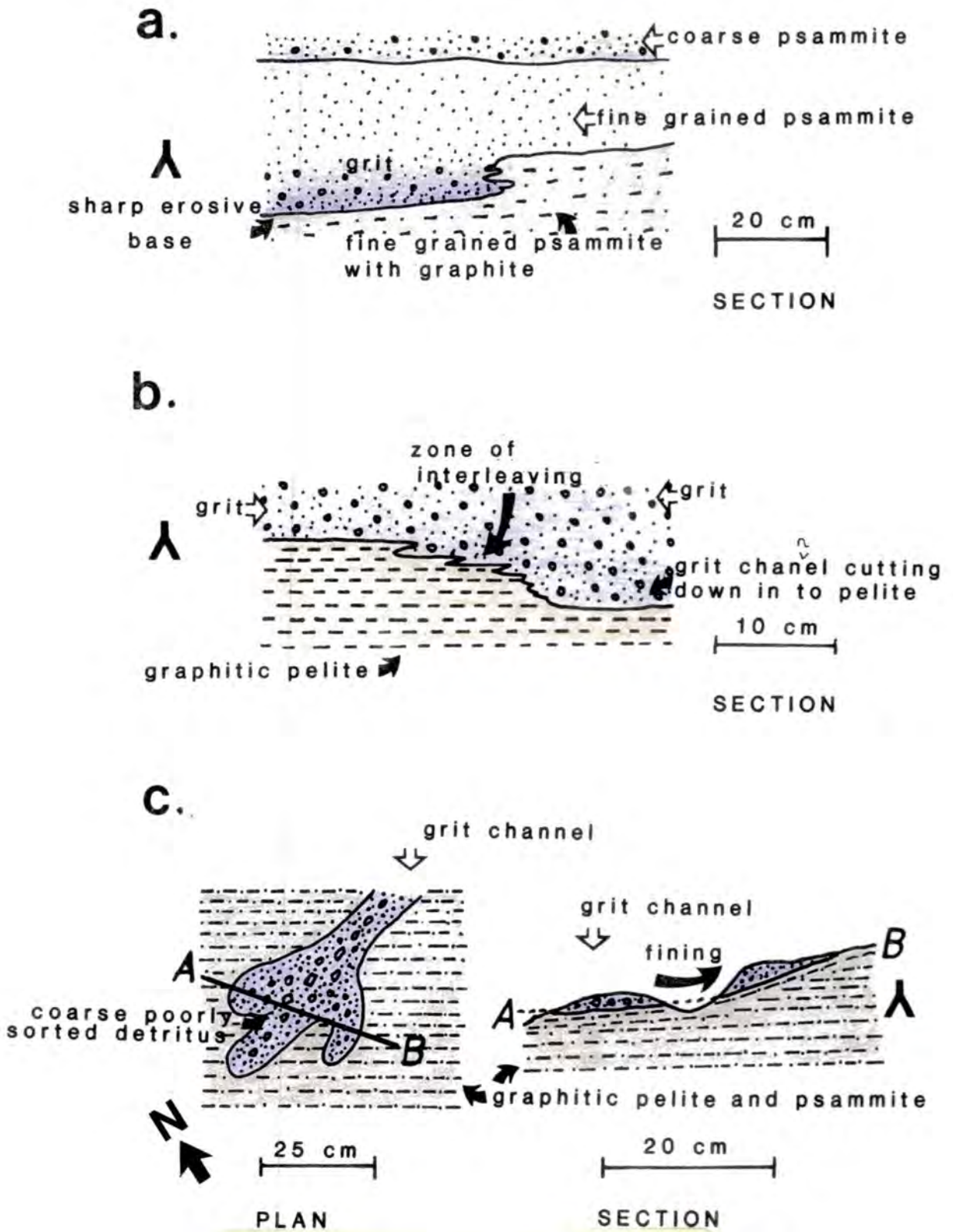


FIGURE 2.2.

DRAWINGS OF  
PALAEOCHANNEL  
STRUCTURES

be readily defined. The Boultypatrick Grits are best studied on Boultypatrick (G 968980), and the lower reaches of Sruhanboy burn (C 035008). Commonly these rocks are massively bedded (beds greater than 1 m being common), dark grey, moderately resistant to erosion and thus typically forming numerous small exposures. They have an average grainsize of 1-2 mm, with coarser beds containing sub-rounded grains of up to 5 mm not being uncommon. The mineralogy of the grits is principally blue quartz, plagioclase feldspar, biotite, muscovite, quartz and opaques. Blue quartz and cream-weathering plagioclase feldspar tend to form the larger grains. Occasionally, channels of coarse grit containing grains up to 7 mm in diameter, and approximately 40 cm wide are identified. They show normal grading in lens shaped deposits (G 962959) (Plate 8b.). Clasts in such deposits are largely of blue quartz and cream weathering feldspar, although some of possible granitic affinity have been noted. Grading in palaeochannel deposits suggests that the Boultypatrick Grits are younger than the Croaghbrid Pelites, as does grading in thin (15 cm) planar bedded deposits (C 020011) (Plate 9a.).

The presence of strong palaeocurrents is also witnessed by graphitic pelite rip-up clasts up to 30 cm in length. These tend to be concentrated in the slightly coarser rocks towards the base of the Boultypatrick Grits (G 967980) (Plate 10a.). Major occurrences of graphitic pelite rip-up clasts have been recorded on Map 1 (map box). The rapidity of deposition of the grits has also been documented by the development of water escape and injection structures on the cm scale (G 961963) (Plate 9b.). Elliptical clasts up to 30 cm, but more commonly 10-15 cm in length have been discovered within the Boultypatrick Grits of Boultypatrick (G 964988) and Elatagh River (C 027016). They weather to dark green, have a vesicular texture and 'weather in' slightly from the surrounding grits (C 027016) (Plates 11a., 11b.). In thin section, the clasts are found to be largely composed of fine grained quartz, plagioclase, opaques, biotite and chlorite. Numerous vesicles are present, no reaction has been gained from di-

lute hydrochloric acid and no carbonate has been seen in thin section. The pumaceous texture of the clasts, together with the mineralogy suggest an acidic volcanic source. Clasts appear to be confined to areas of slightly coarser grit (grains with diameters greater than 3 mm), the occurrences being documented on Map 1 (map box). It is possible that the light pumaceous clasts together with the coarser grit are representative of a palaeochannel fill deposit, thus explaining the localised occurrence of the volcanoclastic rocks.

In general the Boulypatrick Grits appear to coarsen towards the south east in tandem with the increasing thickness of the formation around the hinge of the Ballybofey Antiform (see 4.4). Graphitic pelite interbeds appear to extend for a greater distance up into the Boulypatrick grits in the western portion of the map. Throughout the exposed length of the Boulypatrick Grits, there is commonly a fining upwards trend towards the overlying Lough Eske Psammite.

### 2.3c) Lough Eske Psammite.

Passing upwards transitionally from the underlying Boulypatrick Grits, the Lough Eske Psammites are an extremely thick sequence of massive, essentially homogeneous psammitic rocks. They comprise occasional thin (less than 10 cm) muscovite rich pelitic partings together with quartzite units up to 30 m in thickness.

The Lough Eske Psammites are thinnest (2 Km. approximately) in the north east of the mapped area adjacent to the lateral facies transition with the Termon Pelites (see 2.3d). As with the Boulypatrick Grits, the Lough Eske Psammites thicken abruptly around the hinge of the Ballybofey Antiform (see 4.4), the stratigraphic upper limit lying to the south of the mapped area in ground most recently surveyed by Wood (unpublished Ph.D. studies 1970). An estimate of the thickness of the Lough Eske Psammites in this area would approximate to 6 Km.. The top of the formation can conveniently be taken as the base of the overlying Killeter Quartzite, the boundary originally drawn by Wood (1970).

Garranbane Hill (H 053930) and the higher ground in the south west of the mapped area (Lavagh More (G 935910), Silver Hill (G 906912)) afford the best opportunity to view the Lough Eske psammities. Typically these rocks are pale green/grey, massively bedded (greater than 1 m being common) homogeneous psammities which are relatively resistant to erosion. They are commonly rich in feldspar (especially in the south of the mapped area) and also contain quartz, biotite, muscovite, chlorite and opaques. Highly feldspathic psammities bedded at 20 cm intervals and containing biotite have been noted several Km. south east of the area of detailed mapping (H 172887). There is a distinct reduction in the amount of blue quartz compared to the Boulypatrick Grits.

Within the psammities there is a clear increase in grain size towards the south around the hinge of the Ballybofey Antiform. Adjacent to the lateral facies transition with the Termon Pelites, the average grain size is less than 1 mm, whilst in the south of the mapped area the average increases to approximately 1.5 mm with lenses of 4 mm grain size not being uncommon. A similar trend in grain size variation was noted by Wood (1970) in ground to the south of the mapped area. A slight reduction in grain size takes place throughout the Lough Eske Psammities towards the top of the formation. Wood (1970) has noted an increase in the semi-pelitic content of the formation towards its stratigraphic top.

Graded beds up to 1 m thick and containing rounded clasts of quartz and feldspar up to 1 cm. in diameter have been recorded on Garranbane Hill (H 058938) (Plates 12b., 13a.). On Croaghanierin (H 073912) lenses of coarse grit up to 2 m long, with quartz, feldspar and possible granite pebbles up to 1 cm in diameter show clear inverted grading and represent palaeochannel fill deposits. Such grading suggests that the Lough Eske Psammities are younger than the Boulypatrick Grits, as does grading in thinly bedded (less than 15 cm), quartz rich, finer grained psammite s adjacent to the lateral facies transition with the Termon Pelite. Graded beds in this vicinity may be capped by graphitic pelite,

a feature not exhibited by the coarser rocks farther South (Plate 12a.). Clast supported pebble conglomerates composed of quartz and orthoclase feldspar are found in the south of the area near Lough Sallagh (H 056916). Pebbles in this conglomerate are up to 2 cm in diameter (more commonly 8-9 mm), are poorly sorted and only sub-rounded. Feldspar pebbles would appear to be derived from a more proximal high grade metamorphic rock, with perthitic textures being common in larger clasts (Plate 13b.).

Quartzite units, up to 30 m thick in the case of the Silver Hill quartzite (G 910930), and traceable for 1.5 Km, are found only in the south western portion of the map. These pure, white, well bedded (at 30-40 cm intervals) quartzites contain trough cross bedding and are jointed orthogonally to bedding. They attract a thin brown lichen and produce a slight topographic scarp. Inability to trace such units over large distances suggests a lensoid character. In the adjacent Lough Eske Psammite, thin (less than 10 cm) quartzite beds foreshadow the larger quartzite units over a thickness interval of approximately 30 m. The Lough Eske Psammites adjacent to a small quartzite unit on Lavagh More (G 937914), become much coarser (up to 5 mm in diameter) and contain small (less than 2 cm) graphitic pelite rip-up clasts.

Buff weathering limestones and calcareous pelite bands up to 30 m long and rich in biotite and chlorite have been located within the Lough Eske Psammites at (H 058954) and (G 911294). Such rocks support a slightly more lush vegetation and react with cold dilute hydrochloric acid. They are bedded at approximately 1 m. and have hollows weathering out up to 10 cm long. Again the inability to trace these rocks for long distances suggests a lensoid nature.

In summary, the Lough Eske Psammite becomes finer grained both towards its stratigraphic top (marked by the Killeter Quartzite), and towards its lateral facies equivalent, the Termon Pelite. A reduction in the thickness of the formation also takes place towards the Termon Pelite.

## 2.3d) Termon Pelite.

Passing via a lateral facies transition from the Lough Eske Psammite Formation, <sup>(Pitcher, Shackleton and Wood 1971)</sup> the Termon Pelite is an extremely thick sequence (2 km. in the mapped area) of thinly bedded muscovite rich pelites (some calcareous), psammites, green beds and quartzites. The stratigraphic upper limit of the Termon Pelite may, as with the Lough Eske Psammite, be defined as the base of the overlying Killeter Quartzite (Pitcher, Shackleton and Wood, 1971). The Cummirk River (B 993022) and Deelee River (C 120030) provide the best opportunity for study of the Termon Pelite, the formation as a whole being bog-covered and relatively poorly exposed. Thinly bedded (20 cm), fine grained quartz-rich psammites weathering to grey colour with a pale green tinge, and quartz segregations up to 10 cm long are characteristic of the formation. Such psammites frequently contain muscovite-rich pelite intercalations (averaging 20 cm in width), together with thin (less than 3 cm) pure white quartzite bands. Muscovite rich pelites weather to silvery surfaces, on which biotite and chlorite porphyroblasts up to 2 mm may be seen. In some instances, particularly in the north west of the mapped area, the pelitic partings become distinctly graphitic (C 009032). Lenses of carbonate rich pelite and limestone less than 20 m in length <sup>t</sup> containing calcite, quartz, muscovite, biotite and chlorite also appear to be more frequent towards the north west (B 998028). They frequently contain pods of calcite up to 10 cm long, weather to a light green and may be flinty when struck with a hammer.

Towards the south east, and the lateral facies transition into the Lough Eske Psammite, <sup>interdigitation of Lough Eske Psammite and Termon Pelite on the km scale (C 080015) takes place, also</sup> there is a reduction in the amount of graphitic pelite and muscovite-rich pelite intercalations present in the Termon Formation. This trend in the reduction of the pelitic component is continued through the Lough Eske Psammite around the hinge of the Ballybofey Antiform. Concomitant with the reduction of the pelitic element in the Termon Pelite, there is a progressive development of the psammitic component together with a slight increase in grainsize (>1 mm).

In some instances the Termon Pelite takes on a gritty character with sub-rounded quartz and feldspar grains up to 4 mm in diameter being found in more massive beds (C 075020). As with the Lough Eske Psammite, there is very little blue quartz in these rocks compared to the Boulypatrick Grits.

Throughout the mapped area, the psammitic component of both the Termon and Lough Eske formations has a distinct pale green tinge. In the vicinity of the lateral facies transition within both the Termon and Lough Eske formations, rocks of a true greenbed nature have been located (C 097006). These dark green rocks may be traced laterally for 500 m, are well bedded (40 cm intervals), commonly calcareous and may contain quartz segregations. They are relatively dense, heavy rocks and are largely composed of chlorite, epidote, green-brown biotite, albite, quartz, calcite and opaques (Plate 14a.). Similar rocks have been documented from elsewhere within the Termon Pelite (Pulvertaft 1961). Towards the stratigraphic top of the Termon Pelite, approximately 500 m from the overlying Killeter Quartzite, there is a progressive increase in the frequency of fine grained, pale green quartzite bands (C 120030). These bands are thinly bedded (less than 10 cm) and intercalated with schistose Termon psammite containing occasional thin muscovite pelite partings and biotite seams (Plate 19a.).

In summary, the Termon Pelite coarsens slightly towards its lateral facies equivalent, the Lough Eske Psammite, and also passes via a brief sedimentary transition into the overlying Killeter Quartzite.

### 2.3e) Killeter Quartzite

Entering the mapped area in only the extreme north eastern corner, the Killeter Quartzite is a pure, resistant, white weathering rock forming slightly elevated ground with only moderate exposure. Estimates of thickness are not possible in the mapped area. Wood (1970) estimates a maximum thickness in

the Killeter region of County Tyrone of 1100 m, reducing towards the west and eventually becoming absent (see Chapter 6). Typically, the Killeter Quartzite is a fine grained rock, moderately bedded (50 cm approximately), with a lack of darker heavy mineral bands. Approximately 13 Km. South of Ballybofey in county Tyrone (H 157824), graded beds have been located within this unit. Such pebbly quartzite beds are 25 cm thick, contain quartz grains up to 3 mm at their stratigraphic bases and suggest that the Killeter Quartzite is younger than the Termon/Lough Eske Psammite Formations. Neither Wood (1970) nor the present author have identified any cross bedding in the Killeter Quartzite. Overall stratigraphic relationships of tectonic package B have been summarised on a sedimentary log (Fig. 2.3), and the overall stratigraphic sequence proposed for Central Donegal is shown on Figure 2.4. \*

#### 2.4) Minor igneous intrusions

The mapped area contains relatively few minor igneous intrusions, the most common type being metadolerite/epidiorite. Minor felsites and quartz diorites as well as appinites have also been identified.

##### 2.4a) Metadolerites

The terms metadolerite and epidiorite are synonymous. In the process of metamorphism of a doleritic body, original pyroxene and labradorite are commonly converted to hornblende and a less basic plagioclase (with various other minor constituents). Thus the metamorphosed rock although chemically gabbroic, (hence the term metadolerite), in mineral content is dioritic, and has been named epidiorite by Caledonian geologists in the past. The present author has included the non-genetic term epidiorite on the map sheets (see Map 1, map box). Metadolerites are found throughout the mapped area, being especially well developed at Lavagh Beg (G 925910) and Garranbane Hill (H 055922)

\* Sedimentology and broader stratigraphic implications are discussed on pp. 238-250.

Hypothetical sedimentary log through tectonic package B

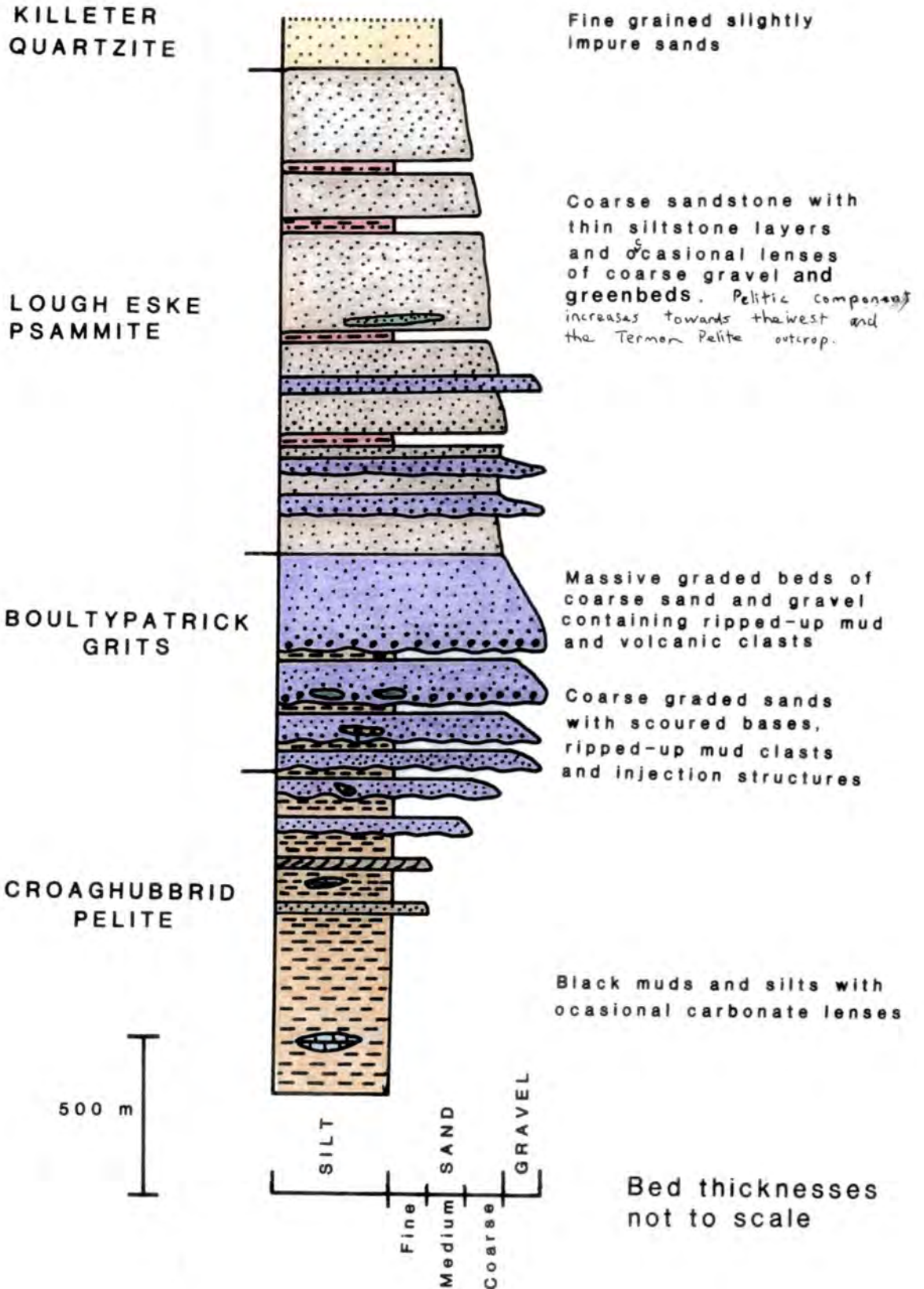


FIGURE 2.3.

FIGURE 2.4.

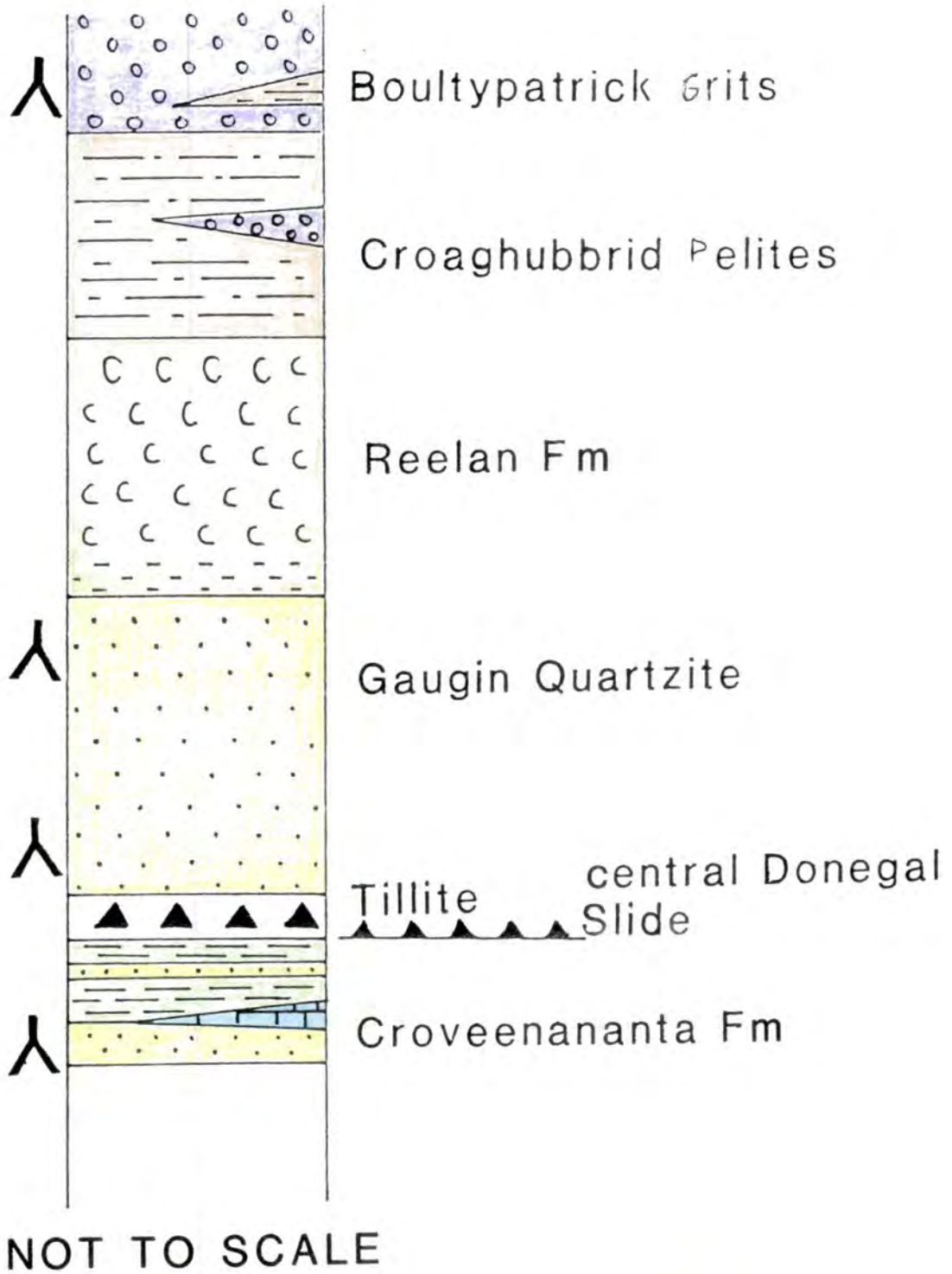


FIGURE 2.4.  
 CENTRAL DONEGAL  
 TECTONIC STRATIG-  
 RAPHY.

where individual sheets may reach up to 50 m in width (Map 1 map box). They weather to a dark green with rusty patina, are well jointed and massive. Occasionally they contain red euhedral garnets 2-3 mm in diameter (G 985972); attract a white lichen and have a tendency to produce topographic ridges with a slightly more lush vegetation. Such topographic ridges enable intrusions to be traced (even through areas of little exposure), and they may 'run' for several hundred metres, hence the local Donegal name of 'runstone'. In some instances, eg. Garranbane Hill (H 055922), Croveenananta (G 935940) clusters of epidote up to 1.5 cm in diameter are seen. They stand proud on weathered surfaces and may give the rock a knobbed appearance. They would appear to pseudomorph original feldspars in the intrusion. In thin section the epidote knots are commonly rimmed by carbonate and occasionally wrapped by hornblende defining a fabric within the metadolerite. Fabrics in the intrusions are parallel to, and intensify towards the margins of the body. The internal metadolerite fabric generally parallels the regional S2 (see 3.3e), and suggests pre-D2 emplacement of the dolerite. Inhomogeneity between metadolerite and country rock produce the intensification of fabric towards the intrusion margins. In thin section metadolerites are seen to comprise hornblende, epidote (in highly varying quantities), albite/oligoclase, calcite, quartz, occasional garnets and opaques.

#### 2.4b) Quartz Diorites

A massive well jointed quartz diorite (An<50, quartz>20at (C 030010), comprising plagioclase (An<50), quartz, hornblende, epidote and opaques. Its contacts are nowhere exposed, although it may be traced for 500 m via a 20 m wide topographic ridge which supports a more lush vegetation. It weathers to a light grey colour, becoming rusty in wet ground and has little lichen cover. Within the intrusion are small (less than 2 cm), often angular xenoliths of country rock composed of amphibole, epidote and quartz. The xenoliths contain a well defined fabric developed at different orientations in adjacent xenoliths (Plate 10b.). The xenoliths them-

selves may be slightly aligned parallel <sup>to</sup> the external S3 fabric. The above field relationships may suggest a post-D2 emplacement (to develop xenoliths with disoriented fabrics), followed by D3 tectonics to produce the alignment of xenoliths. In thin section, the country rock xenoliths are composed of amphibole, epidote and quartz. The quartz diorite comprises plagioclase (less basic than labradorite) quartz, hornblende, epidote and opaques.

#### 2.4c) Appinite

In Donegal, the dominant mineral assemblage of the appinite suite is a coarse grained association of hornblende, plagioclase, sometimes quartz, with biotite and pyroxene as alternative mafic minerals (Pitcher and Berger, 1972). Appinites mapped by the present author at Falgarrow (G 990975) and Three Tops (C 070015) comprise pyroxene up to 4 mm in length, hornblende, plagioclase, biotite, quartz and opaques. It is serpentinised probably by associated hydrothermal fluids. In the field, appinite is a massive, homogeneous, dark green rock with crystals of pyroxene and hornblende clearly visible. It is resistant to weathering, being quite well exposed and forming small hills. To the south west of Altnapaste (H 035950), an appinite body approximately 350 m in diameter was mapped by Pitcher, Shackleton and Wood(1970). On examination of this oval shaped intrusion, it was found to be a structureless metadolerite composed of hornblende, actinolite, epidote, albite, quartz and opaques. It weathers to a dark green, is massive and well jointed, and produces a slight hill in otherwise flat bog.

**PLATE 1a.**

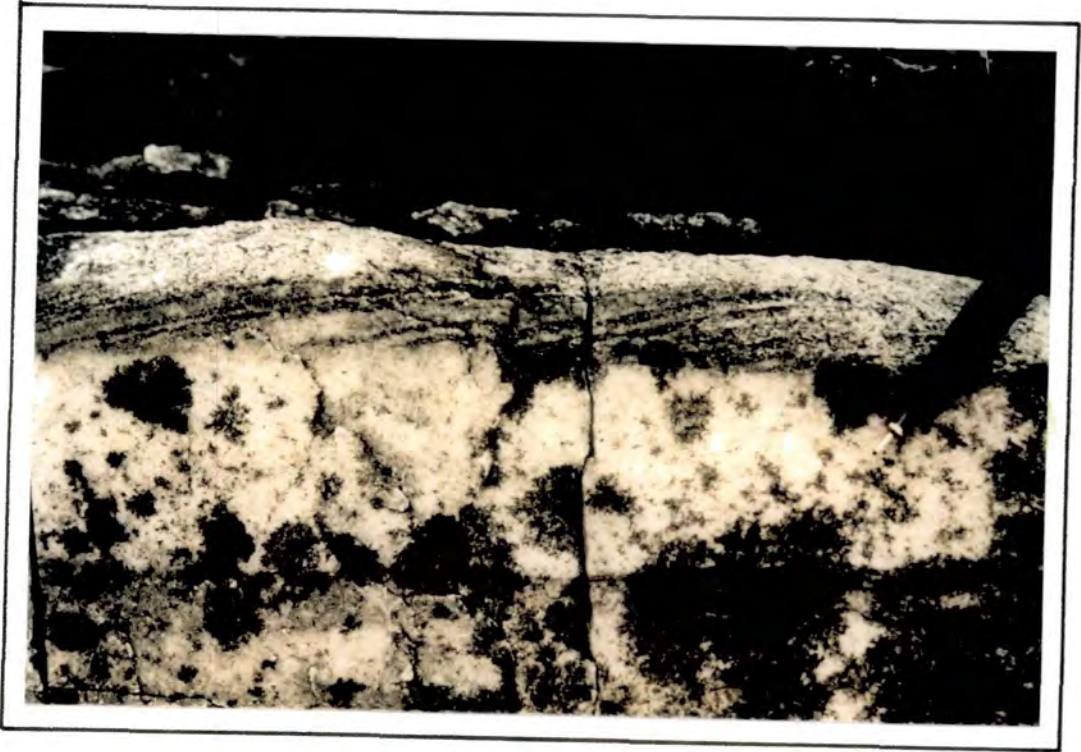
**Locality** - Lacroagh (G 937941)

Inverted cross lamination within pure quartzite bands of the Croveenananta Formation. This cross lamination suggests that the Port Askaig Tillite and Gaugin Quartzite are younger than the Croveenananta Formation.

**PLATE 1b.**

**Locality** - Cashel (H 037965)

Clasts of sheared leucogranite within a psammitic matrix. This deposit represents part of the Port Askaig Tillite Formation in Central Donegal. Intensity of the deformation is related to the proximity of the Central Donegal slide.



a.



b.

**PLATE 2a.**

**Locality** - Slievemullagh (H 004947)

Cross bedding with clear cut offs (shown on the overlay) within the Gaugin Quartzite. The quartzite youngs towards the south (top of photograph) and suggests that the Gaugin Quartzite is older than the Reelan Formation. Lens cap in middle right of photograph for scale.

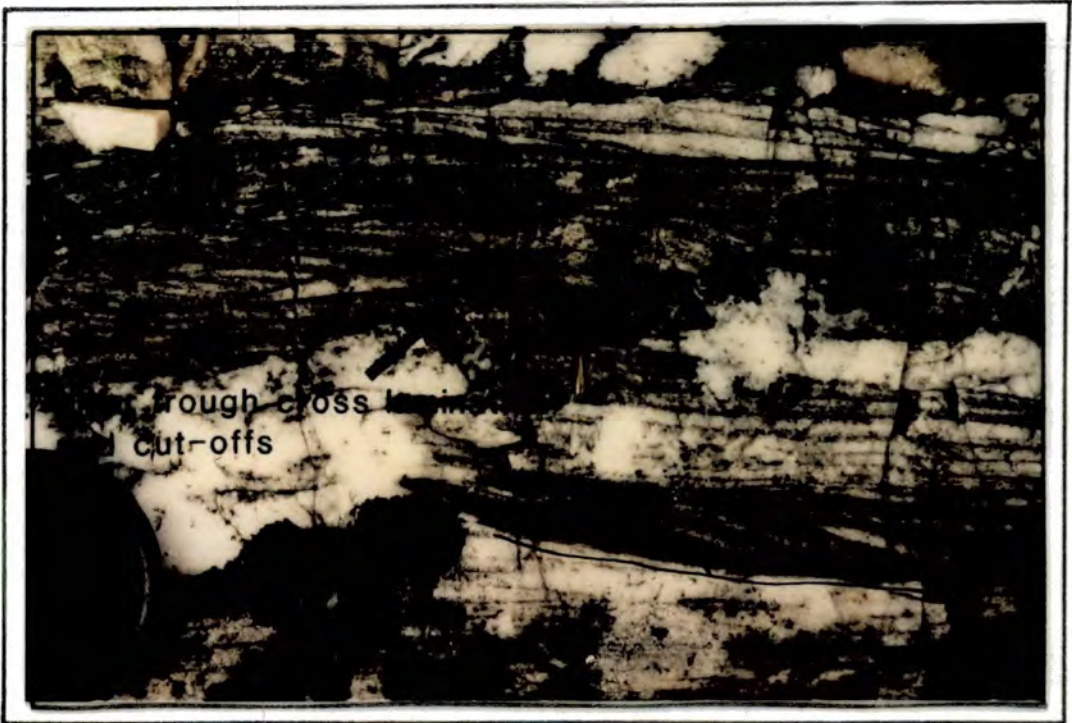
**PLATE 2b.**

**Locality** - Croaghubbrid (G 917932)

Inverted trough cross laminations with clear cut offs (shown on overlay) within a pure quartzite band of the Croveenananta Formation.



a.



b.

**PLATE 3a.**

**Locality** - Gaugin Mountain (G 982954)

Right way up cross bedding (shown on overlay) suggesting that the Gaugin Quartzite is younger than the Port Askaig Tillite, and youngs away from the Central Donegal slide (in this instance) towards the Reelan Formation.

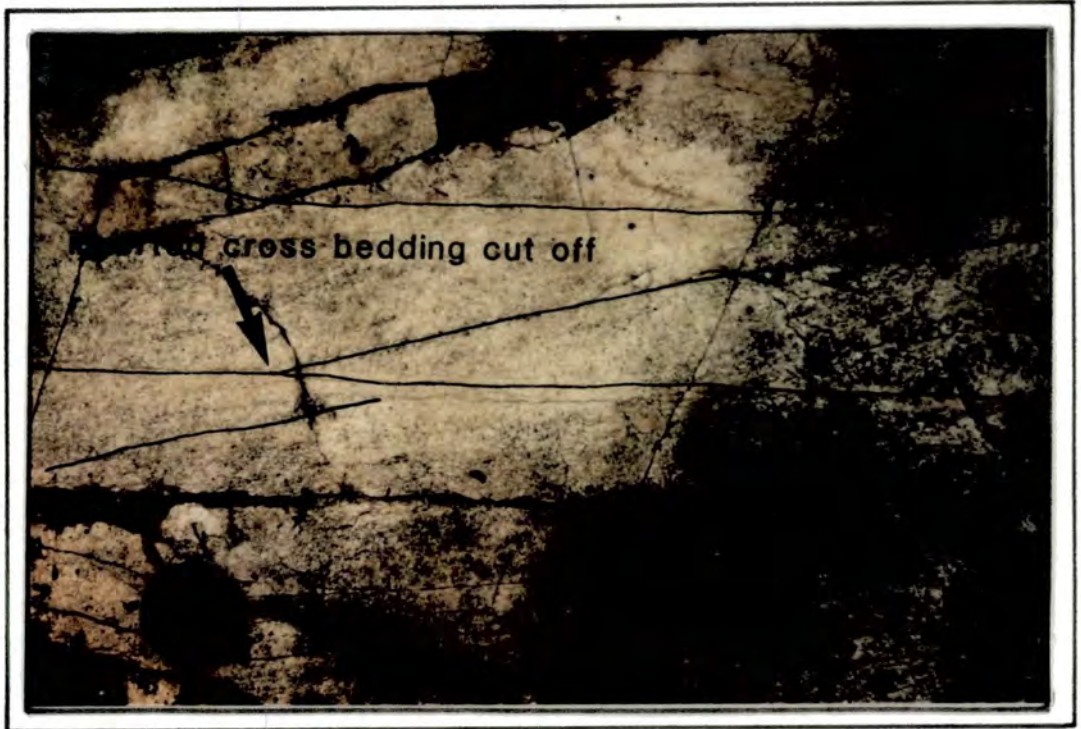
**PLATE 3b**

**Locality** - Slievemullagh (H 003947)

Inverted cross bedding (shown on overlay) suggesting that the Gaugin Quartzite is older than the Reelan Formation. Inversion of the quartzite relates to folding by the Ballybofey Antiform.



a.



b.

## PLATE 4a.

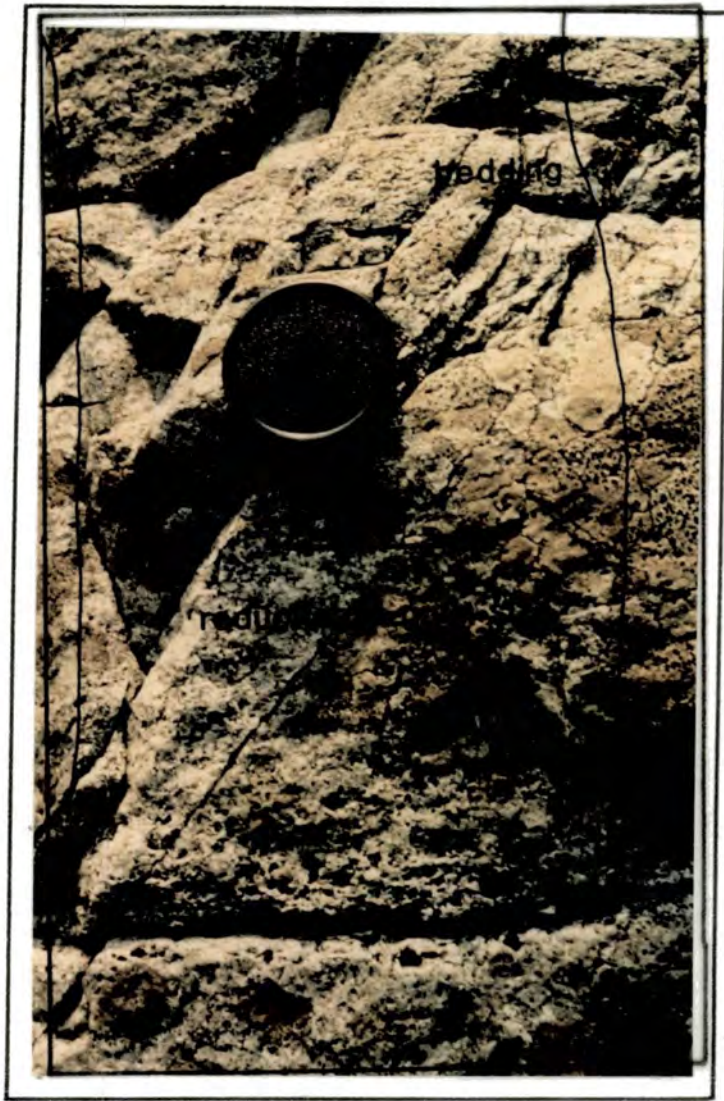
Locality - Gaugin Mountain (G 987955)

Right way up graded unit within the Gaugin Quartzite. Base of graded bed (containing quartz and feldspar grains upto 2mm in diameter) approximately 1.5 cm from the base of the photograph. Top of the graded unit is 1 cm from the top of the photograph, and suggests that the Gaugin Quartzite is older than the Reelan Formation.

## PLATE 4b.

Locality - Altnapaste (H 047961)

Mesoscopic F3 fold pair verging towards the Ballybofey Antiform (towards the right of the photograph) with right way up cross bedding on the long limbs of F3 folds (shown on the overlay). This photograph suggests that the Gaugin Quartzite is older than the Reelan Formation.



a.



b.

**PLATE 5a.**

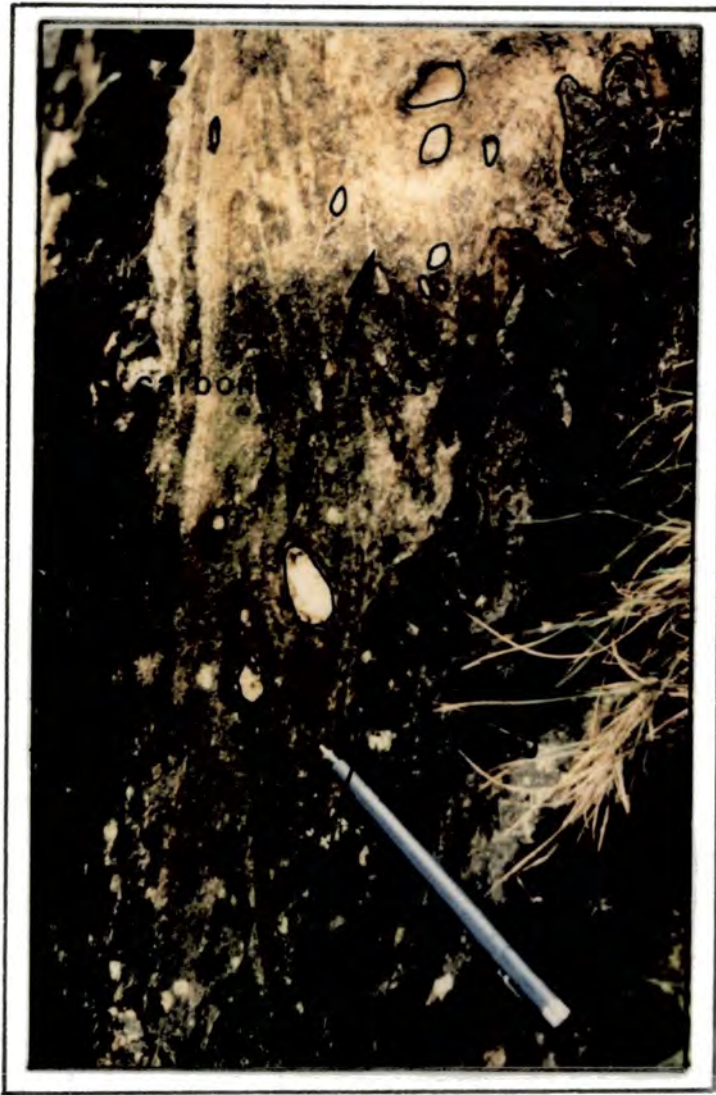
**Locality** - Stragally Bridge, Commeen (H 012963)

Carbonate clasts (outlined on the overlay) within the calcareous pelites of the Reelan Formation. The clasts are upto 3 cm long, wrapped by the S2 fabric and are commonly composed of a recrystallised pink calcite.

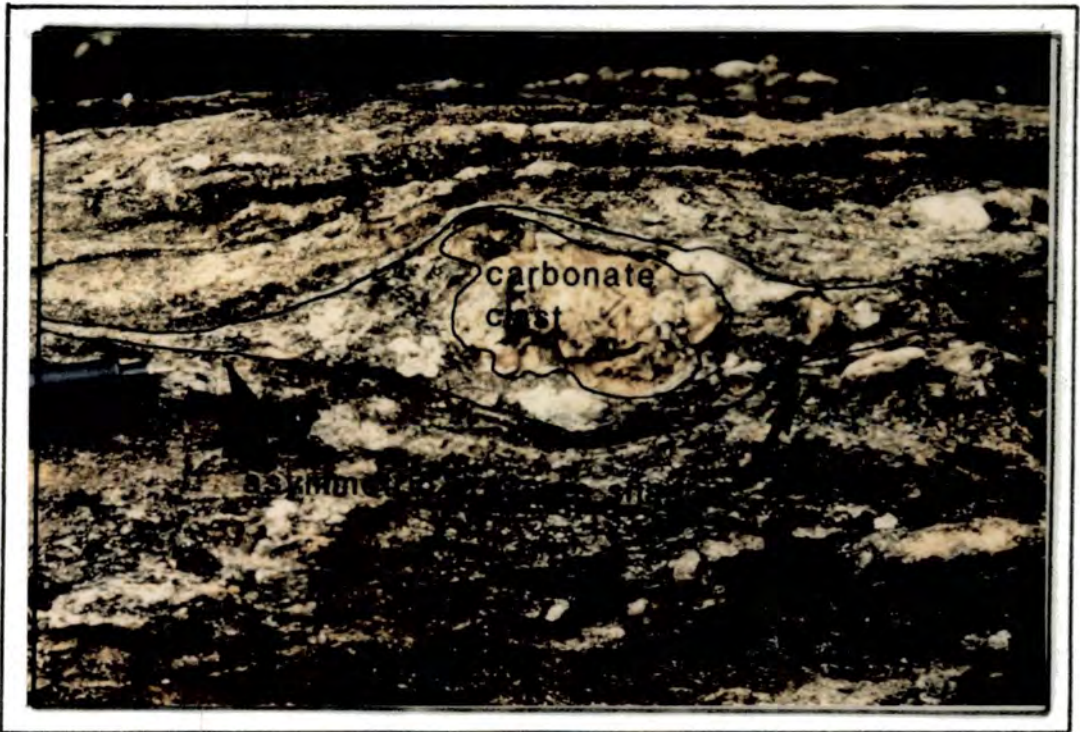
**PLATE 5b.**

**Locality** - Stragally Bridge, Commeen (H 012963)

Carbonate clast (outlined on the overlay) within the Reelan Formation, which is wrapped by the main S2 fabric and has developed asymmetric pressure shadows.



a.



b.

**PLATE 6a.**

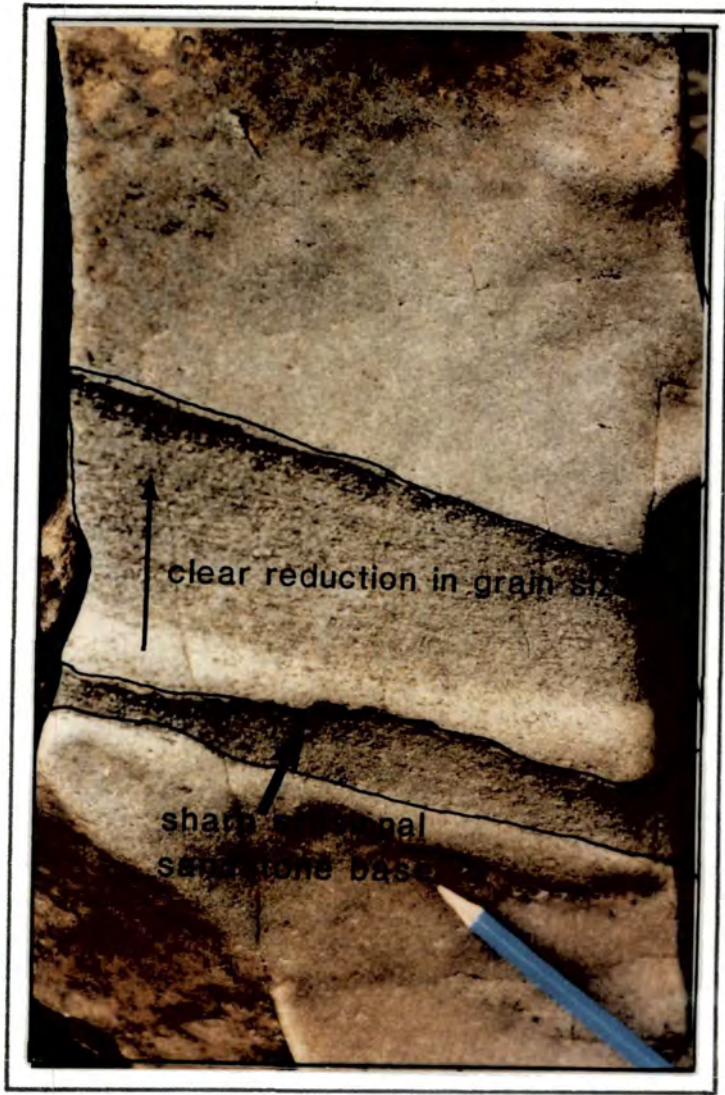
**Locality** - Elatagh River, Altlahan (C 020011)

Right way up graded psammities within the Croaghubbrid Pelite / Boulypatrick Grit sedimentary transition. Graded units are on the 10 cm scale, with sharp erosional bases of psammite, which grade upwards into pelite and suggest that the Croaghubbrid Pelites are older than the Boulypatrick Grits.

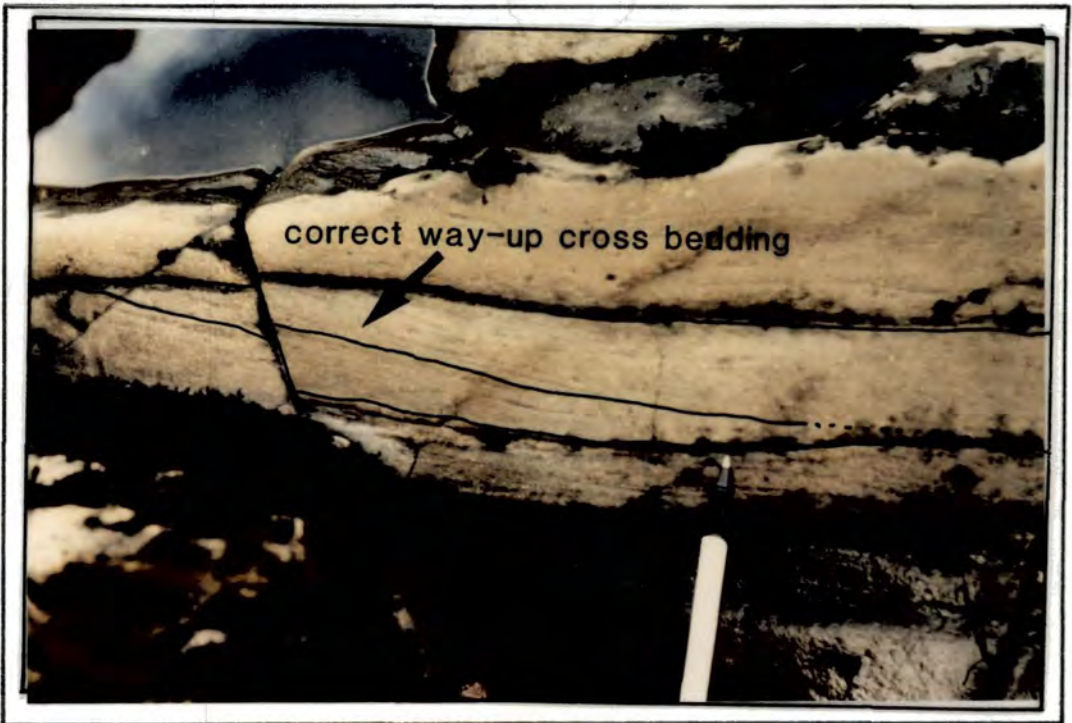
**PLATE 6b.**

**Locality** - River Finn, Annagh Bridge (H 041986)

Right way up cross bedding within the Croaghubbrid Pelite / Boulypatrick Grit sedimentary transition. The overlay to the photograph outlines the cross sets which suggest that the Croaghubbrid Pelites are older than the Boulypatrick Grits.



a.



b.

## PLATE 7a.

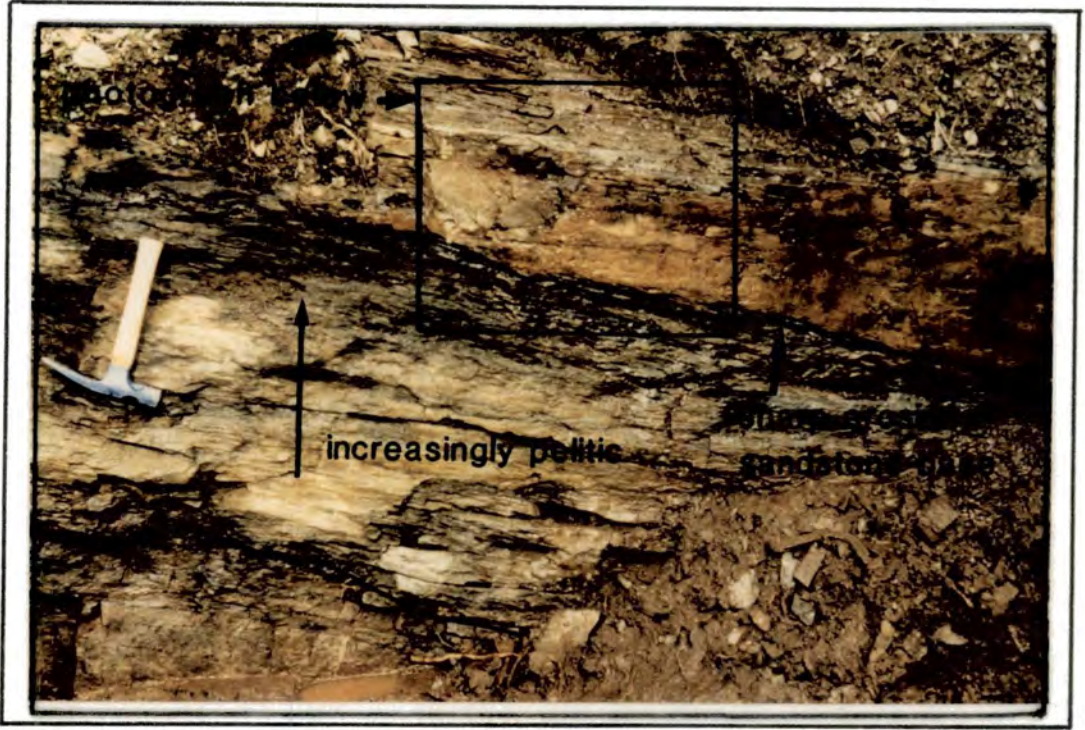
Locality - Letterbrick (C 007013)

Graded units within the Croaghubbrid Pelite / Boulypatrick Grit sedimentary transition. Psammite units possess sharp erosional bases and grade over approximately 75 cm intervals into graphitic pelite. This grading suggests that the Boulypatrick Grits are younger than the Croaghubbrid Pelites.

## PLATE 7b.

Locality - Letterbrick (C 007013)

A close up photograph of the erosional base of a psammite unit shown and outlined in the above photograph (Plate 7a.).



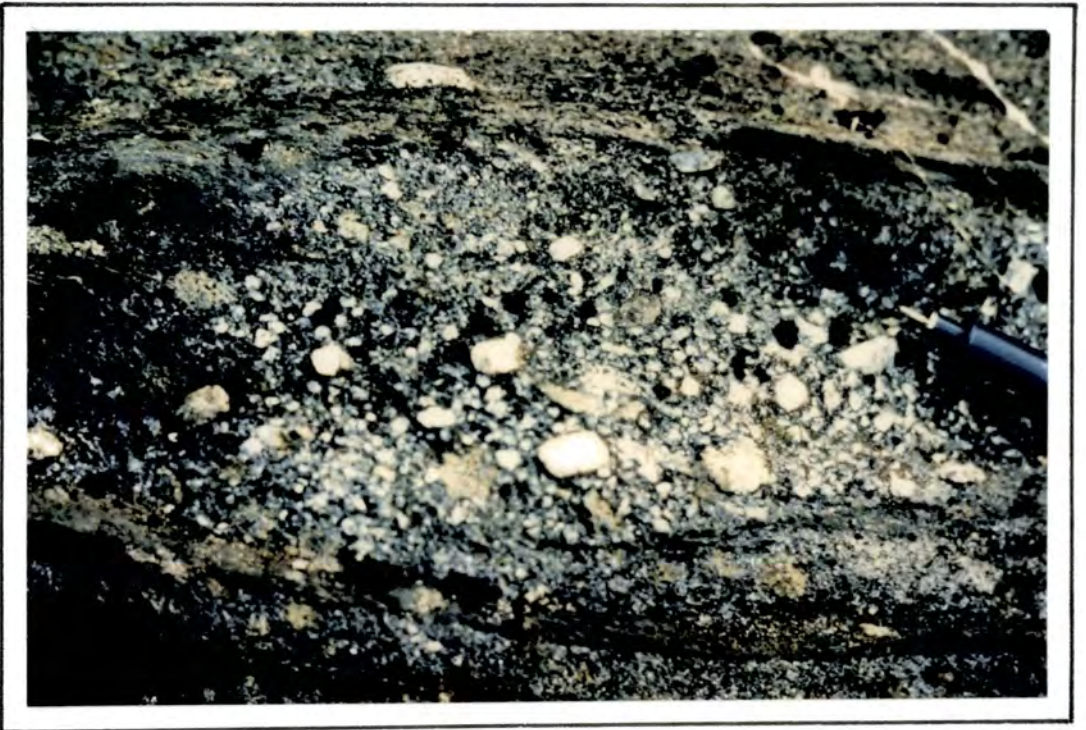
a.



b.



a.



b.

## PLATE 9a.

Locality - Glashydevet (G 961963)

Small scale graded unit from within the Boulypatrick Grits, which on the photograph youngs from right to left and suggests that the Boulypatrick Grits are younger than the Croaghubbrid Pelites.

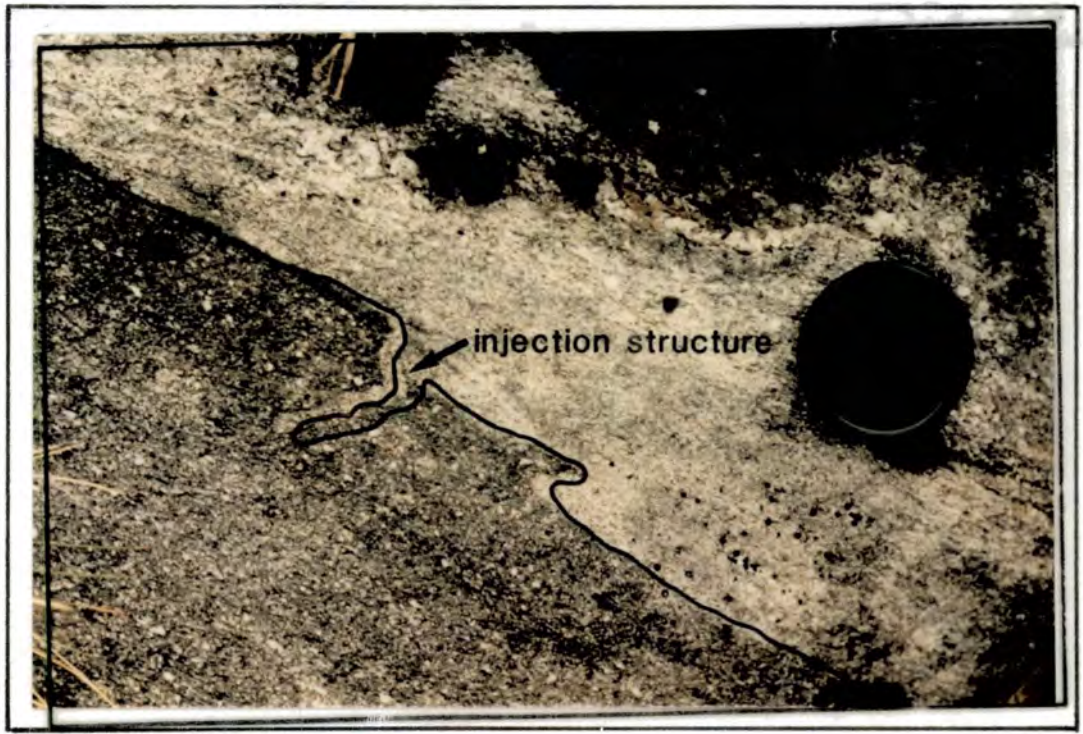
## PLATE 9b.

Locality - Glashydevet (G 961963)

Small scale injection structure from within the Boulypatrick Grits, with finer grained psammities on the upper right hand side of the photograph injecting into coarser grits shown at the bottom left. The younging direction is consistent with that described above from the same locality (Plate 9a.).



a.



b.

**PLATE 10a.**

**Locality** - Boulypatrick (G 979985)

Graphitic pelite rip - up clasts upto 30 cm in length<sup>±</sup> are sometimes developed within the coarse Boulypatrick Grits adjacent to the sedimentary transition with the older Croaghubbrid Pelite. Base of a hammer shank is at the bottom right of the photograph for scale.

**PLATE 10b.**

**Locality** - Galwolie (C 030014)

Quartz - Diorite intrusion containing numerous small ( 5 cm) xenoliths of the adjacent country rock.



a.



b.

## PLATE 11a.

Locality - Atlahan (C 025011)

Volcanogenic clasts upto 30 cm in length (outlined on overlay) within coarse Boulypatrick Grits. The general alignment of the clasts is parallel<sup>to</sup> the main S2 fabric.

## PLATE 11b.

Locality - Atlahan (C 025011)

Close up photograph of volcanogenic clast within the Boulypatrick Grits, note the pumaceous texture and alignment of the clast with the main S2 fabric.



a.



b.

## PLATE 12a.

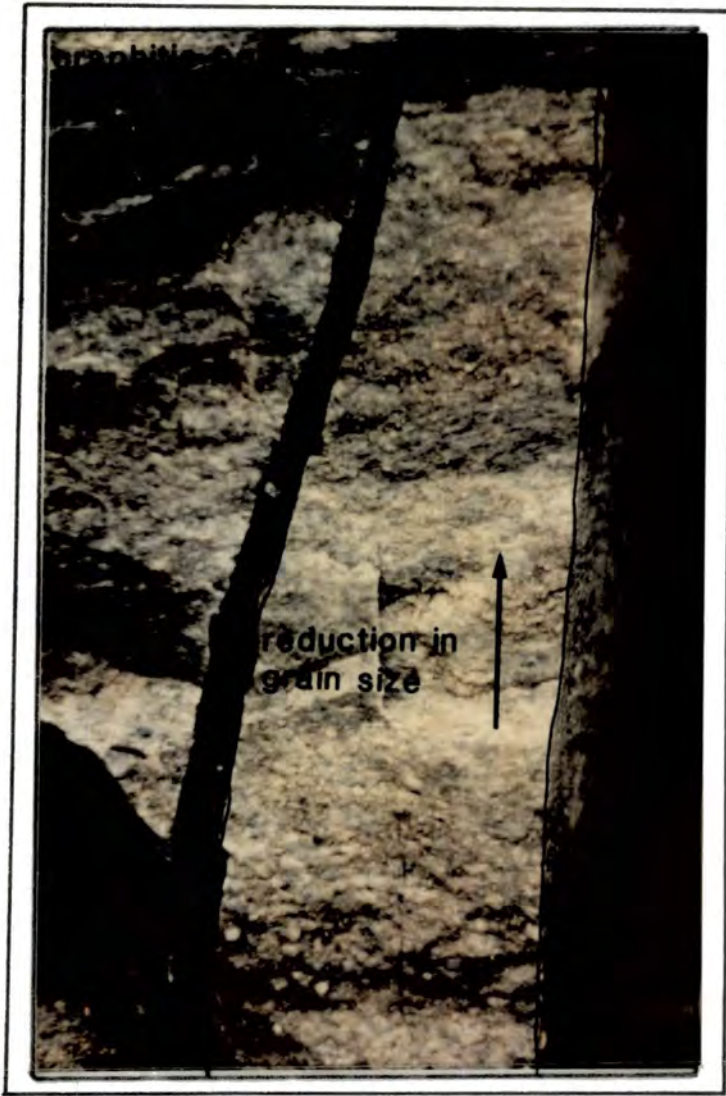
Locality - Sruhanabouy Burn (C 048018)

A graded unit (approximately 15 cm in width) developed within the Lough Eske Psammities. At the base of the bed, quartz and feldspar grains upto 3 mm in diameter are present, whilst towards the top of the unit, the finer grained psammite is capped by graphitic pelite. The grading described suggests that these rocks are the right way up, and that Lough Eske Psammities are younger than the Boultypatrick Grits.

## PLATE 12b.

Locality - Garranbane Hill (H 058936)

A coarse graded unit from within the Lough Eske Psammities, with quartz and feldspar grains upto 1 cm in diameter at the stratigraphic base (top bedding line shown on the overlay). A reduction in grain size takes place towards the bottom of the photograph, with a thin layer of coarse grains marking the stratigraphic top of the bed. Inversion of the unit is related to the Ballybofey Antiform, the grading suggesting that the Lough Eske Psammities are younger than the Boultypatrick Grits.



a.



b.

## PLATE 13a.

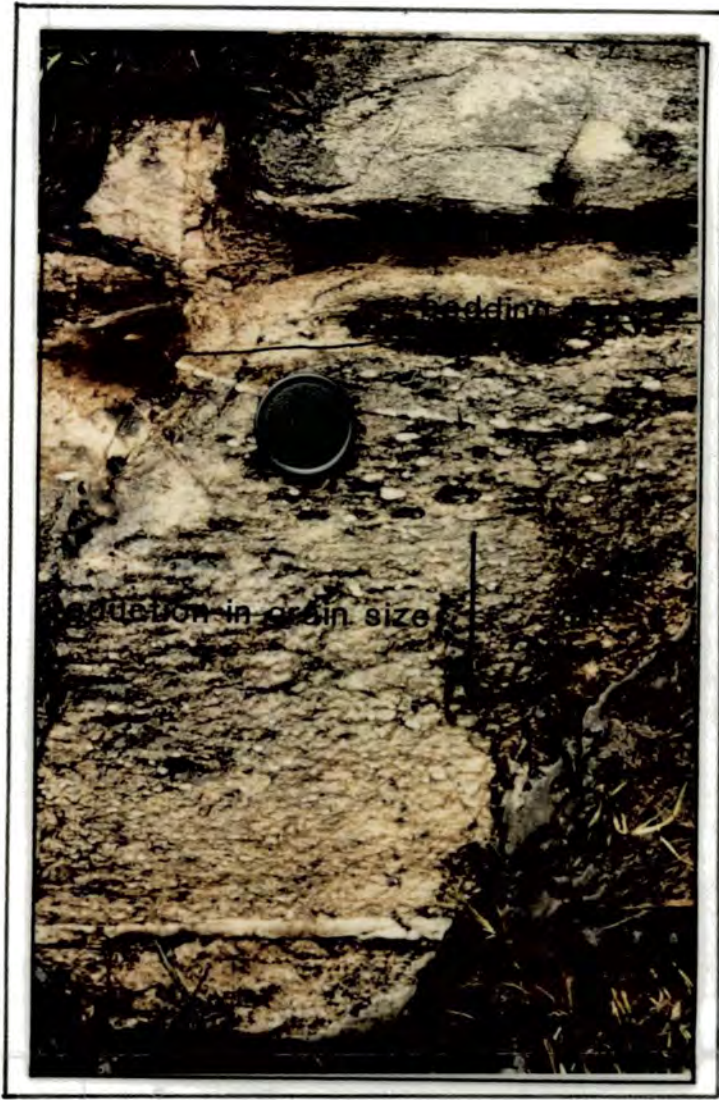
Locality - Garranbane Hill (H 053930)

Coarse graded unit within the Lough Eske Psammities, quartz and feldspar grains reaching 1 cm in diameter at the stratigraphic base (bedding line shown on overlay). The psammite fines towards the bottom of the photograph and indicates that the psammities are inverted (by the Ballybofey Antiform) and younger than the Boultypatrick Grits.

## PLATE 13b.

Locality - Lough Sallagh (H 056916)

A massive conglomerate of quartz and feldspar pebbles showing little signs of grading. Clasts are commonly less than 3 cm in diameter and only sub-rounded.



a.



b.

## PLATE 14a.

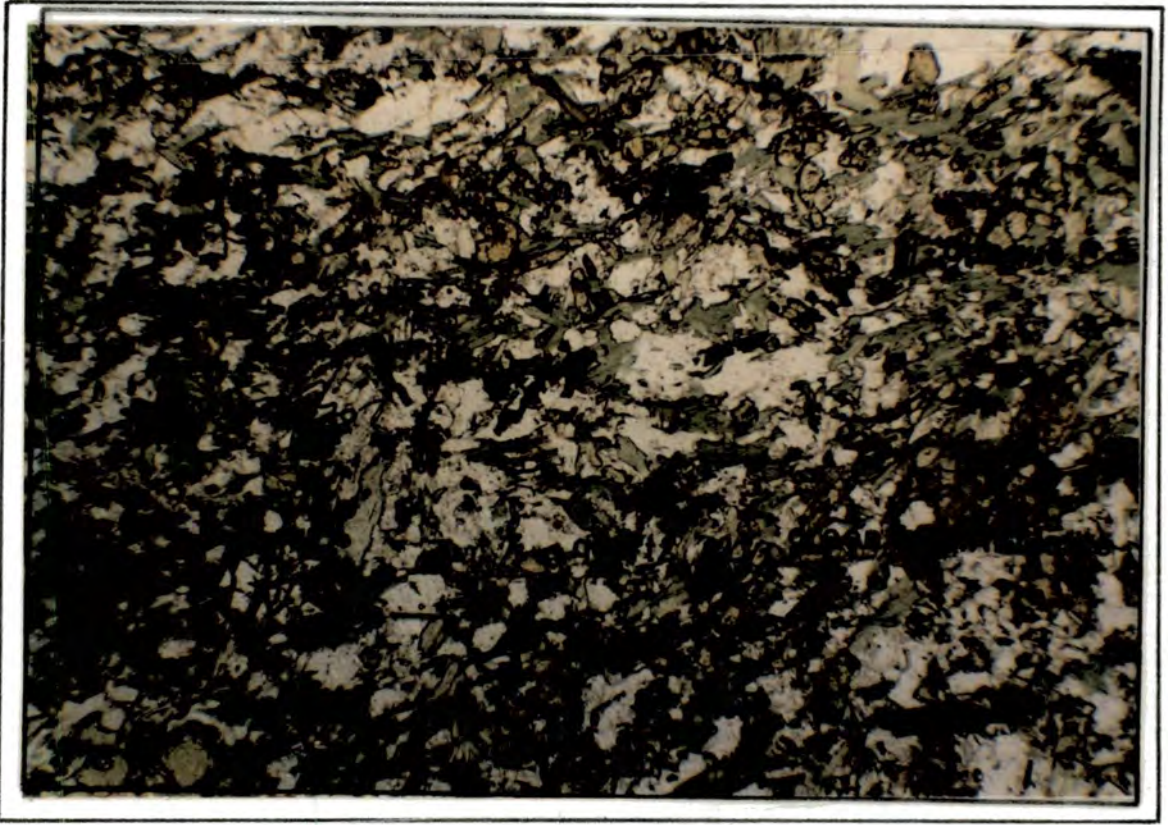
Locality - Meenanorna (C 093005)

Photomicrograph taken under crossed polars of Green beds developed within the Termon Pelite. The length of the field of view is 4 mm, and the main mineral types present are outlined on the overlay.

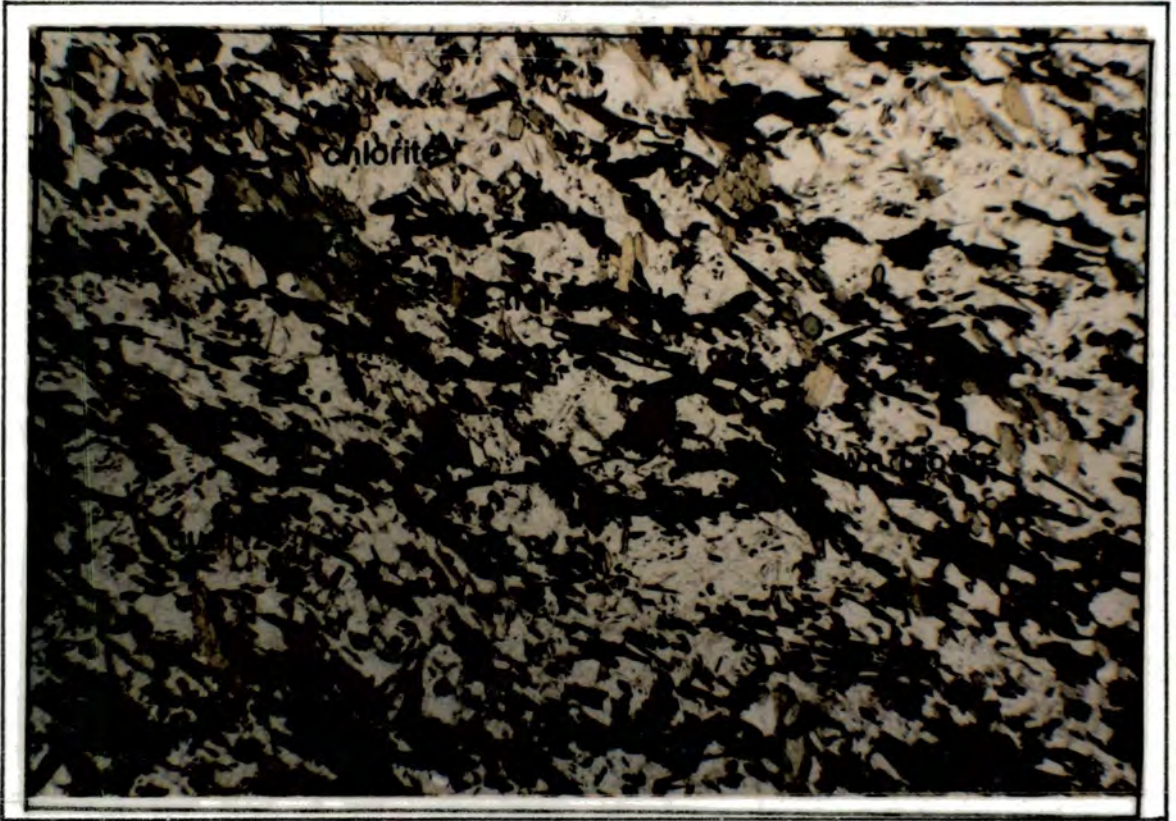
## PLATE 14b.

Locality - Shanaghy Burn, County Tyrone (H 167763)

Photomicrograph taken under crossed polars of Green beds in the Upper Dalradian of County Tyrone. The length of the field of view is 4 mm, and the main mineral types present are outlined on the overlay.



a.



b.

60'

**CHAPTER 3**  
**EARLY DEFORMATION:**  
**THE CENTRAL DONEGAL SHEATH FOLDS.**

CHAPTER 3  
EARLY DEFORMATION:  
THE CENTRAL DONEGAL SHEATH FOLDS.

3.1) Introduction and justification of structural techniques employed.

A sequence of deformational events which can be recognised and correlated throughout the mapped area forms a basis for structural interpretation throughout the following three chapters.

A deformational phase (D) is associated with a specific set of tectonic structures, i.e folds (F), cleavage (S). Each phase and its structures are given a numerical subscript implying their age relative to other phases. Thus D1, producing F1 and S1, precedes D2 (F2, S2) e.t.c. Bedding is not a tectonic structure and is designated S0. The intersection of the cleavage of a particular phase (Dn) with bedding (Sn/S0) is parallel to fold axes of that age (Fn), and both structures are collectively referred to as B lineations (Bn).

Events of different ages have been distinguished using the standard methods of structural fieldwork augmented by thin section microscope observations. This is based on the recognition that earlier structures are deformed by later structures. Thus, earlier cleavages may be folded by later folds, crenulated by later cleavages, or offset by later faults. Earlier folds may be refolded by later folds or cross cut by later cleavages.

The system of fold description proposed by Fleuty (1964) is employed, tightness; attitude of axial plane and axial planar cleavage; plunge and trend of B lineations; and the range in length of the middle limbs. The term middle limb is used to describe the two short limbs joining adjacent hinges of an asymmetric fold pair. Extensional or shear crenulations related to shearing during a deformational event (Dn), have been denoted (Sn-E), and associated crenulation axes (Bn-E).

The geometrical relationships of structures to earlier surfaces are described using the terms vergence and facing. When dealing with a series of inequant minor folds, the middle limbs of these structures appear to have rotated out of an attitude now preserved by the normal (unfolded) limbs. The vergence of these folds is defined as the horizontal direction in the profile plane of the fold to which the upper component of this rotation is directed (Bell 1981). This term can be extended to the relative orientation of cleavage and bedding which would imply a sense of fold vergence, even though bedding itself is not visibly folded

Major phases of deformation may produce structures which invert portions of stratigraphy. It is useful to describe the geometry of such structures in terms of facing. A fold is said to face (Shackleton 1958) in the direction, normal to its axis and in its axial plane in which younger beds are met. This term can be extended to minor folds and cleavage congruous with major folding. Facing of gently plunging folds as shown on maps, has been rotated parallel the axial plane through the acute angle to the horizontal.

The system of deformation chronologies so defined, inherently leads to the concept of sequential 'pigeon hole' events. Such a concept is too simple especially in relation to major deformations and the associated minor crenulations which frequently follow. Indeed, extensional shear crenulations have been seen to deform fold axes of the same generation. The D number system was, however, found to be the most useful basis for structural investigation of this is

polydeformed terrain.

The mapped area has been divided into three major sub-areas for structural interpretation (see Figure 1.5). Deformation ( $D_n$ ) will be described and correlated from each of the sub-areas, prior to a description of the next event ( $D_{n+1}$ ).

$D_1$  is associated with the development of the Central Donagall Slide (marked on map 1 and 10, map box), which separates rocks younging in opposite directions across it. This slide was reactivated and refolded by  $D_2$  shearing towards the SE leading to the development of km scale sheath folds (Fig 3.11). The  $D_3$  Ballybovey Antiformal complex (Chapter 4) is a major overturned antiform which refolds the  $D_2$  folds (see maps 3 and 10 map box) and is associated with overshear towards the S.E. (Fig 3.11).  $D_7$  is a late deformation of regional significance, producing N-S trending refolds of the earlier formed structures.

### 3.2) The first deformation (D1)

The earliest fabric is an alignment of muscovite, chlorite and quartz, being best observed in the hinges of later folds. S1 could nowhere be distinguished with satisfaction in the field. However, thin section studies from quartzite in the hinge of the D3 Gaugin Synform (see 4.2) (G 980950) clearly reveal its presence (Plate 15a.). No B lineations associated with the first deformation have been mapped, and hence the suggestion of S1 vergence to the west or north west is tentative and based on wider regional correlations (see Chapter 6).

Although minor features associated with the first deformation have since been largely obliterated by later deformation, a major dislocation which originates at this stage has been recognised. This structure, named the Central Donegal slide <sup>(named on Map 1 and 10, map box)</sup> can be traced for approximately 20 Km along strike before being cut by later ductile dislocations or Caledonide (NE-SW) faults.

The slide, now marked by a zone of tectonic schist (see 3.3f.) everywhere separates rocks which ubiquitously young away from it. Little apart from the broad geometry remains of the form of this early structure.

After unfolding later deformations, it would appear that the Central Donegal slide separated younger rocks (tectonic package B) above, from older rocks below (tectonic package A), (Figure 3.1). As such it had an overall lag geometry (younger rocks being emplaced over older), but with a probable thrust shear sense (see Chapter 6). It is probable that the Central Donegal slide was initiated as a discrete zone of displacement, in the lower greenschist facies of metamorphism. This Central Donegal slide, marked by tectonic schist and a reversal in younging is clearly folded by structures of D2 and D3 age. ✱

### 3.3) The second deformation (D2) - Map 2 (map box)

The overall structure relating to the second deformation is that of kilometre scale sheath folds suggesting shear towards the south east. Prior to a description

\* Topography has no significant affect on the refolding outcrop pattern.

KEY TO OPPOSING PAGE



BOULTYPATRICK GRITS



CROAGHUBBRID PELITES



CENTRAL DONEGAL SLIDE



REELAN FORMATION



GAUGIN QUARTZITE (WITH TILLITE AT BASE)



CROVEENANANTA FORMATION



DIRECTION OF YOUNGING



TECTONIC PACKAGE B



TECTONIC SCHIST



TECTONIC PACKAGE A

# POST D<sub>1</sub> GEOMETRY

TECTONIC PACKAGE B

TECTONIC PACKAGE A

- Termon / Lough Eske Fm.
- Boulypatrick Grit
- Croaghubrid Pelite
- central Donegal slide
- Reelan Fm.
- Gaugin Quartzite (tillite at base)
- Croveenananta Fm.
- Tectonic Schist

sedimentary transition

Central Donegal Slide

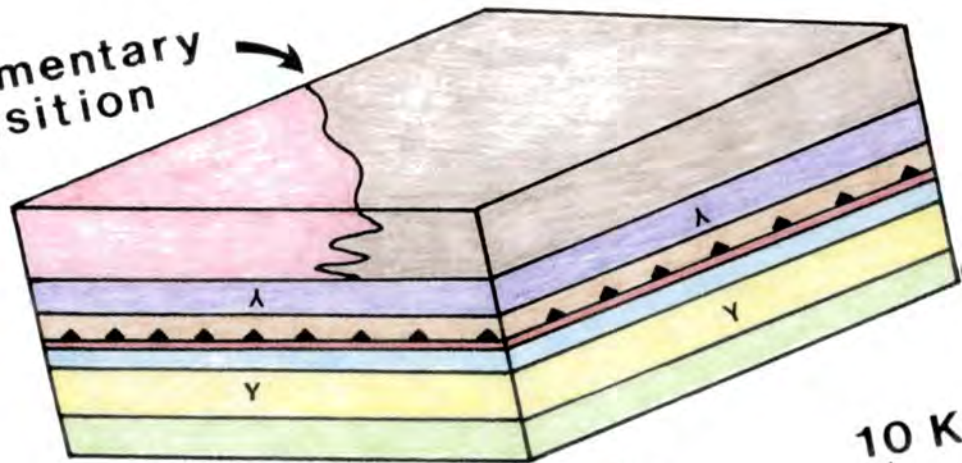


FIGURE 3.10

of the sheath folding in central Donegal, a general account of such structures will be given.

### 3.3a) Sheath folding

Fold axes are commonly regarded as being sub-perpendicular to the trend of tectonic transport, which is assumed to parallel the stretching lineation. However, many zones of intense ductile strain exhibit folds which lie oblique to, and occasionally sub-parallel to the transport trend (stretching lineation). These folds are found to display strong curvilinearity along the fold axis, which in extreme cases may result in a conical three dimensional form termed a sheath fold. Thus sheath folds are in essence highly curvilinear folds elongated parallel to the trend of tectonic transport (Quinquis et al, 1980, Carreras et al, 1977, Minnigh 1980, Roberts et al, 1984, Holdsworth and Roberts, 1984, Holdsworth et al, 1987, Borradaile 1972, Henderson 1981, Lacassin and Mattauer 1985). An example of a small scale sheath fold from the Moine rocks of the Northern Highlands of Scotland is shown in Plate 16a., whilst more complicated refolding relationships and multiple generations of sheath folds are displayed in Plate 16b.

Generation of sheath folds is commonly regarded as a passive rotation towards the transport direction of fold axes which initiated at approximate right angles to this trend. Such rotations require progressive ductile deformation, with both external pure shear (irrotational) and simple shear (rotational) being capable of producing sheath folds (Figure 3.2.).

The process of generating a sheath fold in a simple shear regime is shown diagrammatically in Figure 3.2b. Fold axes initially form at approximate right angles to the transport direction, with the axial (XY) plane inclined at  $45^\circ$  to the shear plane. Natural folds possess a slight initial hinge curvature which with progressive simple shear is accentuated as the axial plane rotates towards the shear plane.

Individual fold hinges which lie on opposing sides of the stretching lineation will rotate in a counter sense (towards this lineation), with in the axial (XY)

FIGURE 3.2.

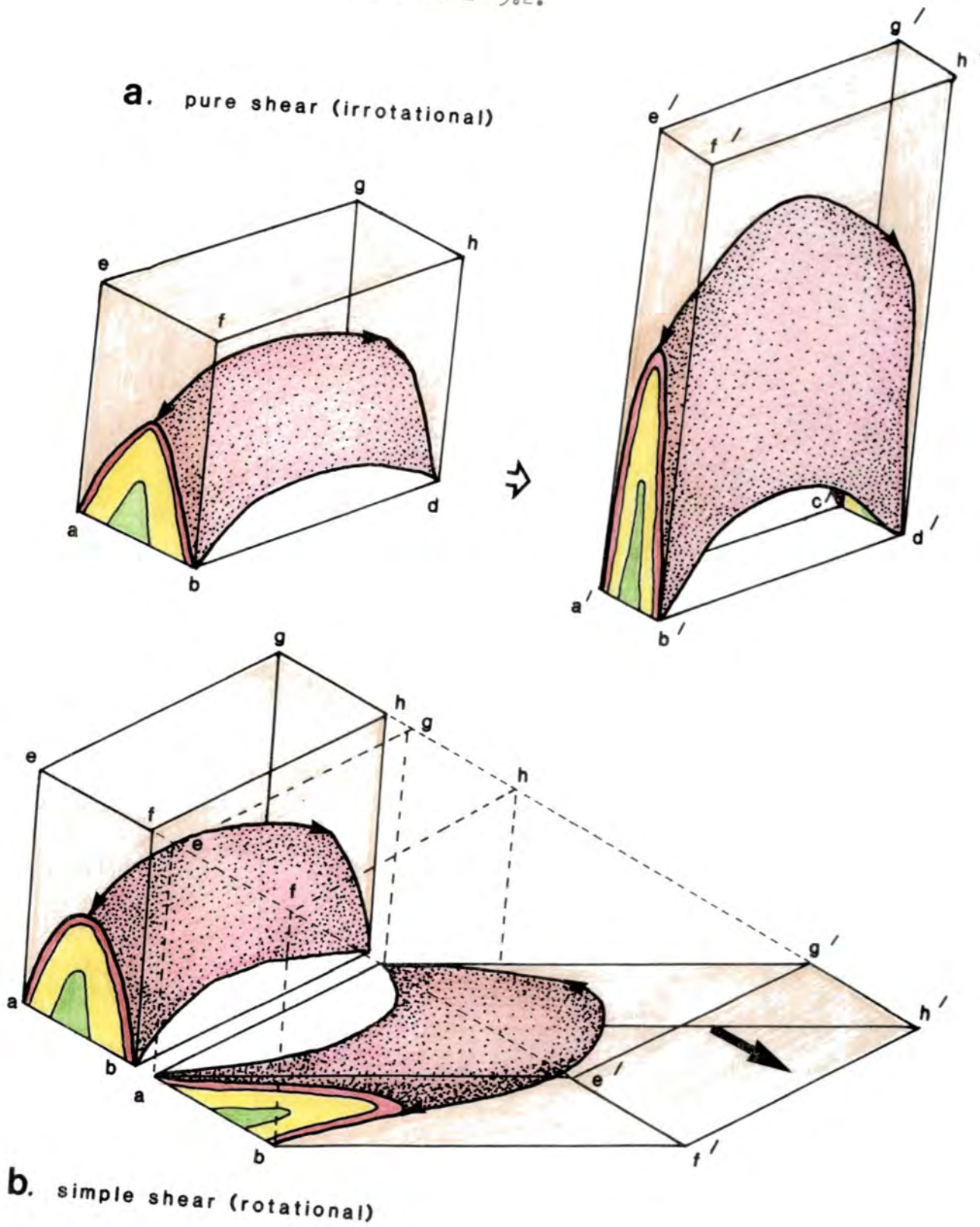
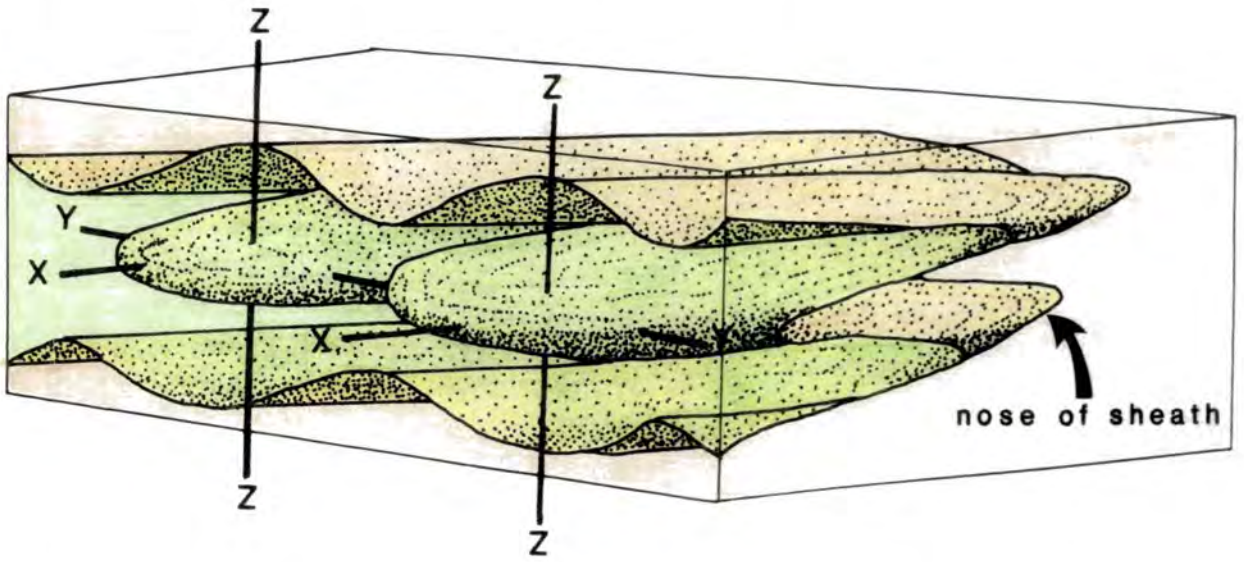


FIGURE 3.2.

MECHANISMS OF  
SHEATH FOLD  
GENERATION.

a. Block diagram of sheath folds (with axes)



b. Orthogonal sections through principal axes of sheath folds

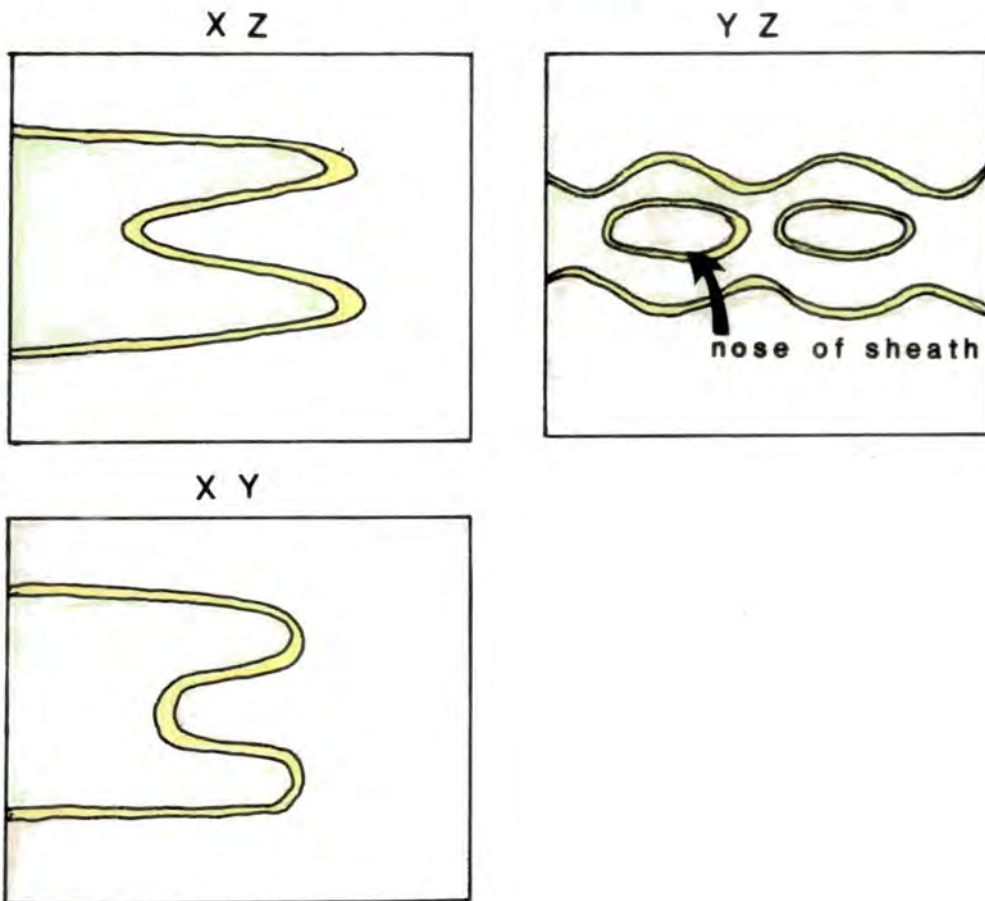


FIGURE 3.3.

plane of the developing fold. In areas of intense ductile simple shear, sheath folds with axial (XY) planes lying at low angles to the shear plane, and fold hinges (X) developed parallel to the stretching direction may be seen. A block diagram of sheath folds and associated principal axes is shown in Figure 3.3.

Sheath folds on a Kilometre scale are thought to comprise the major D2 structure of central Donegal. Their overall geometry will be described in detail following a description of minor D2 structures seen throughout the mapped area.

In general throughout the area, S2 lies close or parallel to bedding and is defined by a grain shape and alignment fabric of quartz, biotite, muscovite and opaques. <sup>(Plate 15b)</sup> The crenulating nature of the S2 fabric is only rarely preserved in the hinges of later folds eg. Gaugin Synform (D3) (G 980950) (Plate 15a.).

### 3.3b) D2 Area 1

The second deformation is responsible for the main fabric seen at outcrop on the upper normal limb of the Ballybofey Antiformal complex (D3) (Chapter 4.). However on the inverted limb of this structure, the component of D3 shearing has increased substantially, and only in rare instances e.g. Silver Hill (G 910910), can both S2 and S3 fabrics be distinguished with certainty. Hence, on the inverted limb the main fabric has been identified and mapped as a composite cleavage (S2-S3).

The present disposition of S2 surfaces is clearly governed by later folding relating to the D3 Ballybofey Antiformal complex, and the Ballard Antiform (D7), (Map 2- map box). Over much of area 1, S2 dips moderately to steeply North (Figure 3.4a.). Only on the northern slopes of Gaugin Mountain (G 980960) does it dip consistently south, due to the influence of D3 folding.

The composite S2-S3 fabric on the inverted limb of the Ballybofey Antiformal complex (D3) has been treated as a separate data sub-set for structural analysis (sub-area 1B, Figure 3.4c.). It dips consistently to the north over much

**Figure 3.4a.**

**S2 - Area 1.**  $n = 1552$ , maximum concentration of data = 066/59S, mean = 087/88N, pole to the great circle = 30/090 (corresponds to refolding by F3 ).

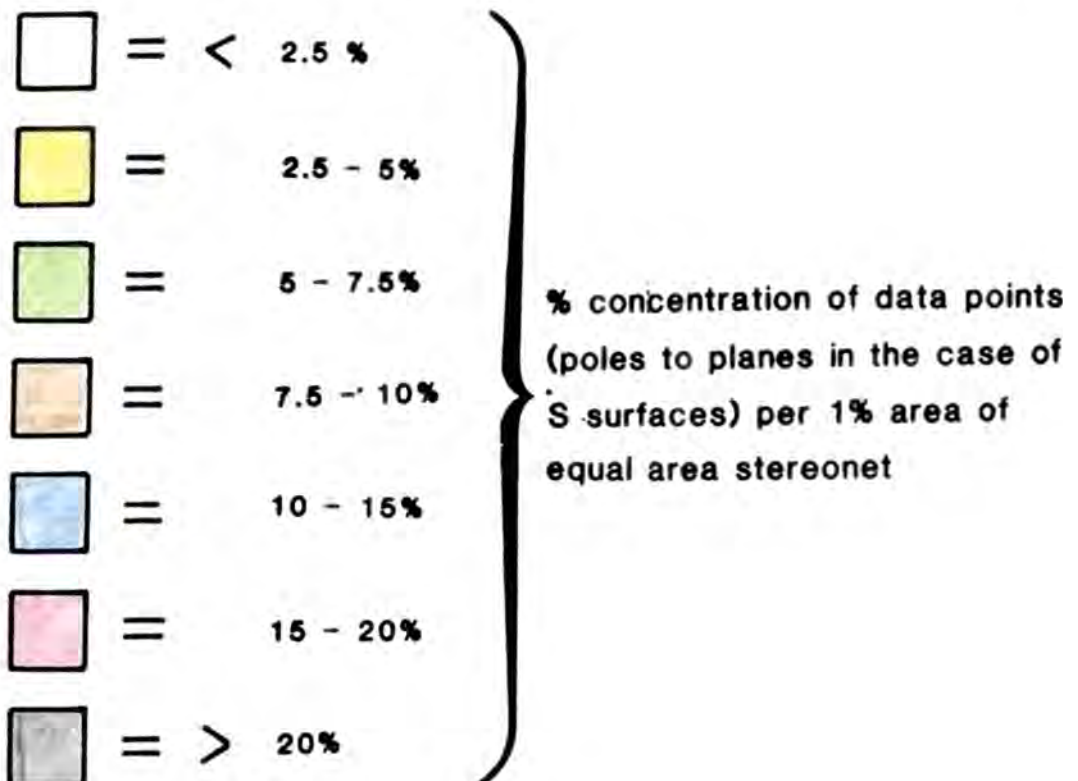
**Figure 3.4b.**

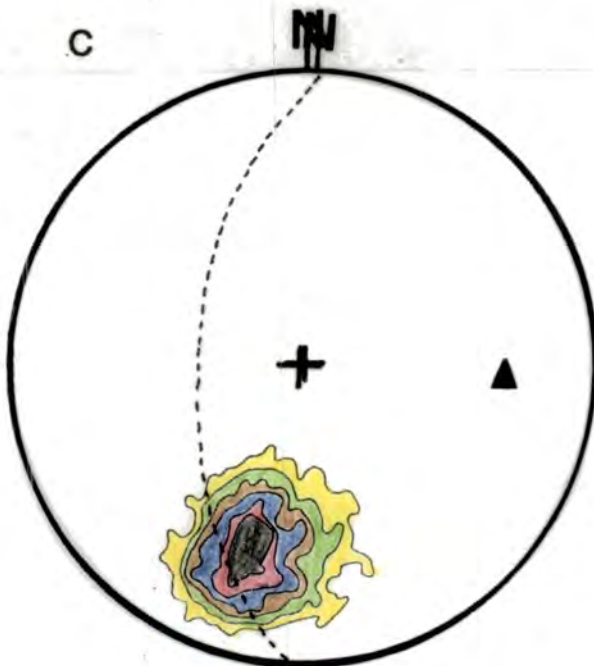
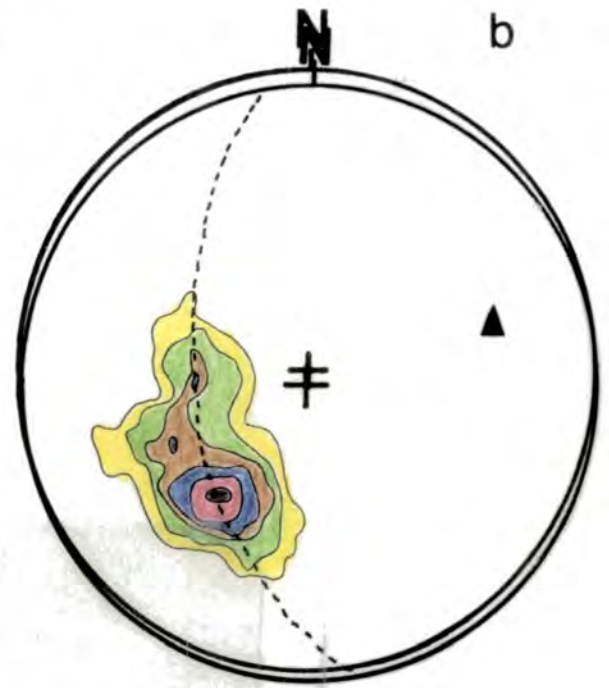
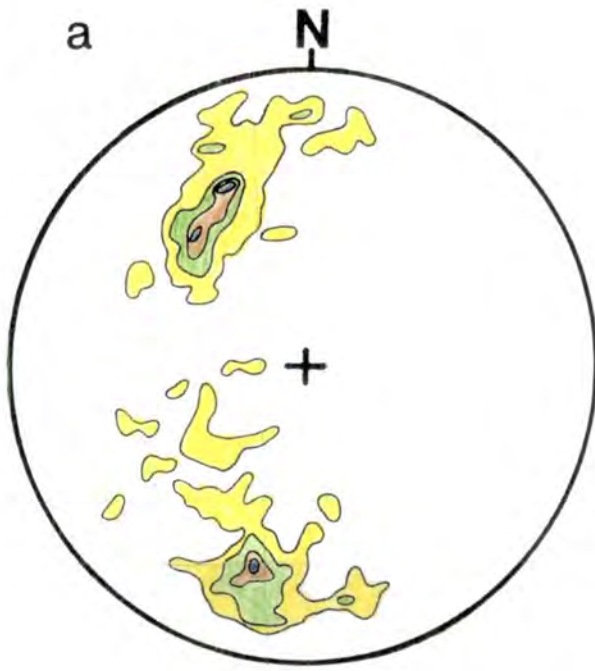
**S2 - Gaugin Synform (F3).**  $n = 91$ , maximum concentration of data = 124/44N, mean = 139/41N, pole to the great circle = 32/079 (corresponds to refolding by F3).

**Figure 3.4c.**

**S2-S3 - Area 1b.**  $n = 2013$ , maximum concentration of data = 104/57N, mean = 102/59N, (S2-S3 is a composite cleavage developed on the inverted limb of the D3 Ballybofey Antiform).

**Contour intervals on equal area stereograms shown on facing page**





of the area at moderate to steep angles.

Few folds have been observed at outcrop scale that can be unambiguously correlated with the second deformation. The scarcity of such data may be attributed to the intensity of D2, with F2 becoming intrafolial, and also to the intensity of deformation associated with the Ballybofey Antiformal complex (D3). Where F2 folds have been observed, they are found to be small scale (short middle limbs less than 50 cm), tight folds that are defined by bedding (S0), and coplanar S1.

S2 is axial planar to F2, the intersection of S2 with S0 and S1 producing an intersection lineation which parallels minor F2. These linear elements associated with the second deformation have collectively been termed B2 lineations, and plunge gently/moderately to the east in sub-area 1 (Map 2 - map box), (Figure 3.5a.). Small scale sheath folds (Y axes of less than 30 cm in length) have been observed in the banded limestones and calc-pelites of the Reelan Formation at Stragally bridge (H 012962). S2 is developed parallel to the XY plane of the sheath, whilst a mineral elongation lineation parallels minor F2 hinges and plunges down through the 'eye' of the sheath (Plates 17a., 17b.). The rarity of observed sheath folds within the mapped area may be related to the requirement of a Y Z oriented exposure cutting through the nose or cap of a sheath, together with the necessity of a banded or well foliated rock to aid in the definition of the sheath form.

↕  
 D2 structures appear to have no consistent sense of vergence through area 1. <sup>New paragraph</sup> Associated with the second deformation is the development of a strong mineral elongation lineation, defined largely by quartz and occasional feldspar. From grain shapes this lineation is thought to be a stretching lineation, and therefore represents the direction of maximum extension, i.e. the X axis of the finite strain ellipsoid. On the inverted limb of the D3 Ballybofey Antiform, it is apparent that no new stretching lineation has developed in areas of high D3 strain. The mineral elongation lineation observed within this area (area 1 B)

Figure 3.5a.

**B2 Lineations - Area 1.**  $n = 16$ , maximum concentration of data = 40/088, mean = 30/091.

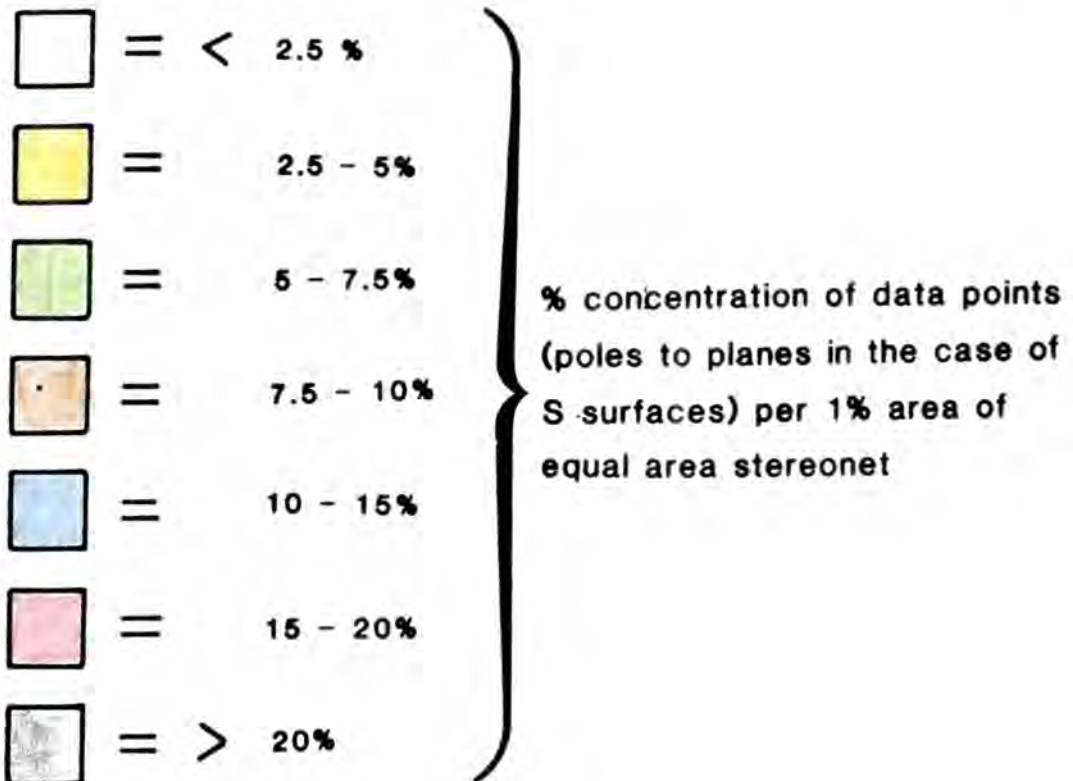
Figure 3.5b.

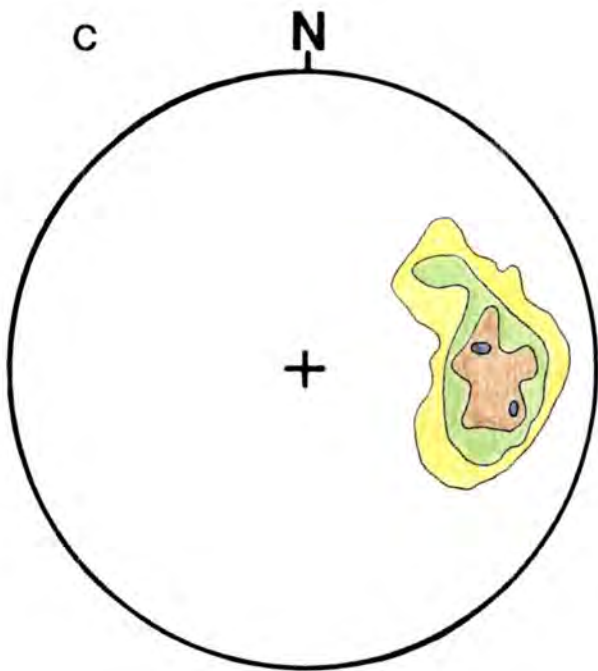
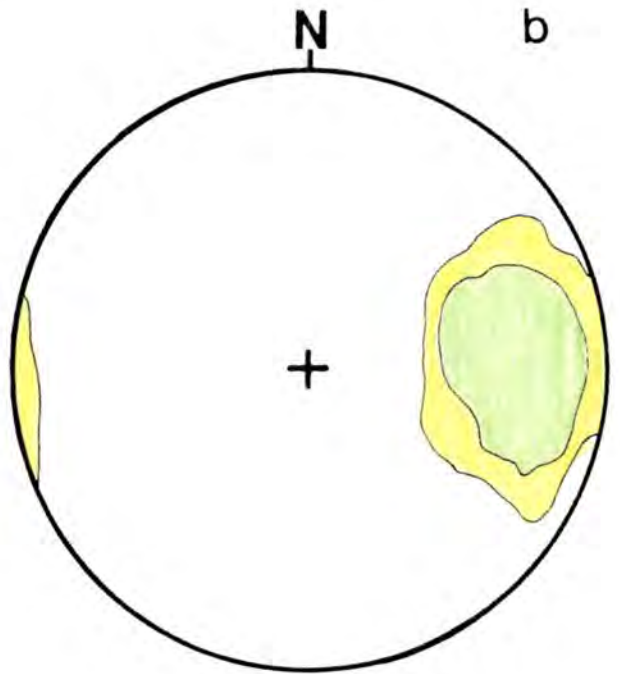
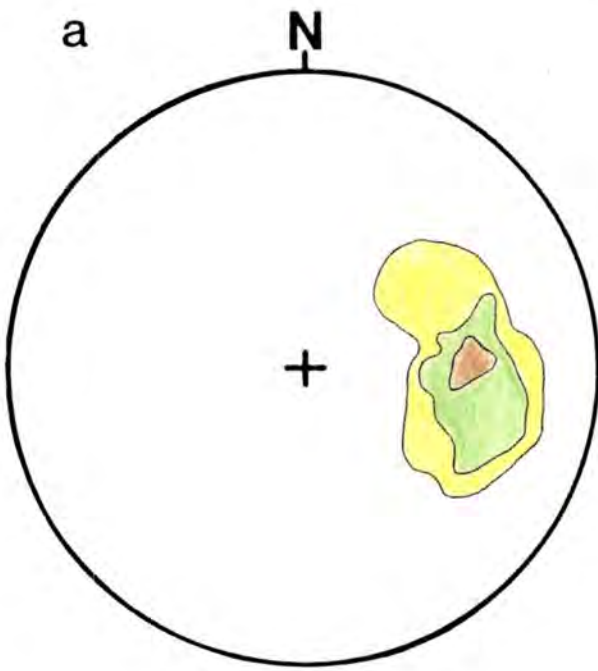
**B2 Lineations - Area 2/Area 3.**  $n=8$ , maximum concentration of data = 32/090, mean = 23/090.

Figure 3.5c

**B2 Lineations - whole of map area.**  $n = 24$ , maximum concentration of data points = 37/083, mean = 27/090.

**Contour intervals on equal area stereograms shown on facing page**





may be a composite structure produced during coaxial second and third deformations. In zones of intense D2-D3 deformation e.g. Croveenananta townland (G 945940), F2-F3 axes are found to parallel the stretching lineation producing mullion structures (Plate 18b.). On the upper normal limb of the Ballybofey Antiform (D3), the mineral stretching lineation parallels B2 and plunges gently towards the south east on S2 (Figure 3.6b.). Slight variations in the plunge and azimuth of the stretching lineation are due to the effects of later D3 folding followed by late stage warping (D9). The stretching lineation is clearly folded by the D3 Gaugin Synform on Gaugin mountain (G 982950) (Map 14 - map box). Stretching lineations have also clearly been reoriented in the vicinity of the D7 Ballard Antiformal hinge (Map 9 - map box). On the inverted limb of the D3 Ballybofey Antiform, and to the north of D3 tectonic sliding adjacent to the Lough Eske Psammite (Map 13 - map box), lies a zone of intense D2 and D3 shear. Within this area mineral lineations are of a composite D2-D3 nature and commonly plunge gently to the north west on the S2-S3 fabric (Figure 3.6c.), (Map 13 map box). Farther south within the Lough Eske Psammite the mineral elongation lineation plunges gently/sub-horizontally to the north west on the composite S2-S3 fabric (Figure 3.6d.). It would appear that the Central Donegal slide represents a structural break, separating gently south east plunging D2 mineral elongation lineations in the north, from composite D2-D3 gently north west plunging mineral elongation lineations in the south (Map 9 - map box). To account for this variation in attitude, a late D3 clockwise rotation (looking North) of approximately  $30^\circ$  is postulated along the Central Donegal slide. Mineral elongation lineations for the whole of area 1, trending West North West-East South East and of variable plunge (as discussed above) are shown on Figure 3.6a.

### 3.3c) D2 Area 2

S2 dips consistently towards the north east (Figure 3.7a.) and is axial planar to mesoscopic F2, with short limbs less than 1 m long and of a tight reclined

**Figure 3.6a.**

**Mineral elongation lineation - Area 1.**  $n = 672$ , maximum concentration of data points = 13/290, mean = 1/112. Spread of data points corresponds to refolding by F3, F7 and F9 folds.

**Figure 3.6b.**

**Mineral elongation lineation - Sub-Area 1a.**  $n = 261$ , maximum concentration of data points = 42/125, mean = 27/114. The spread of data points corresponds to refolding by F3, F7 and F9 folds as above (Figure 3.6a.).

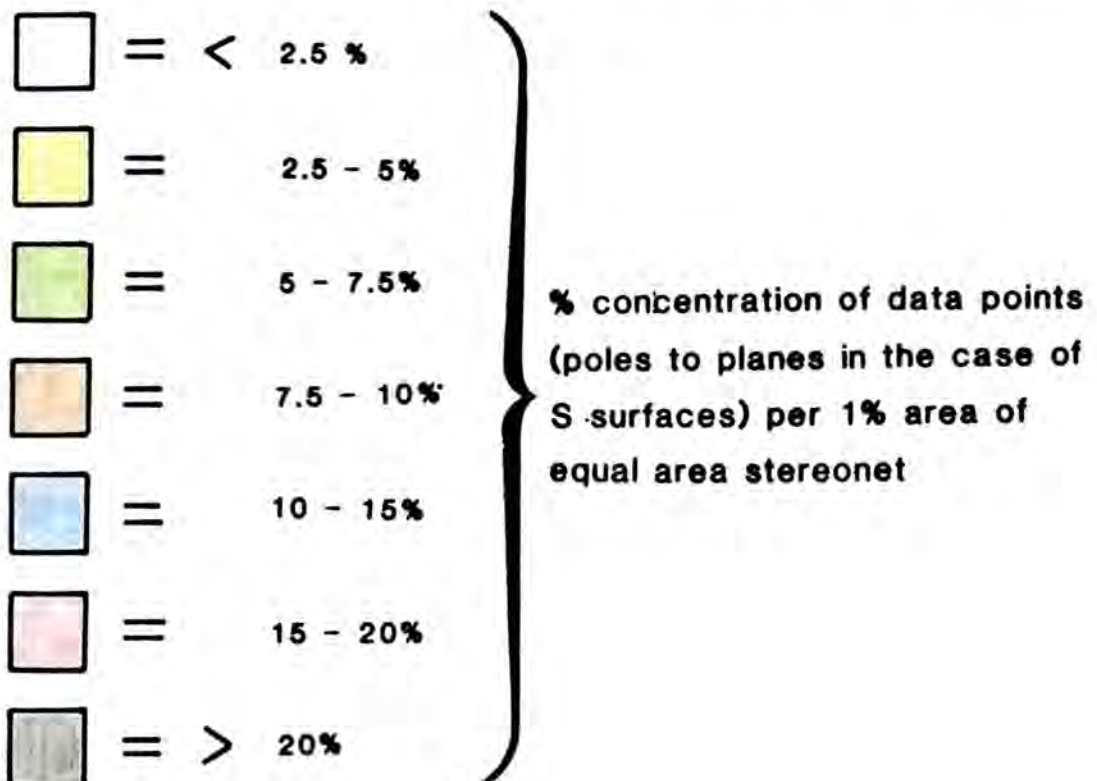
**Figure 3.6c.**

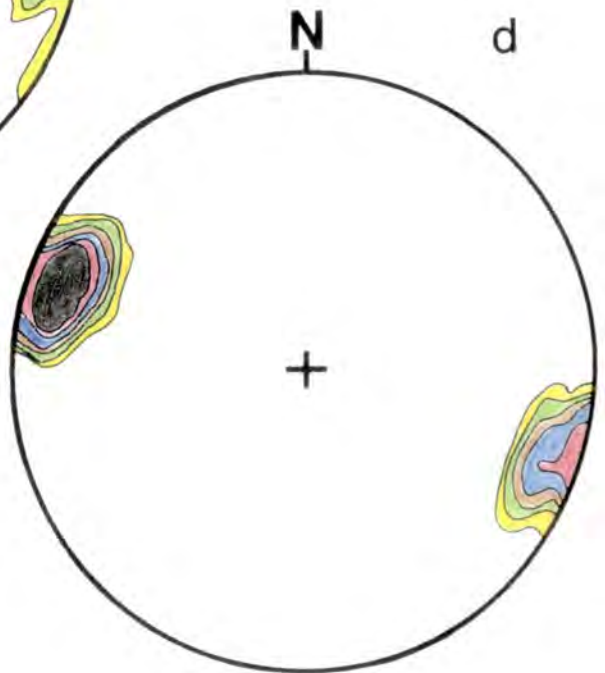
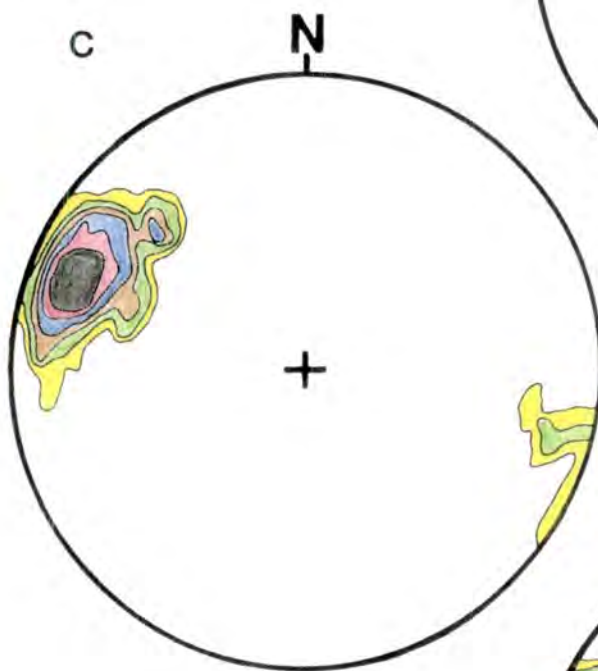
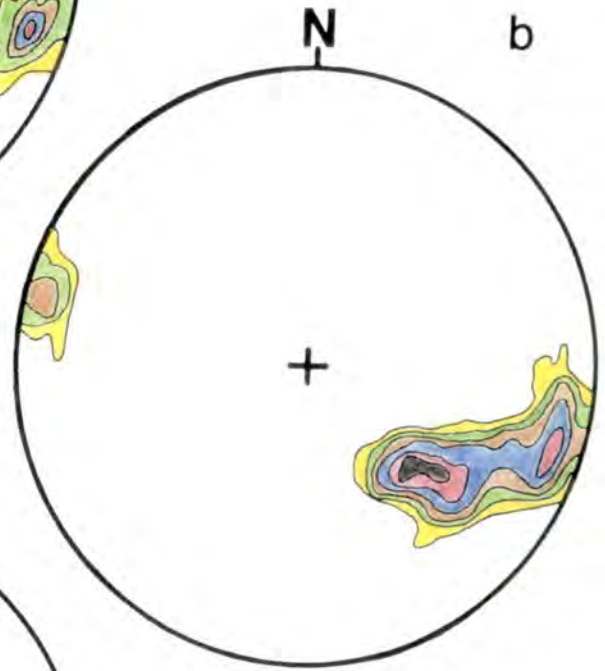
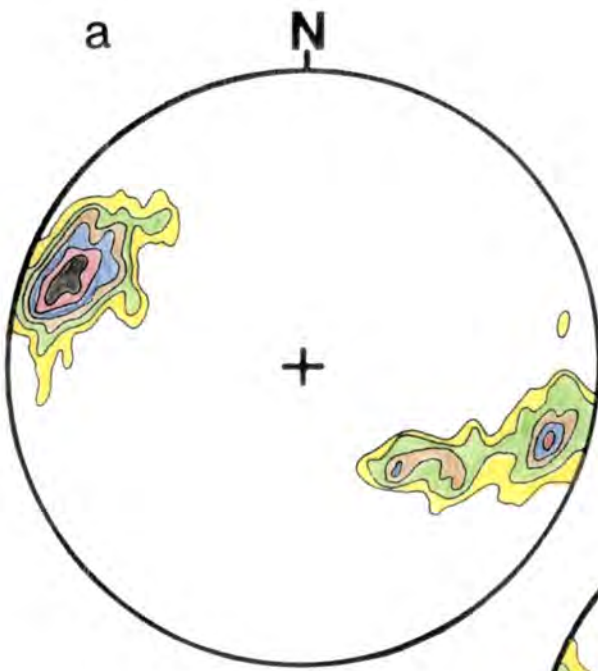
**Mineral elongation lineation - Sub-Area 1b. (data confined to the north of the the D3 Ballybofey slide)**  $n = 335$ , maximum concentration of data points = 16/294, mean = 16/291

**Figure 3.6d.**

**Mineral elongation lineation - Sub-Area 1b. (data confined to the south of the D3 Ballybofey slide)**  $n = 76$ , maximum concentration of data points = 11/287, mean = 7/290

**Contour intervals on equal area stereograms shown on facing page**





**Figure 3.7a.**

**S2 - Area 2.**  $n = 847$ , maximum concentration of data points = 142/30N,  
mean = 135/28N.

**Figure 3.7b.**

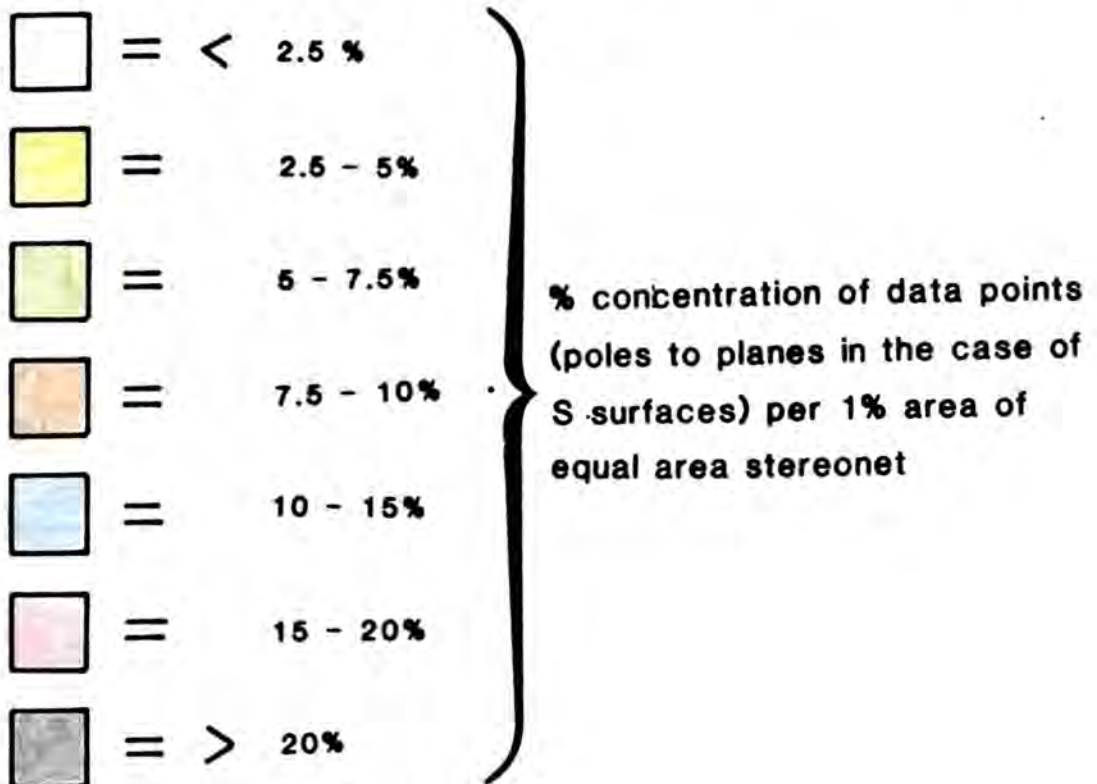
**S2 - Area 3.**  $n = 1864$ , maximum concentration of data points = 164/40N,  
mean = 166/38N.

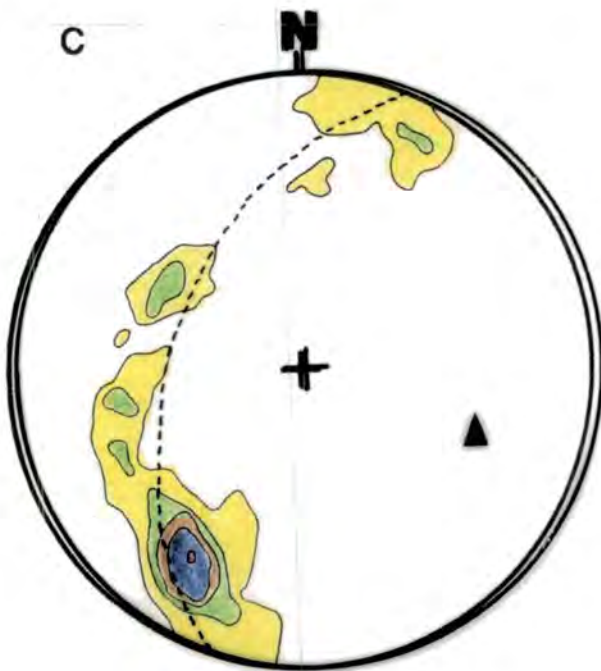
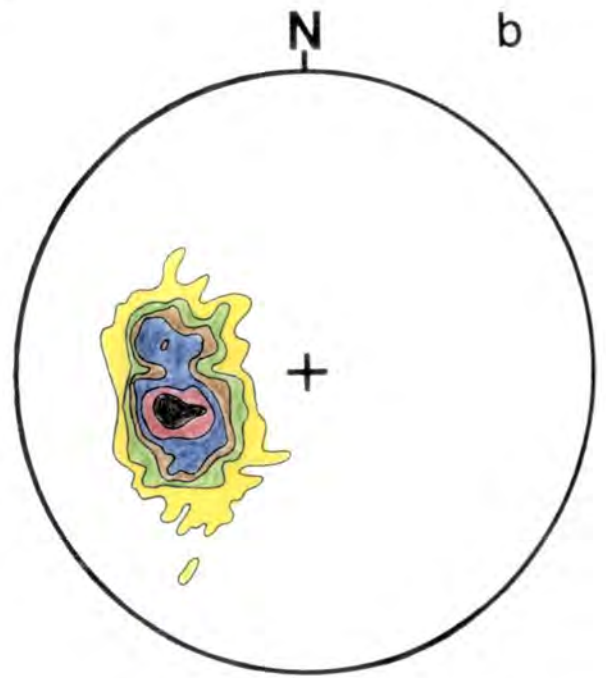
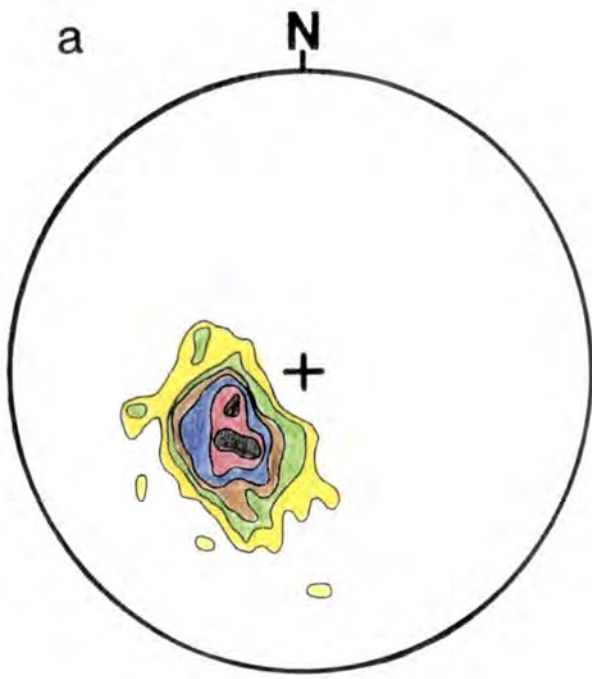
**Figure 3.7c.**

**S2 - Altnapaste / Gorey Hill Sub-Area.**

$n = 90$ , maximum concentration of data points = 123/65N, mean = 134/66N,  
pole to the great circle = 40/110 (corresponds to refolding by the F3 Bally-  
bofey Antiform).

**Contour intervals on equal area stereograms shown on facing page**





attitude (Altlahan (C 027008)). F2 fold axes and S2/ S0-S1 intersection lineations are parallel (B2), plunging gently to the East North East (Map 2 map box) (Figure 3.5b.). The mineral elongation lineation associated with the second deformation plunges gently to the south east on S2 (Map 9- map box) (Figure 3.8a.). In the northern part of area 2 the disparity in orientation between B2 and the D2 mineral elongation lineation suggests a lower state of D2 strain and limited rotation of F2 towards the stretching (X2) direction.

There is no consistent sense of D2 vergence, although in the northern part of area 2 there is a greater tendency for S2 to face and verge North on S0-S1. In the southern portion of area 2 southerly vergence and facing are more common. This is suggestive of the presence of a F2 axial trace running along the northern slopes of Crocknahamid and Boulypatrick in the central portion of the mapped area (Map 2 - map box). The repetition of Boulypatrick Grits to the north of the River Finn and on Boulypatrick itself (G 968980) also suggest the existence of such a hinge.

### 3.3d) D2 Area 3

In Area 3, S2 is folded around the D3 Ballybofey Antiform, this is most clearly witnessed in the Altnapaste / Gorey quartzite bodies (Map 16 - map box) (Figure 3.7c.). S2 dips more steeply to the East North East on the lower inverted limb of the Ballybofey Antiform, the upper normal limb being of a more gently dipping nature (Map 2 - map box). Few B2 lineations have been identified in area 3, observations suggest that they plunge gently towards the east on S2 (Figure 3.5b.). The mineral elongation lineation developed in area 3 is an intense structure plunging gently towards the south east on S2 (Map 9, Map 16 map box), (Figure 3.6b). In some instances within the Altnapaste/Gorey quartzite bodies, D2 fold axes have rotated in to parallelism with the stretching direction (defined by the mineral elongation lineation) to produce mullion structures (Plate 18a.).

Figure 3.8a.

**Mineral elongation lineation - Area 2.**  $n = 14$ , maximum concentration of data points = 12/118, mean = 8/116.

Figure 3.8b.

**Mineral elongation lineation - Area 3.**  $n = 299$ , maximum concentration of data points = 27/133, mean = 26/128.

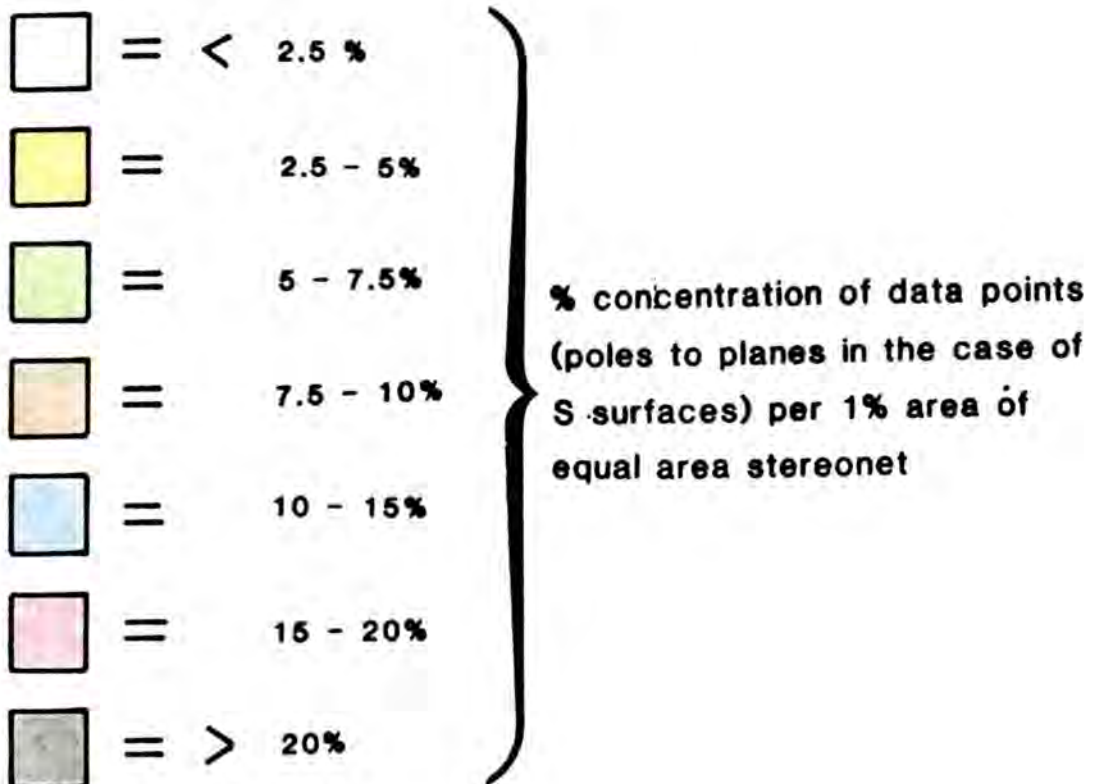
Figure 3.8c.

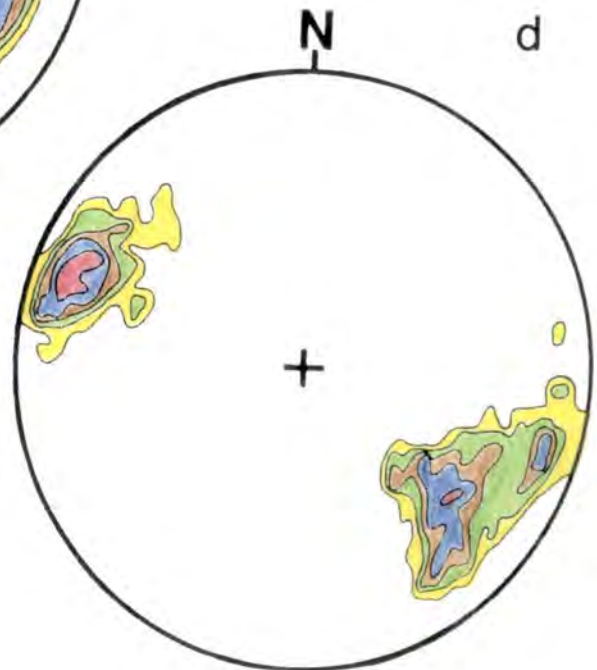
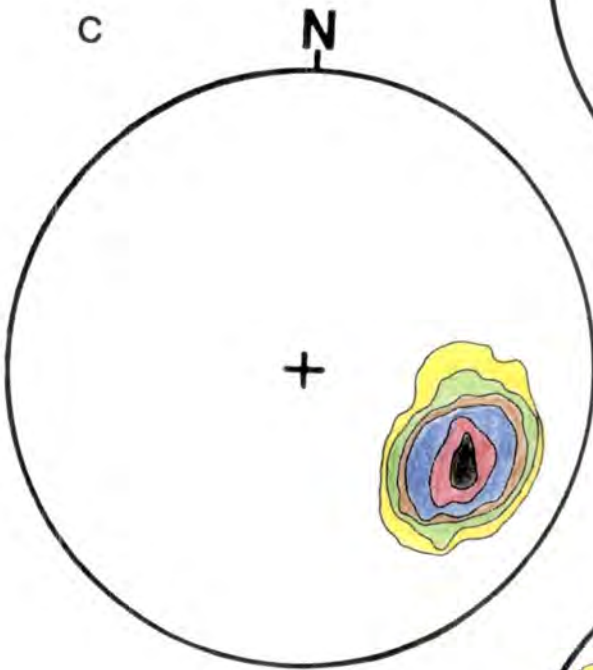
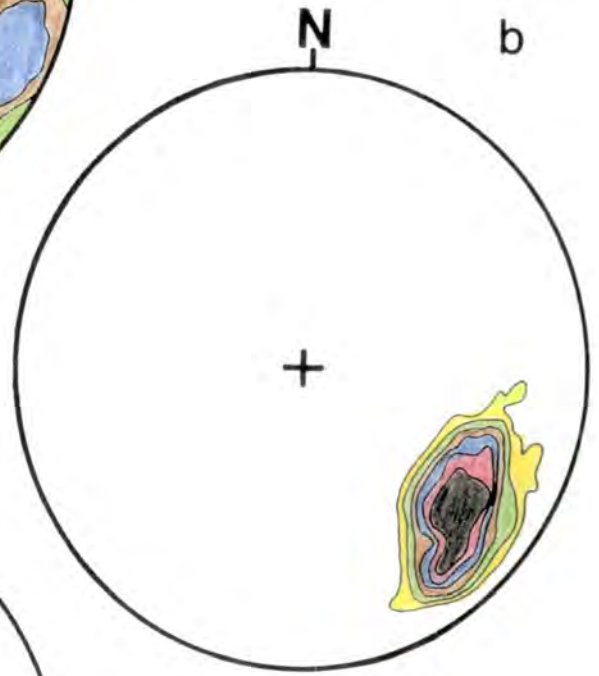
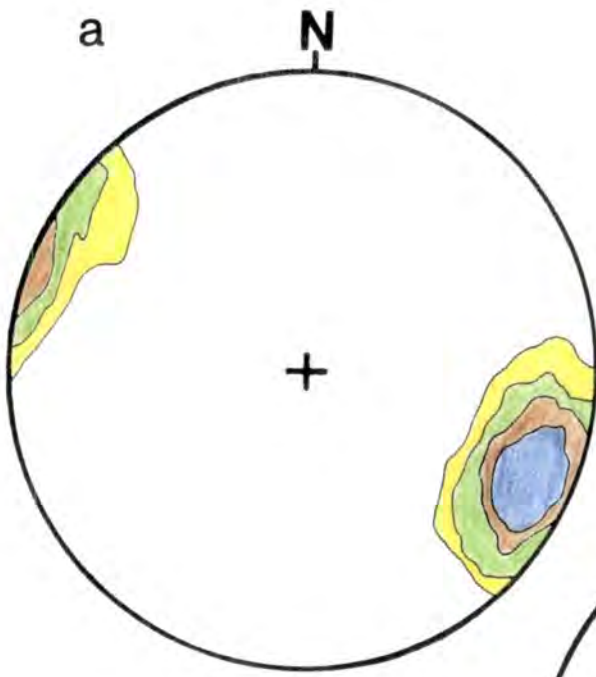
**Mineral elongation lineation - Altnapaste / Gorey Hill Sub-Area.**  $n = 32$ , maximum concentration of data points = 32/120, mean = 36/116.

Figure 3.8d.

**Mineral elongation lineation - whole of map area.**  $n = 985$ , maximum concentration of data points = 12/290, mean = 9/117. Bimodal distribution is a product of refolding by F3, F7 and F9, together with rotations along later slide planes.

**Contour intervals on equal area stereograms shown on facing page**





### 3.3e) D2 synthesis

On the gross scale the refolding affects of the D2 folds on the Central Donegal slide are apparent, as are the later refolding structures associated with the Ballybofey Antiformal complex (D3) (Map 10 map box).

In the south eastern portion of the mapped area (sub-area 3) it is apparent that prior to the development of the Belshade Fault, the Altnapaste/Gorey quartzite bodies constituted a single mass (Map 2 - map box). Restoration of movement on the Belshade Fault to enable the Altnapaste/Gorey quartzite bodies to coincide (together with partial restoration of the displaced Barnesmore pluton contact) suggests an original net sinistral displacement of 3 Km on this fault. In addition, slickenside observations on Altmore cliff (H 052957) indicate a downthrow to the south east which from the restoration was approximately 1.4 Km. From work within the Barnesmore Pluton, Walker and Leedal (1954) also suggest a significant downthrow towards the south east on the Belshade Fault, as do Pitcher et. al. (1964) in their regional synthesis of the Leannan Fault system. The restored quartzite body then forms a single mass enclosing pockets of Reelan Formation calcareous pelites, and is itself enveloped by tectonic schists of the Central Donegal slide and the Croaghubbrid Pelites of tectonic package B (see section 2.3a.). The quartzite mass forms a closed outcrop pattern, which when the affects of the Ballybofey Antiform (D3) are removed, is eye shaped. This outcrop pattern is indicative of a Z Y cross section through the the 'nose' or 'cap' of a sheath fold (Quinquis et al., 1978). The present approximate Y Z erosional section exposes a Y axis of the order of 5 Km long, and a Z axis of 0.75Km (Figure 3.9.). The intense mineral elongation lineation and mullion structure previously described plunge gently towards the south east down through the 'eye' of the sheath (Figure 3.8c.). These structures are representative of the X direction in the sheath and parallel B2 lineations measured in the whole of the area (Figure 3.5c.).

Shear sense (asymmetric pressure shadows, extensional crenulations) (Simp-

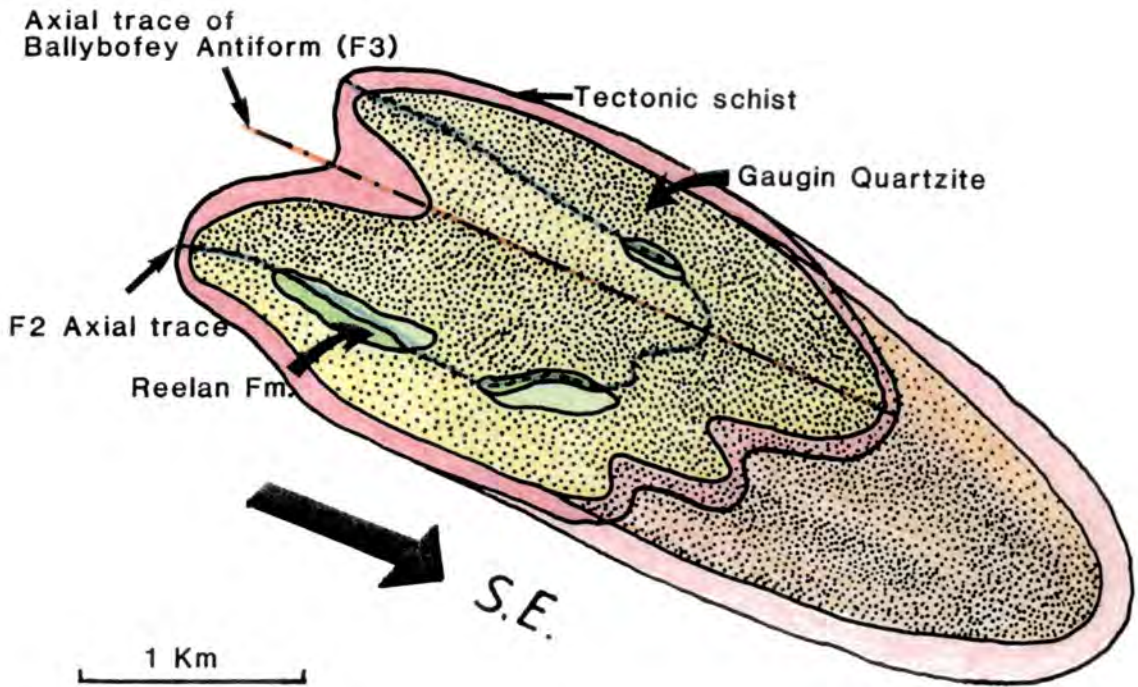
son and Schmidt 1983) within the tectonic schists of the Central Donegal slide which envelopes the Altnapaste/Gorey quartzite body are consistent with the quartzite mass having been sheared and 'intruded' laterally into the surrounding metasediments of tectonic package B (see 2.3). Thus, the suggestion is that the Altnapaste/Gorey sheath sheared towards and closes towards the south east.

Approximately 2 Km West of Altnapaste in sub-area 1, the gross outcrop pattern of the Reelan Formation is clearly controlled by the refolding affect of the Ballybofey Antiform (D3) on an earlier hinge (Map 10 - map box). This early hinge is regarded as originating during the second deformation as it folds the Central Donegal slide and its associated younging reversal of D1 age (Commeen (H 010965)). The repetition of Gaugin Quartzite at Slievemullagh (H 010950) and Bindoo (H 035963) is directly attributable effects of this D2 Commeen fold. A reversal in younging across the F2 axial trace is witnessed by the positioning of the Port Askaig Tillite at the stratigraphic base of the Gaugin Quartzite on either limb of the D2 Commeen fold (western limb - Gaugin Mountain (G 085960), eastern limb - Tonduff (H 043955)).

Thus, the Reelan Formation is preserved in the hinge zone of the D2 Commeen fold which has subsequently been refolded by the Ballybofey Antiform (D3). This is analogous to the preservation of pockets of Reelan Formation in the Altnapaste/Gorey D2 sheath fold. In the case of the Altnapaste/Gorey sheath fold the Reelan Formation is completely enveloped by the Gaugin Quartzite. Clearly this is not the situation in the Commeen fold, with the Gaugin Quartzite frequently being absent adjacent to the tectonic schists of the central Donegal slide (Commeen (H 010965), Ballard (H 023955)) (Map 2, Map 15 Map box). The gradual thinning and in some instances necking of the Gaugin Quartzite (Drumderrydonan (H 003965)) are regarded as lower strain <sup>expressions prior</sup> to its complete cut out by tectonic sliding (see 3.3e).

Gaugin Quartzite is present in the hinge of the Ballybofey Antiform (D3) at

**a.** SCHEMATIC DIAGRAM OF FOLDED ALTNAPASTE/GOREY SHEATH (D2)



**b.** SCHEMATIC DIAGRAM OF ORIGINAL D2 SHEATH (WITH SHEAR SENSE)

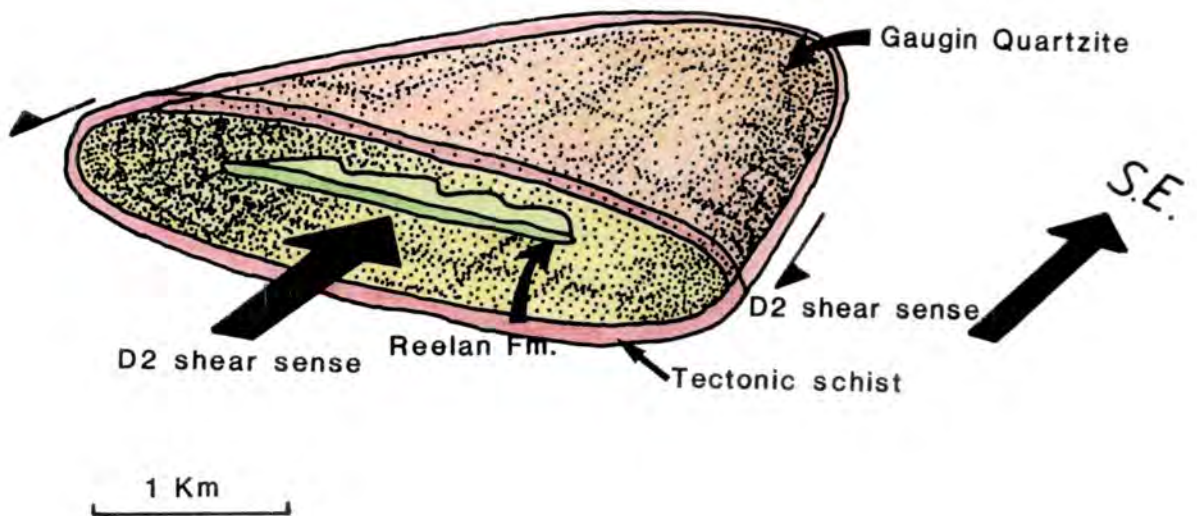


FIGURE 3.9.

Bindoo (H 035963). Moving away from this hinge zone the quartzite is thinned and excised on both the upper and lower limbs of the Ballybofey Antiform. This indicates that a component of D3 shear is partially responsible for the cutting out of the Gaugin Quartzite adjacent to the Central Donegal slide. Indeed Gaugin Quartzite and tectonic schists relating to the Central Donegal slide have been cut out against a D3 tectonic slide on the lower inverted limb of the Ballybofey Antiform (D3) (Letterkillew (H 015943)) (Map 2 map box). Thus, prior to polyphase tectonic sliding (D1-D2-D3), the presently exposed dismembered Gaugin Quartzite lenses constituted a single body which completely enveloped the Reelan Formation in the hinge of the D2 Commeen Fold.

To the south of Gaugin Mountain (G 925940) the hinge of the D2 Commeen Fold is defined by the closure of the Reelan Formation in the surrounding Gaugin Quartzite. Approximately 1 Km farther west of this closure, the axial trace of the Commeen Fold appears to have been cut out against the tectonic schists of the Central Donegal slide during D3 sliding (see 4.6) (Maps 2,14 map box). To the south and west of Gaugin Mountain, the Croveenananta Formation is enclosed by the Gaugin Quartzite in the hinge of a D2 fold, the Croveenananta Fold. As this fold has rocks older than the Gaugin Quartzite preserved in its hinge it is impossible to equate with the Commeen Fold (which has rocks younger than the Gaugin Quartzite in the hinge zone).

The Reelan Formation/tectonic schist contact at Commeen (H 010965) defines the original position of the Gaugin Quartzite at this horizon. The absence of the quartzite in this D2 hinge zone suggests excision of the quartzite during D1 tectonic sliding, or more probably early during the second deformation. As in the case of the D2 Altnapaste /Gorey sheath Fold there is a strong mineral elongation lineation which plunges gently towards the north east through out the D2 hinge zone. The presence of this mineral lineation together with the partially dismembered 'eye' shaped outcrop pattern is similar to the more complete geometry of the Altnapaste/Gorey D2 sheath fold. It is apparent that both

the Commeen Fold and the Altnapaste/Gorey sheath fold had a similar original geometry. Gaugin Quartzite encloses the younger Reelan Formation, and is itself enveloped by tectonic schists of the Central Donegal slide and younger rocks of tectonic package B. The present state and disposition of these D2 folds is a product of intense later deformation associated with the Ballybofey Antiformal complex (D3). The original geometries of both folds are similar, both being envisaged as km scale sheath folds. The present ground surface forms an approximate Y Z cross section through the nose of each sheath.

As both the Altnapaste/Gorey D2 sheath fold and the Commeen Fold have the youngest rocks of tectonic package A in the core of the fold, it is apparent that they both have the same structural geometry ie. they will close in the same direction. This being the case, the necessity arises for a D2 fold of opposing geometry ie. a return hinge, to be present between the two major sheaths. Outcrop patterns dictate that the return hinge is smaller, and apart from the overall geometry detailed above there is little structural evidence available to define its position precisely (as shown on Map 2 and 10 map box). The siting of the D7 Ballard Antiform (see 5.4)(Map 7 and 15 map box) may have been influenced by the earlier D2 return hinge, and adds to the extreme structural complexity of this small area (Map 10 map box).

Tracing the D2 Commeen Fold northwards through the tectonic schists of the Central Donegal slide and into tectonic package B is hindered by limited exposure on Crocknahamid (H 007988), and lack of lithological variation. However, the presence of a D2 fold of similar geometry to the Commeen Fold is demanded on a gross scale by stratigraphic repetitions.

The Boultypatrick Grits form a continuous right way up outcrop through out the northern portion of the map (Map 2 map box). They are underlain by the older Croaghubbrid Pelites, and pass upwards via a sedimentary transition into the younger Lough Eske Psammities (see Chapter 2). Adjacent to the Leannan Fault on Boultypatrick itself (G 980955), the Boultypatrick Grits are clearly

overlain by the older Croaghbrid Pelites in the core of the D3 Crocknahamid Antiform (Map 10). This lower inverted limb of the D2 Commeen Fold has been upfolded in the hinge of the D3 Ballybofey Antiformal complex. The axial trace of the D2 Commeen Fold must therefore lie between the two major outcrops of the Boultypatrick Grits in the valley of the River Finn (Map 2 map box). The presence of such a hinge zone is verified by the change in vergence of D2 structures in this area (see 3.3c).

Thus, the Commeen Fold can be traced approximately across the northern flank of Boultypatrick until it is cross cut by the Leannan Fault system (Pitcher et al., 1964). There is no indication of Boultypatrick Grit outcrops converging towards the west. The grits are simply on the limbs of the D2 Commeen Fold, the sheath closure being defined solely by Gaugin Quartzite and tectonic schists of the Central Donegal slide. The overall structure of the D2 Commeen Fold is shown in section 2, map box.

The Croveenananta Fold, as mentioned previously has preserved in its hinge rocks of the Lower Dalradian or Appin Group (as defined by Harris and Pitcher, 1975), the Croveenananta Formation. The fold axial trace trends East-West and is confined solely to the lower inverted limb of the D3 Ballybofey Antiform. Lenses of Port Askaig Tillite Formation upto 25 m in length are confined to the hinge of the fold adjacent to the Gaugin Quartzite (Croveenananta (G 950942), Crolack (G 977943)). As expected, a reversal in the younging direction (clearly defined by cross bedding) takes place in the Gaugin Quartzite across the proposed axial trace, with beds inverted and younging to the south on the southern limb (Plate 1a.). South of Gaugin Mountain at Crolack (G 980942) the hinge of the Croveenananta Fold is defined by the closure in the Croveenananta Formation. Following the axial trace east (Map 2 and 14 map box), it must pass to the south of the D2 Commeen Fold which as previously mentioned has rocks younger than the Gaugin Quartzite (Reelan Formation) within its hinge, and as such cannot be equated with the Croveenananta Fold. The axial trace

of the Croveenananta Fold must after passing to the south of the D2 Commeen Fold be cut out against the D3 tectonic slide on the inverted limb of the Ballybofey Antiform (Map 2 and 14 map box). At Croveenananta (G 945944), the uninverted Gaugin Quartzite on the northern limb of the Croveenananta Fold is cut out over a distance of 300 m against the tectonic schists of the Central Donegal slide (Map 2 and 13 map box). This suggests late D2 and D3 movement along this portion of the slide, and results in the Croveenananta Formation being juxtaposed directly against tectonic schists and the Croaghubbrid Pelites of tectonic package B (see 2.3a) (Map 13 map box). The marked rapidity of thinning of the Gaugin Quartzite against the Central Donegal slide is suggestive of ramping through the Gaugin Quartzite in this area (Map 13 map box). Such ramping may have acted as a locus for later D5 deformation which intensifies in this region to produce a buckling of stratigraphy on a Kilometre scale (Map 13 map box).

To the west of the Carnaween Fault at Croaghubbrid (G 910930), Gaugin Quartzite is preserved adjacent to the tectonic schists of the Central Donegal slide (Map 2 and 11 map box). The highly strained nature of the Gaugin Quartzite in this area has prevented the identification of way up evidence. However the axial trace of the Croveenananta Fold must be present within the Croveenananta Formation, between the mylonitic Gaugin Quartzite adjacent to the tectonic schists in the north, and the large body of inverted Gaugin Quartzite at Carrigan (G 909924) to the south. The apparent convergence of the Croveenananta Formation towards the west adjacent to the Leannan Fault, together with the folding of quartzite bands within the Croveenananta Formation, indicate the presence of a D3 synformal hinge (Croaghubbrid Synform) in this area (see 4.5)(Map 11 map box). Cross bedding within these quartzite bands indicates an inverted sequence younging towards the south. The D2 Croveenananta Fold axial trace must therefore be present in the calcareous pelites immediately to the north of the inverted quartzite bands (Map 11 map box).

The D3 Croaghbrid Synform must fold the axis of the D2 Croveenananta Fold, the refolded axial trace passing through the poorly exposed calcareous pelites of the Croveenananta Formation to the north of the inverted Gaugin Quartzite at Carrigan (G 909924) (Map 11). The structure of the Croveenananta Fold is shown in section 1 (map box).

Due to the intensity of deformation associated with the D3 Ballybofey Antiform, the original form of the Croveenananta Fold is not easy to perceive. It is obvious that as the Croveenananta Fold has rocks older than the Gaugin Quartzite in its hinge, it must have opposing geometry to either the Altnapaste/Gorey D2 sheath fold or the D2 Commeen Fold (both with younger rocks within their hinge zones). Thus, the Croveenananta Fold represents a return hinge to the Altnapaste/Gorey D2 sheath fold and the D2 Commeen Fold. It is apparent that the return hinge represented by the Croveenananta Fold is not positioned or 'stacked' directly above the D2 Commeen Fold. It represents a lateral continuation of a complex three dimensional form, which has since been dislocated by D3 shear on the inverted limb of the Ballybofey Antiform. The Croveenananta Fold is a lateral equivalent to the small D2 return hinge positioned between the Altnapaste/Gorey D2 sheath fold and the D2 Commeen Fold in the Ballard area (H 940960).

The Leannan Fault system is considered to downthrow consistently towards the south east (Pitcher et. al. 1964). The presence of a large fault bounded slice of Croveenananta Formation to the west of the Carnaween Fault may therefore represent a deeper structural view through Dalradian structure. Its presence implies that much of the Gaugin Quartzite exposed to the east of the Carnaween Fault is underlain by the Croveenananta Formation. At the present erosional level, the Gaugin Quartzite to the east of the Carnaween Fault is inverted (map 1 map box). As such, a D2 hinge is required below the present erosional level to produce a reversal in younging away from the underlying Croveenananta Formation (section 1 map box).

The presence of the Croveenananta Formation to the west of the Carnaween Fault indicates the presence of a D2 return hinge of similar geometry to the Croveenananta Fold. The axial plane of such a fold would lie below the present erosional level to the west of the Carnaween Fault

In order for the overall D2 geometry to be consistent with the observation of inverted Croaghubbrid Pelite and Boultypatrick Grits having been overthrust towards the south during D3 (see 4), then a deep D2 fold of similar geometry to the Commeen Fold is required. The only evidence for such a fold are the gross geometrical observations sited above.

### 3.3f) Tectonic schists of the Central Donegal slide

Tectonic schists have been regarded as representatives of slide zones, having developed as a result of 'tectonic and metamorphic convergence during syn-kinematic metamorphism' (Rast 1957). Rocks adjacent to slide zones appear to become texturally and mineralogically similar, the originally different lithologies becoming less easy to distinguish and separate (Roberts and Treagus 1975) (but see also Treagus 1987). The lithology within this nebulous zone is referred to as a tectonic schist. A general review of tectonic schists and slide zones is given in Hutton (1979), and also Hutton (1983).

Tectonic schists can thus be thought of as being derived from two or more lithologies adjacent to the tectonic slide. As a tectonic slide cuts out stratigraphy, lithologies on at least one margin of the tectonic interface will vary. This being the case, tectonic schist compositions and textures should change in tandem with the variations in lithology adjacent to the tectonic slide. The tectonic schist developed at a pelite/pelite interface will be markedly different from that developed at a quartzite/pelite or quartzite/psammite juncture. Indeed in the author's experience, tectonic schists at a quartzite/psammite interface are rarely developed to a significant extent.

Major tectonic slides are capable of juxtaposing rocks of different metamor-

phic grade eg. Sgurr Beag slide (Powell et. al. 1981) As such, a tectonic schist developed within this regime will undergo not only a strain gradient between the juxtaposed lithologies, but also a thermal gradient. In addition, as tectonic schists have developed along synmetamorphic ductile faults (slide zones), they represent a channeling structure along which diffusional flow of gaseous fluids and volatiles will take place (Beach 1976). Prograde metamorphic reactions result in dehydration and volatile release (via diffusion) into the surrounding rock (Turner 1981 p. 92). The original siting of a syn-metamorphic slide may thus not only be influenced by ductility contrasts between adjacent units, but by the capacity of different lithologies to release volatiles during prograde metamorphism, and their capability to transmit these volatiles. Pelites have a greater capacity than quartzites to release gaseous fluids during metamorphism, and as such it is interesting to note that many, but not all, tectonic slides within the Dalradian are situated at the base of quartzites which are underlain by pelites. It may be that during prograde metamorphism, the original pelite/quartzite interface trapped volatiles released via diffusion from the underlying pelite, the quartzite acting as a form of 'cap rock'. The greater concentration of volatiles along this interface, the increased ductility contrast as well as a possible early sedimentary history in some instances (Soper and Anderton 1984), would aid in the initiation and continued movement of a tectonic slide. Migration and diffusion of volatiles along a tectonic slide leads to heat and chemical transfer (Atherton 1977) which are integral components of tectonic schist development. Ductile shear of albite porphyroblasts within the tectonic schists of the Central Donegal slide is suggestive of high temperature deformation (450-500°C according to Simpson 1985), as well as possible fluid transfer. Thus, the migration of volatiles, the strain and possible thermal gradients, as well as juxtaposed lithological types are all factors in the formation of tectonic schists.

Slide zones may thus be represented by tectonic schists, with originally widely spaced units being juxtaposed and 'converging' within this lithology.

Slide zones will be reactivated if oriented favourably in relation to the principal stresses of a later deformation. This will give rise to a complex slide zone with several generations of movement (possibly in different directions) having taken place along its length. If the tectonic slide and its associated tectonic schist are not oriented favourably for reactivation, they may act as any other deformed part of the stratigraphy, being folded and even cut out against later cross cutting tectonic slides.

The tectonic schists of the Central Donegal slide have developed within rocks which have suffered lower amphibolite facies of metamorphism (defined by Turner 1981), and there is no break in metamorphic grade across the slide zone. The best development of tectonic schists occurs where the Gaugin Quartzite (tectonic package A) has been juxtaposed against the Croaghbrid Pelites of tectonic package B (see Chapter 2). This interface commonly represents the base of the Gaugin Quartzite with lenses of Port Askaig Tillite Formation upto 25 m in length being found enveloped within the tectonic schists (see chapter 2) (Gaugin Mountain (G 980950)).

The Central Donegal slide at this particular horizon produces a very distinctive schistose rock, noted by original survey geologists (North West and Central Donegal Geological survey memoir 1891), as well as later workers (Pitcher, Shackleton and Wood 1971, Pitcher and Berger 1972). Typically the tectonic schist is less than 30 m thick, although it is tectonically thickened in the hinge of the D3 Ballybofey Antiformal complex (Gaugin Mountain (G 980944)), (Map 2 map box). It is a grey weathering rock with few joints, little lichen cover and has limited effect on topography or vegetation. The rock contains numerous randomly oriented biotite porphyroblasts upto 4 mm in length as well as garnets upto 2 mm in diameter. Good examples of the tectonic schists of the Central Donegal slide are exposed at Clogher South (G 960940), and Croaghbrid (G 910930). A gradation across the tectonic schist in the relative proportion of the quartzite / pelite components is related to the mixing and 'convergence' of the deforming

rocks as previously mentioned. The tectonic schist is everywhere bounded on one margin by the Croaghubbrid Pelites of tectonic package B. These graphitic pelites become more foliated as the tectonic schist is approached. Within 20 m of this junction, they become indurated with quartz which produces a flinty affect when the rock is struck with a hammer. An example of such a deformed graphitic pelite is shown in rock sheet 1, specimen B (map box). These rocks exhibit a planar fabric, and contain more biotite porphyroblasts than the typically less deformed rocks of the Croaghubbrid Pelites. In thin section, the deformed graphitic pelite is seen to contain biotite, quartz (including quartz ribbons), opaques (graphite), garnet and muscovite (Plate 19b.). This more highly deformed graphitic pelite passes via a rapid gradation into the more typical, easily defined tectonic schists marked on Map 2 (map box).

There is a significant increase in the amount of quartz in the tectonic schists compared to the Croaghubbrid Pelite. This, together with the presence of numerous biotite porphyroblasts has been the significant factor in defining the 'contact' between the two units. The junction between the Croaghubbrid Pelite and the tectonic schists as mapped is in fact a tectonic transition over a 2 m interval. The tectonic schists adjacent to the Croaghubbrid Pelite are commonly a coarse, schistose, biotite-rich rock. They contain more tourmaline and biotite porphyroblasts than the surrounding lithologies, possibly suggesting volatile / fluid movement within the tectonic schist zone.

As mentioned previously, the amount of quartz within the rocks has significantly increased, producing the coarse biotite-rich, quartz-rich schist shown on rocksheet 1, specimen A (map box). Within this coarse schistose rock any remnants of bedding have been destroyed. However, towards the Gaugin Quartzite on the opposing margin of the tectonic schists, the quartzitic component within the schists increases and a compositional layering becomes evident. This banding may be of metamorphic or sedimentary origin (or a combination of both), is extremely planar and developed at 20 cm intervals (Plate 20a.). The now

more quartzitic tectonic schist retains the numerous large biotite porphyroblasts of its more schistose counterpart adjacent to the Croaghubbrid Pelite. In addition it has also developed large (upto 4 mm in diameter), red euhedral garnets which may stand proud on weathered surfaces. Quartz ribbons upto 30 cm in length are now more clearly evident within the tectonic schist.

As the amount of quartz within the tectonic schist increases towards the Gaugin Quartzite, it appears to become increasingly strained until quartz mylonites are developed. However, this apparent strain profile is deceptive, the author believing that the higher strained rocks are represented by the more schistose lithologies adjacent to the Croaghubbrid Pelite. This view is supported by the observation of Port Askaig Tillite Formation preserved as lenses within the tectonic schist (Gaugin Mountain ( G 980950)) (Plates 21b., 35b.) As this formation is located at the stratigraphic base of the Gaugin Quartzite, any major dislocation would be required to operate towards the Croaghubbrid Pelite margin of the tillite lenses. Thus, the superficial strain profile may largely be a result of the the compositional variation within the tectonic schists. It may also be related to temporally, as well as spatially, migrating localised displacement zones within and through the tectonic schist unit. The slide represented by the tectonic schist was probably never a single movement 'zone' occupying the entire width of the schists. It would appear more plausible that the present tectonic schist unit represents the total spatial variation of numerous more discrete, localised planes of dislocation. These localised shears migrated with time through the zone now occupied by the tectonic schists.

Evidence of high strain and shear is witnessed throughout the tectonic schist zone by extensional crenulations (Berthé 1979) in the more schistose lithologies adjacent to the Croaghubbrid Pelite ( Gorey Hill (H 090970)(Plate 22a.). Such structures are also noted in the more quartzitic form of tectonic schist adjacent to the Gaugin Quartzite (Croaghubbrid ( G 910930)(Plate 22b.).

The shear structures mentioned above are representatives of both the second

and third deformations. However there is no evidence to suggest that on a gross scale the displacement zone migrated with time in a sequential manner through the tectonic schist unit i.e. D2 is not more pronounced towards one margin of the tectonic schist and D3 towards the other. Thus, it can be suggested that earlier D1-D2 movement zones, if suitably oriented, will be reactivated and utilized by D3 shear in the majority of instances. This view is supported by the observation that the width of the tectonic schist does not increase in areas where D3 sliding is more apparent i.e. in the inverted limb of the D3 Ballybofey Antiform.

Thus, the possibility exists that during a single deformation, numerous discrete planes of localised shear may migrate sequentially and in a ordered manner to produce a tectonic schist zone i.e. slides within slide zones. However, reactivation of the slide zone during a later possibly unrelated deformation, and at different metamorphic conditions will not continue to widen the tectonic schist unit. Stress systems associated with the two deformations are unlikely to be exactly coaxial. As such, dislocation planes which had become locked in the earlier deformation (leading to a migration of the active shear and an increase in the width of the tectonic schist unit) may be reactivated and once more utilised. Early displacement zones which are not favourably oriented in relation to the later stress field may be destroyed and cut out against later sliding (Ballard (H 015940)). A single line traverse depicting the tectonic schists of the Central Donegal slide is shown in rock sheet 2 and Plates 23a. - 23d. . As mentioned previously, a major factor in the development and character of tectonic schists is the nature of the lithological types juxtaposed along the tectonic slide. The cutting out along the Central Donegal slide of the Gaugin Quartzite against the Croaghubbrid Pelite at Drumderrydonan (H 012967) and Ballard (H 023955), presents an opportunity to study the nature of the tectonic junction along which two groups of pelites have been juxtaposed.

Towards the slide junction, the Croaghubbrid Pelites become increasingly foliated and contain numerous large biotites upto 2 mm in length. They also

have become indurated with fine grained quartz (with a flinty fracture), as well as quartz ribbons which in some instances are 2 mm thick and extend parallel the main fabric for 30 cm, Ballard (H 0239550). The graphitic pelites contain an increasing amount of biotite porphyroblasts as they pass via a brief 2 m transition into mica-rich tectonic schists. These rocks contain numerous quartz ribbons upto 30 cm in length set in a biotite rich matrix (Plate 20b). Within the tectonic schists there is an increase in the proportion of albite porphyroblasts compared to the adjacent rocks. Vague traces of compositional banding at approximately 30 cm intervals are present as are wisps of graphitic pelite upto 20 cm in length which are presumably derived from the Croaghbruid Pelites.

The contact of the tectonic schists with the calcareous lithologies of the Reelan Formation is, as would be expected a transitional zone of increasingly calcareous pelite away from the tectonic schist. The Reelan Formation contains numerous biotites adjacent to the tectonic slide zone, as well as an increasing number of albite porphyroblasts. Typically, the tectonic schists of a pelite / pelite interface are of a more convoluted and mixed nature than those involving quartzites. Also, as the amount of quartz involved in a pelite / pelite junction is obviously less than that concerned with an interface of quartzite, there is a reduction in the development of a distinct mineral elongation lineation (usually defined by quartz).

### 3.3g) D2 kinematics of the Central Donegal slide

As mentioned previously (see 3.2), the Central Donegal slide is a structure which originated during the first deformation, and was later reactivated on several occasions (3.3e). During the second deformation tectonic schists associated with the Central Donegal slide are thought to have developed. These tectonic schists were later folded around the hinge of the D3 Ballybofey Antiform (Gaugin Mountain (G 980950) Map 2 map box).

It should be remembered that maps are a two dimensional representation of

a three dimensional form. Therefore shear senses shown on Map 2 (Map box) in the tectonic schists of the Central Donegal slide have been approximated to some degree via a rotation into the plane of the map. The half arrow head on the shear sense symbol (Map 2 map box) indicates the direction of relative lateral transfer within the map plane (as in a strike slip fault). The solid triangle along the length of the arrow indicates the margin which has undergone relative downshear. Due to the rotation of the lateral shear component through the acute angle to the horizontal (represented by the plane of the map), an approximate dip slip shear sense will be susceptible to apparent lateral reversals in shear. An example of such an apparent reversal is shown in the Gorey Hill (H 090970) area of Map 2 (map box). In this case approximate dip slip D2 shear paralleling the mineral elongation lineation clearly undergoes an apparent lateral reversal in shear sense around the hinge of the D3 Ballybofey Antiform (Map 2 map box). This is obviously the result of the later folding of the sub-horizontal shear axis (defined as lying at right angles to the Shear direction within the shear plane). Thus, the major feature to note regarding the D2 shear sense in the tectonic schists surrounding the Altnapaste/Gorey D2 sheath fold, is the dip slip shear sense. D2 shear sense within the tectonic schists of the Central Donegal slide has been deduced from a number of kinematic indicators. Extensional crenulation cleavages / shear bands (Berthé 1979, Platt and Vissers 1980) have been found to be reliable and consistent kinematic indicators of localised shear (Plates 22a., 22b.). Shear sense has also been established via observations of asymmetric pressure shadows (Simpson and Schmidt 1983). All such kinematic indicators have been used collectively and have been found to give consistent results. The deduction of D2 shear sense from quartz c axes was not undertaken within the tectonic schists, due to the possibility of 'resetting' by later metamorphism, small scale shear inhomogeneities around porphyroblasts, and the effects of later D3 shear along the polyphase Central Donegal slide.

In all instances the D2 down shear component approximately parallels the

mineral elongation lineation, and is towards the axial plane of the D2 Altnapaste/Gorey sheath fold. The suggestion is clearly that prior to the D3 Ballybofey Antiform, the Gaugin Quartzite body (tectonic package A) forming the core of the D2 sheath fold, was moving laterally towards the south east at a greater rate than the Croaghbrid Pelites of tectonic package B which surround it. The displacement discontinuity between tectonic package A and tectonic package B appears to have largely <sup>been</sup> taken up along the separating Central Donegal slide. Thus, D2 sheath folding utilised the favourably oriented fundamental plane of weakness represented by the original D1 Central Donegal slide. D2 shear along this slide zone was not intrinsic to sheath fold development.

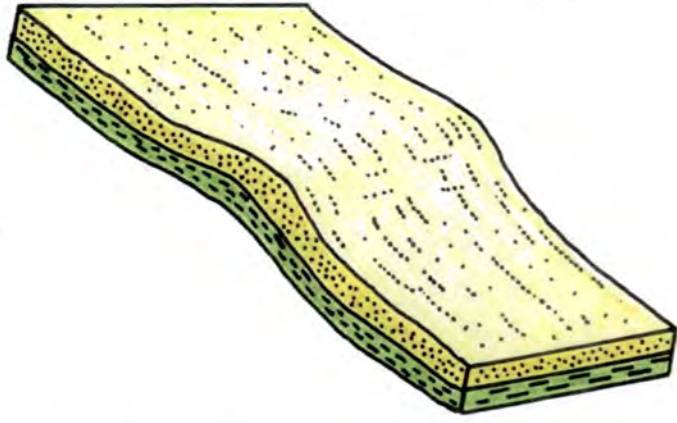
The Central Donegal slide and its associated tectonic schists are therefore representative of a more discrete, localised deformation associated with D2. Such localised deformation along numerous discrete planes of displacement may or may not have the same kinematic sense as the regional shear intrinsic in the production of Km scale sheath folds. However, the present study has found no evidence for a counter sense of displacement along localised shear planes adjacent to 'return hinges' of sheath folds. (Map 2 map box). This being the case, the evidence suggests that both localised deformation along the Central Donegal slide and overall regional shear has been laterally towards the south east. The return hinges of the sheath folds have simply been behaving as 'passive markers' in relation to the developing sheath folds of opposing geometry actively shearing towards the south east. The evidence described apparently supports a simple shear mechanism of sheath fold development (Figure 3.2b.). A pure shear (irrotational strain) model of sheath generation would inherently give equal emphasis to the development of curvilinear hinges of both geometries, ie. no small 'return hinge' would be preserved. Another failure in the pure shear model of Km scale sheath generation is the requirement of an extreme amount of vertical loading necessary in the development of sheath folds with sub-horizontal axial planes. The metamorphic history does not support the theory of such a load-

ing having developed early during the second deformation. Indeed, the post-D2 pre-D3 metamorphic climax supports the simple shear model of sheath fold generation. Whilst loading (and presumably therefore metamorphism) are required to produce sub-horizontal pure shear sheath folds, they are in all probability a product of large scale crustal shear associated with Km scale simple shear generated sheath folds (Figure 3.10.).

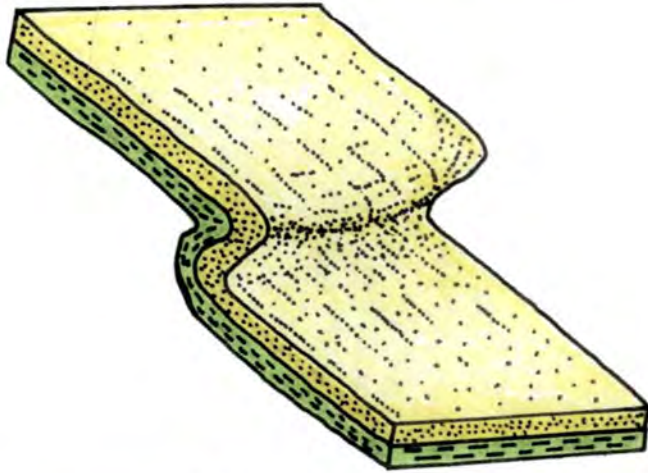
As the major sheath folds are shearing laterally towards the south east, it can thus be deduced that they are closing in that direction (see Figure 3.10.). In summary, the geometry of the Altnapaste/Gorey sheath fold, the D2 Commeen Fold and the proposed D2 fold adjacent to the Leannan Fault are similar, all shearing and closing towards the south east (Map 2 map box). The D2 Croveenananta Fold and the D2 Ballard Fold have a consistent opposing geometry to the D2 folds mentioned above, and represent the incompletely developed return hinges. Adjacent to these return hinges, there has been no localised shear along the Central Donegal slide in a counter sense to the overall regional shear towards the south east. A summary block diagram of the post D2 structural configuration is shown in Plate 24.

Pitcher, Shackleton and Wood (1971) described a  $D_1$  fold closure from Graigin Mountain (see Fig 1.3). However, the presence of a strong, spaced fabric ( $S_2$ ) passing around the hinge of this fold (Plate 15a), shows that this closure can not be of the first generation, and taking vergence data into account, is in fact an  $F_3$  fold. The present author believes the early fold closure to pass to the north of Bultypatrick prior to being dislocated by the Leannan Fault system (Pitcher et al. 1964) (see map 2 and map 10, map box).

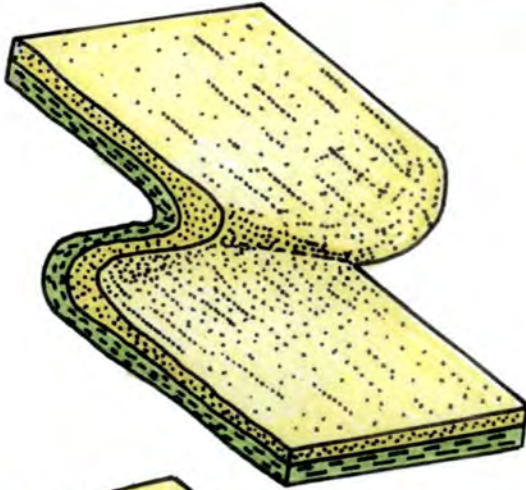
t.1



t.2



t.3



t.4

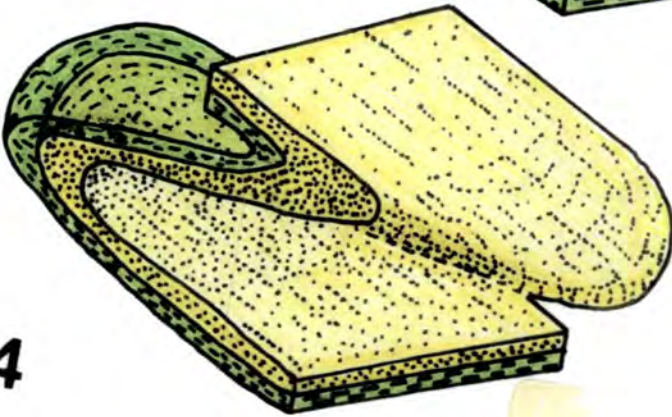


FIGURE 3.10.  
SIMPLE SHEAR  
GENERATED  
SHEAR

## PLATE 15a.

Locality - Gaugin Mountain (G 981953)

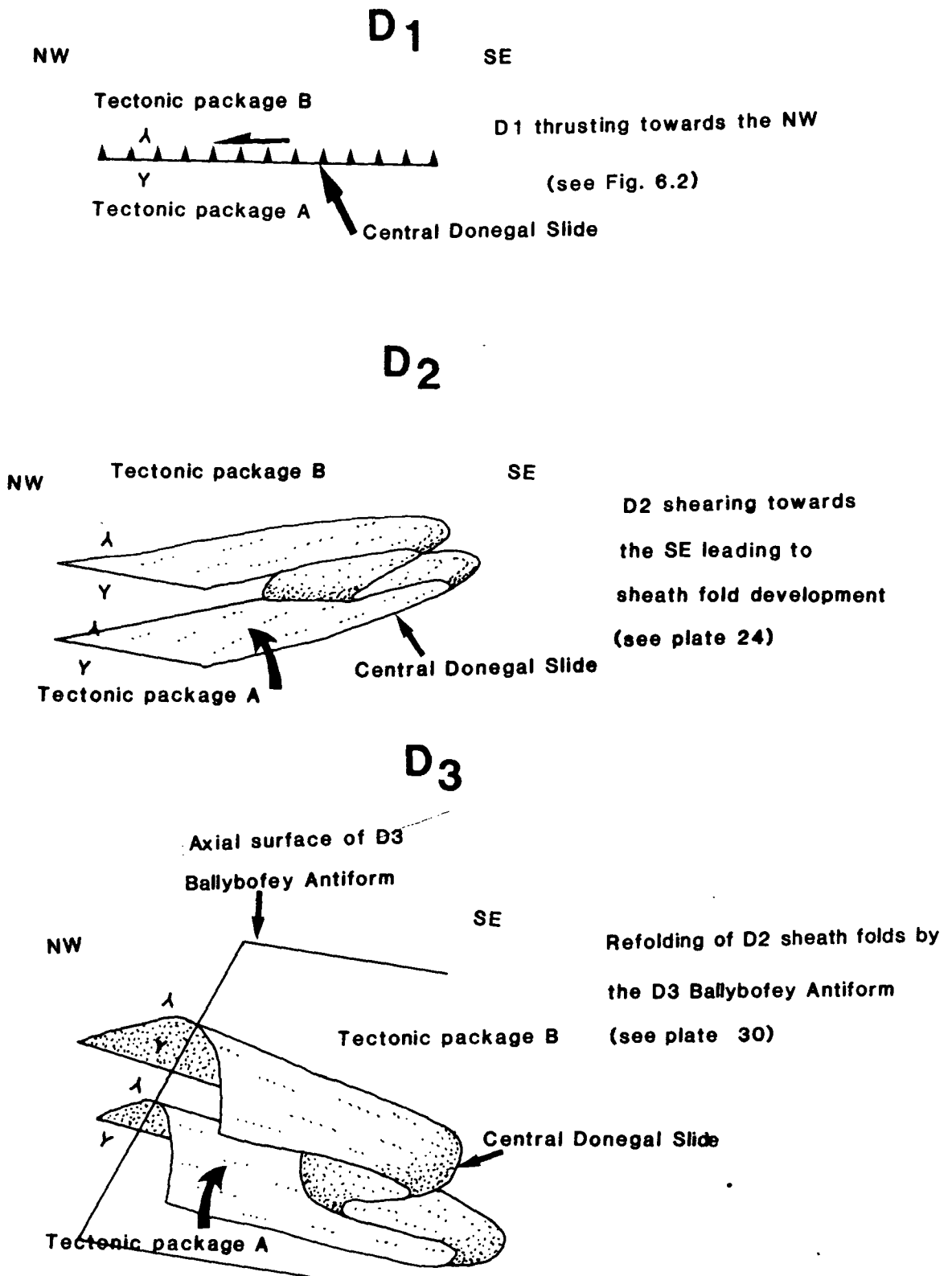
Photomicrograph under crossed polars, with a length<sup>t</sup> of field of view of 4 mm. S2 is clearly visible within the Gaugin Quartzite (shown on the overlay), is spaced, and deforms an earlier alignment of quartz and muscovite (S1 on the overlay). The S2 fabric portrayed is folded around the D3 Gaugin Synform.

## PLATE 15b.

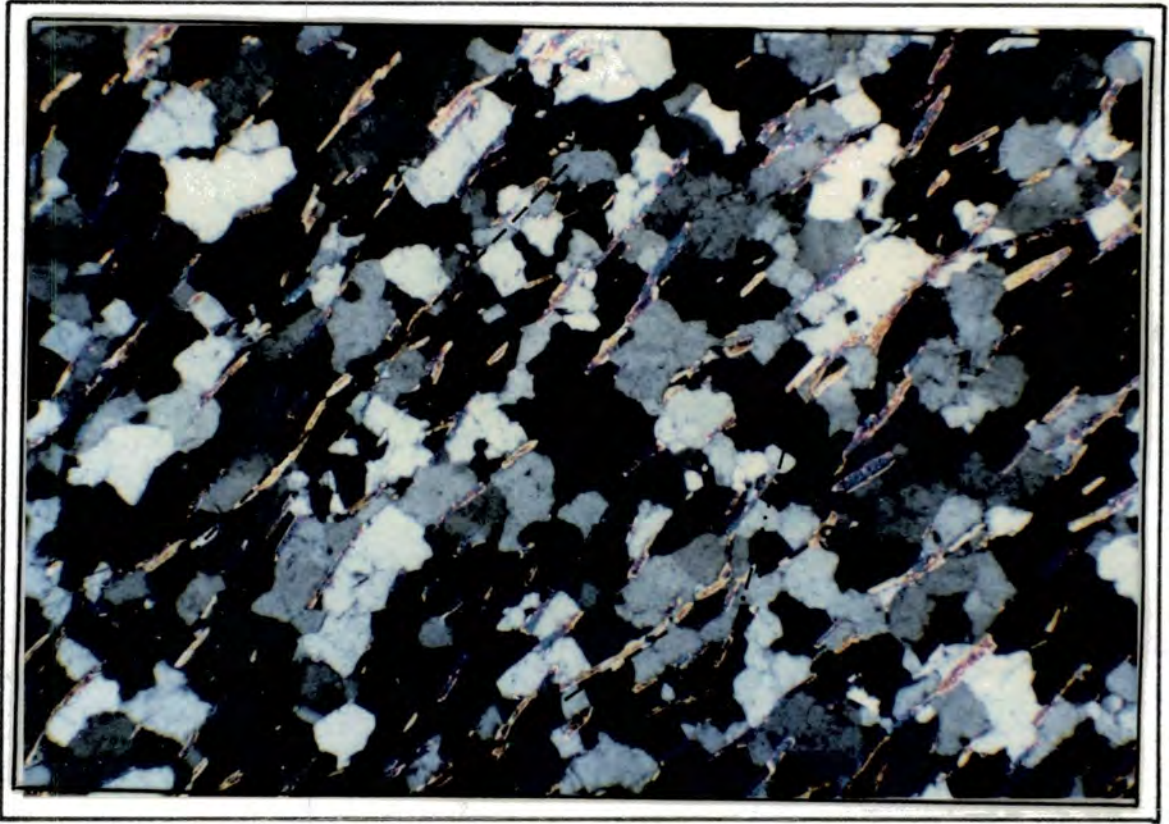
Locality - Ballynatone (H 100965)

Photomicrograph taken under crossed polars, with a length<sup>t</sup> of field of view of 4 mm. An intense S2 fabric is developed in the Boulypatrick Grits close to the Central Donegal slide, in the hinge of the Ballybofey Antiform. Quartz ribbons have started to develop and muscovite and biotite are aligned.

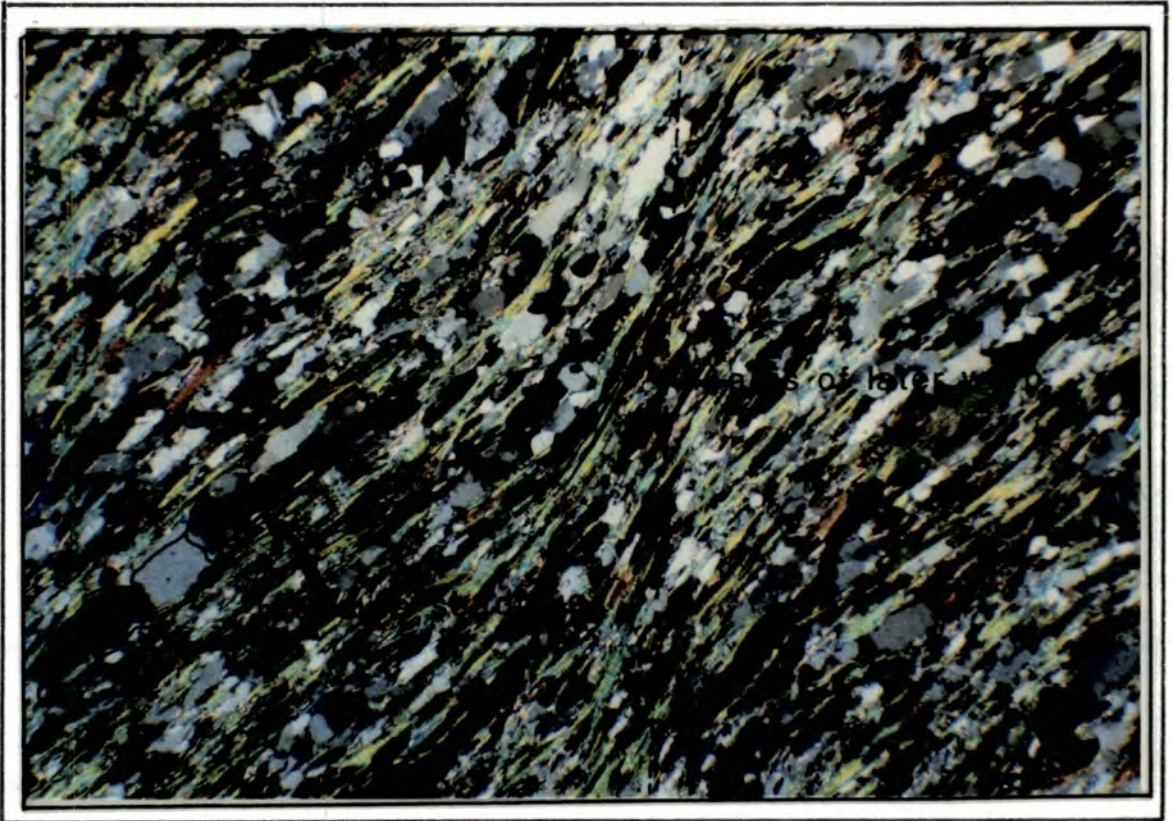
Figure 3.11



a.



b.



**PLATE 16a.**

**Locality – Tongue, Sutherland, Scotland.**

The photograph shows the development of a small scale sheath fold within Moine psammities. The mineral stretching lineation plunges into the page away from the observer and parallels the X axis of the sheath fold (shown on the overlay). The geometry of the sheath closure in the X direction is not apparent from the photograph.

**PLATE 16b.**

**Locality - Tongue. Sutherland, Scotland.**

Complex refolding sheath relationships from Moine psammities. This photograph shows at least two generations of sheath folding. The two sets of sheath folds appear to share the same X axis (the stretching direction), but have Y axes at approximate right angles to each other.



a.



b.

**PLATE 17a.**

**Locality** - Stragally Bridge, Commeen (H 012963)

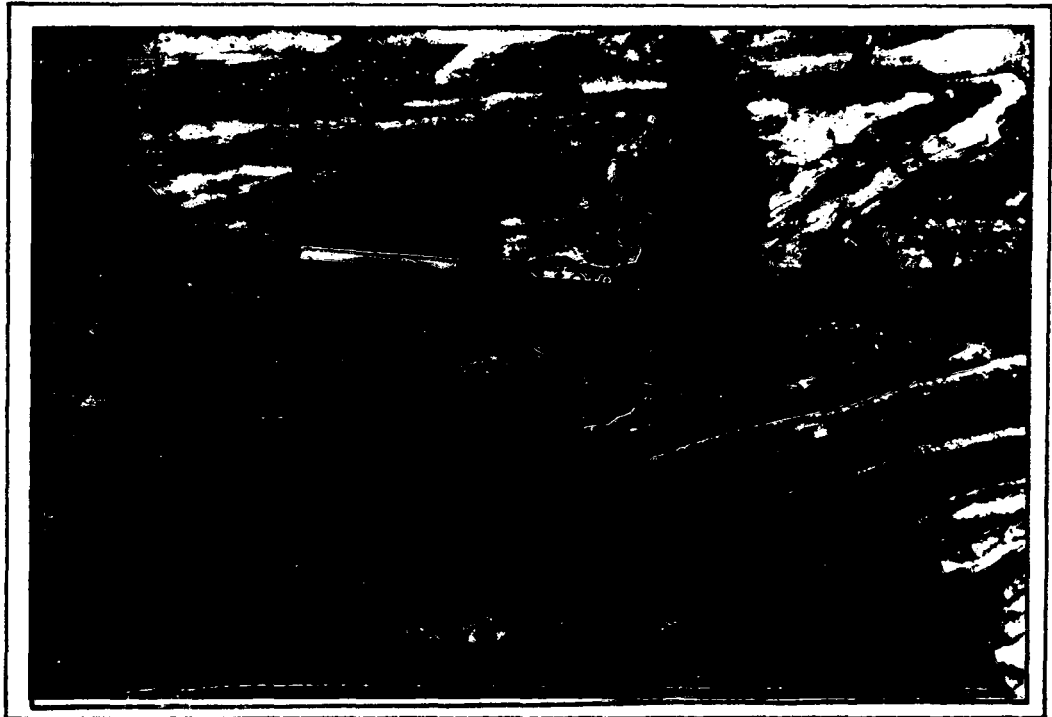
This photograph shows highly deformed calcareous pelites of the Reelan Formation within the hinge zone of the F2 Commeen Fold. Marked on the overlay is the position of plate 17b., which displays sheath fold development.

**PLATE 17b.**

Close up view of the eye - shaped pattern produced by sheath folding in the Reelan Formation. The mineral elongation lineation plunges away from the observer towards the left hand side of the photograph.



a.



b.

**PLATE 18a.**

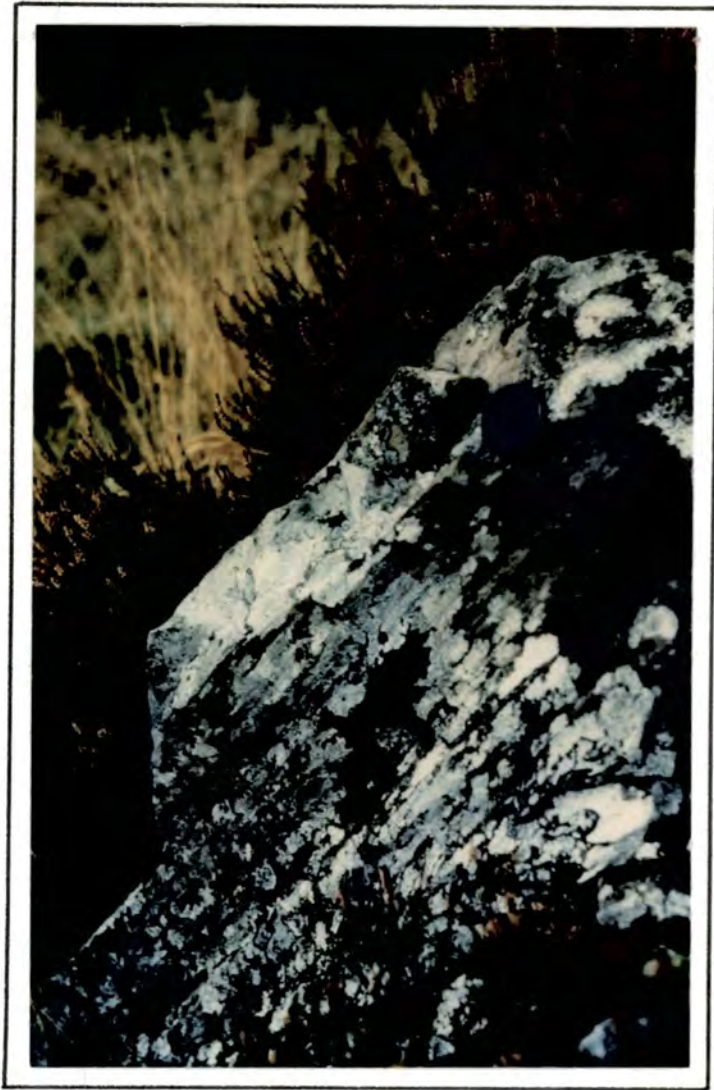
**Locality -** Gorey Hill (H 091978)

Mullion structures developed within the Gaugin Quartzite and plunging towards the bottom left of the photograph.

**PLATE 18b.**

**Locality -** Lacroagh (G 932938)

Intense stretching and mullion development within the Gaugin Quartzite. Mullions plunge away from the observer and towards the bottom right of the photograph.



a.



b.

## PLATE 19a.

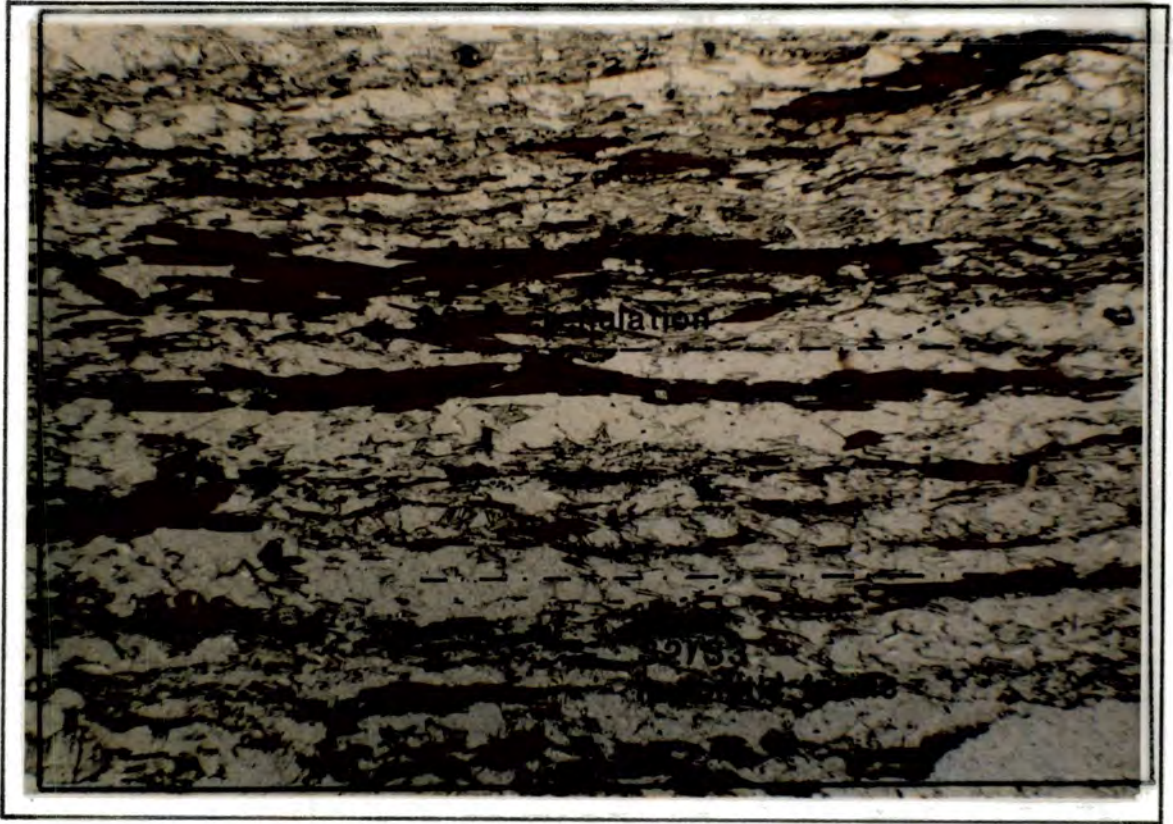
Locality - Lettershanbo (C 121034)

Photomicrograph taken under crossed polars with a length of field of view of 4mm. The rock contains biotite porphyroblasts, muscovite, quartz, chlorite and opaques, and is representative of moderately strained Termon Pelite adjacent to the Killeter Quartzite.

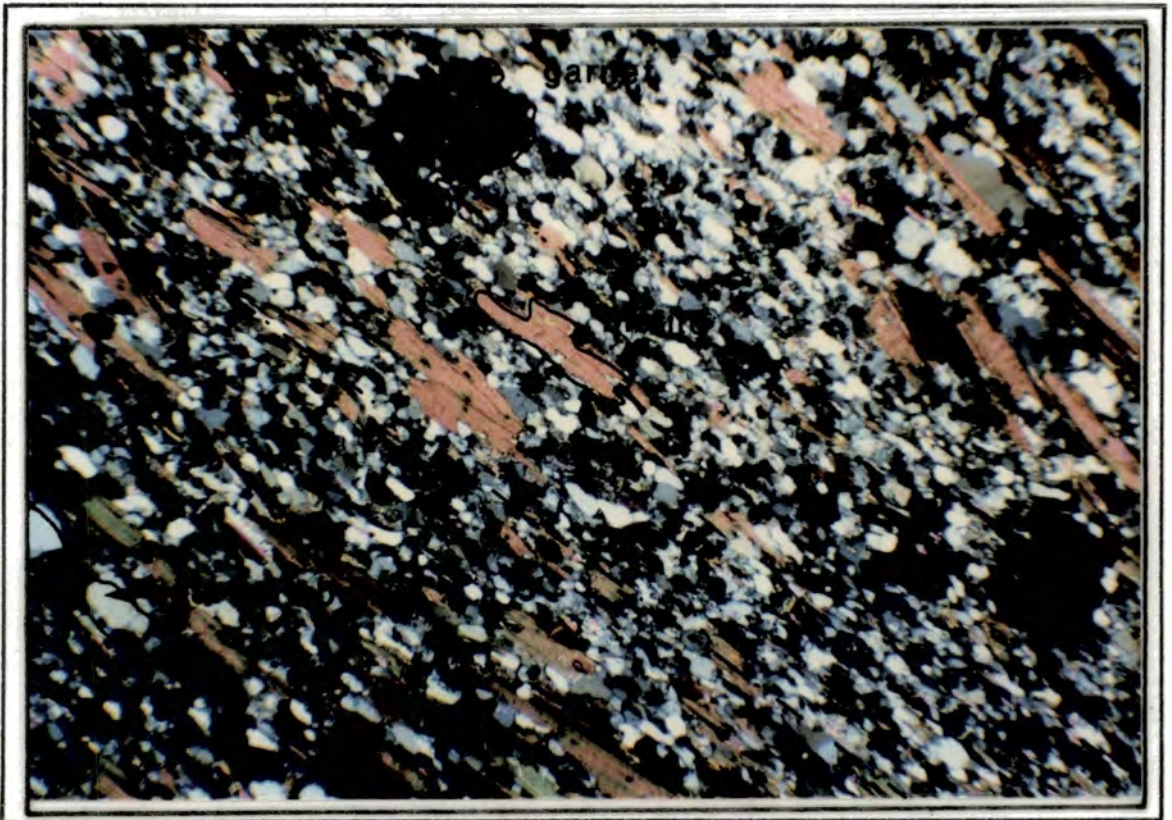
## PLATE 19b.

Locality - Tonduff (H 034971)

Photomicrograph taken under crossed polars with a length of field of view of 4mm. The tectonic schist shown is developed within the hinge of, and is folded by the D3 Ballybofey Antiform. It therefore is representative of a D1 and D2 high strain zone. MP5 porphyroblasts of garnet overprint the main S2 fabric associated with the development of quartz ribbons (shown on the overlay). Large biotite porphyroblasts are ubiquitous.



a.



b.

**PLATE 20a.**

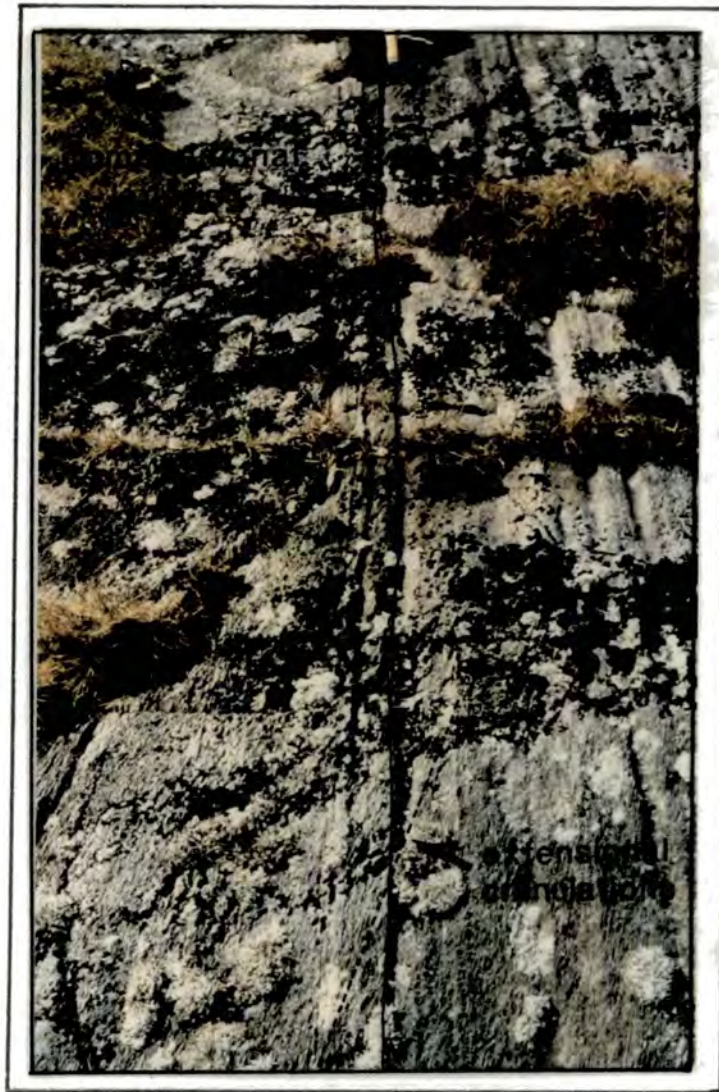
**Locality -** Croaghubbrid (G 910933)

Photograph (looking West) of compositional banding within tectonic schists being cross cut by extensional crenulations relating to the third deformation (outlined on the overlay). Compositional banding is extremely planar and extends for tens of metres along this quartzite / pelite tectonic interface.

**PLATE 20b.**

**Locality -** Ballard (H 024952)

Tectonic schists developed at a graphitic pelite / calcareous pelite interface. Numerous small quartz ribbons are set in a biotite rich matrix. Compositional banding is not apparent on the photograph.



a.



b.

**PLATE 21a.**

**Locality** - Lacroagh (G 931939)

Clast of leucogranite within psammities of the highly deformed Port Askaig Tillite Formation. The suggested sense of shear (dextral) is given on the overlay.

**PLATE 21b.**

**Locality** - Altnapaste (H 037965)

Extremely highly deformed psammities of the Port Askaig Tillite Formation adjacent to the Central Donegal slide. Within the psammities are sheared clasts of leucogranite, which parallel the main S2 <sup>b</sup>facic and are outlined on the overlay.



a.



b.

**PLATE 22a.**

**Locality** - Ballynatone (H 097965)

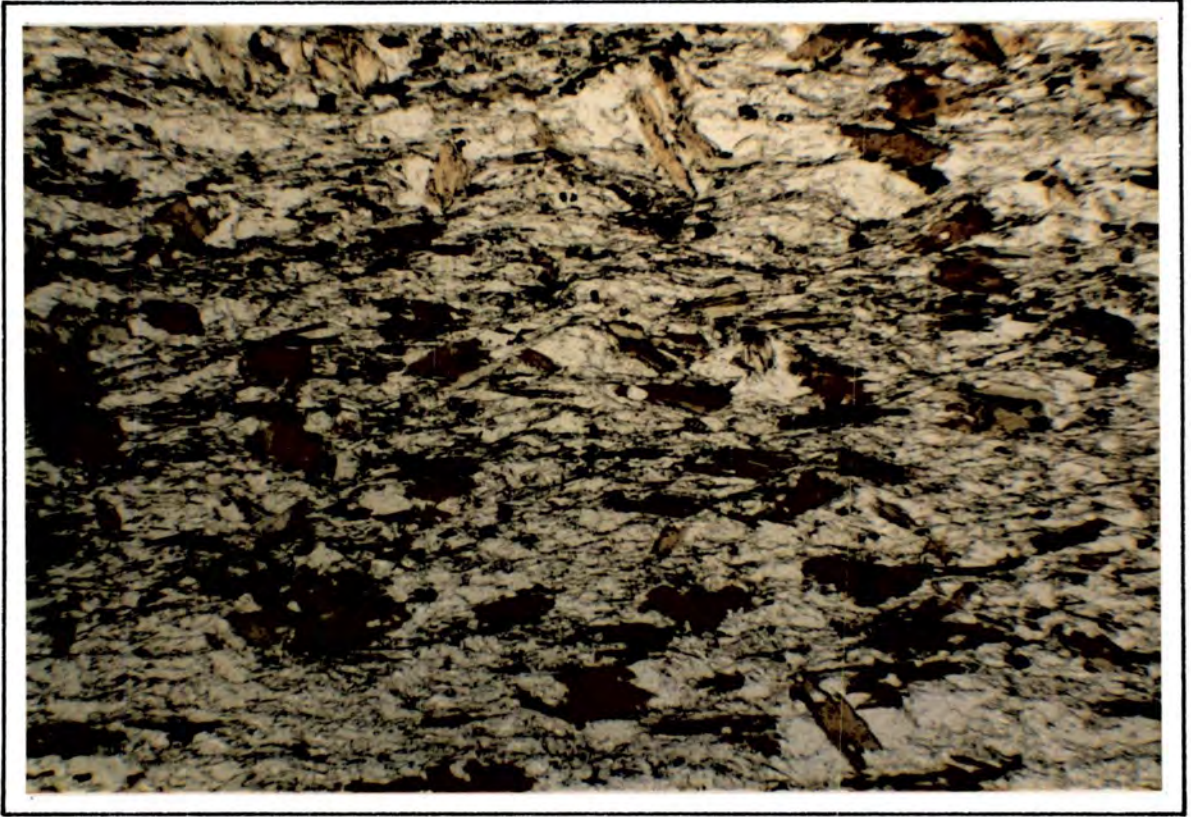
Tectonic schists associated with the Central Donegal slide, displaying extensional crenulations related to the second deformation (S2 - E) and development of large scale sheath folds. The rock contains ubiquitous biotite porphyroblasts.

**PLATE 22b.**

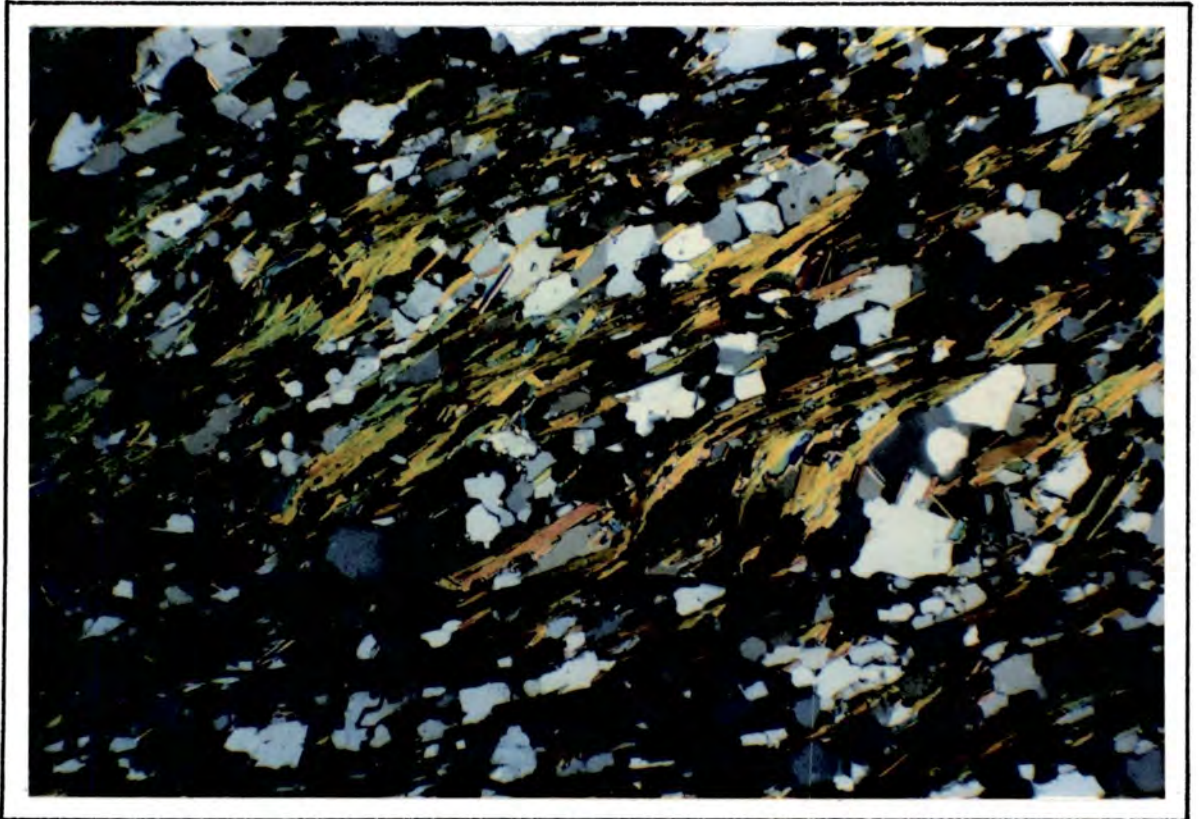
**Locality** - Croaghubbrid (G 913933)

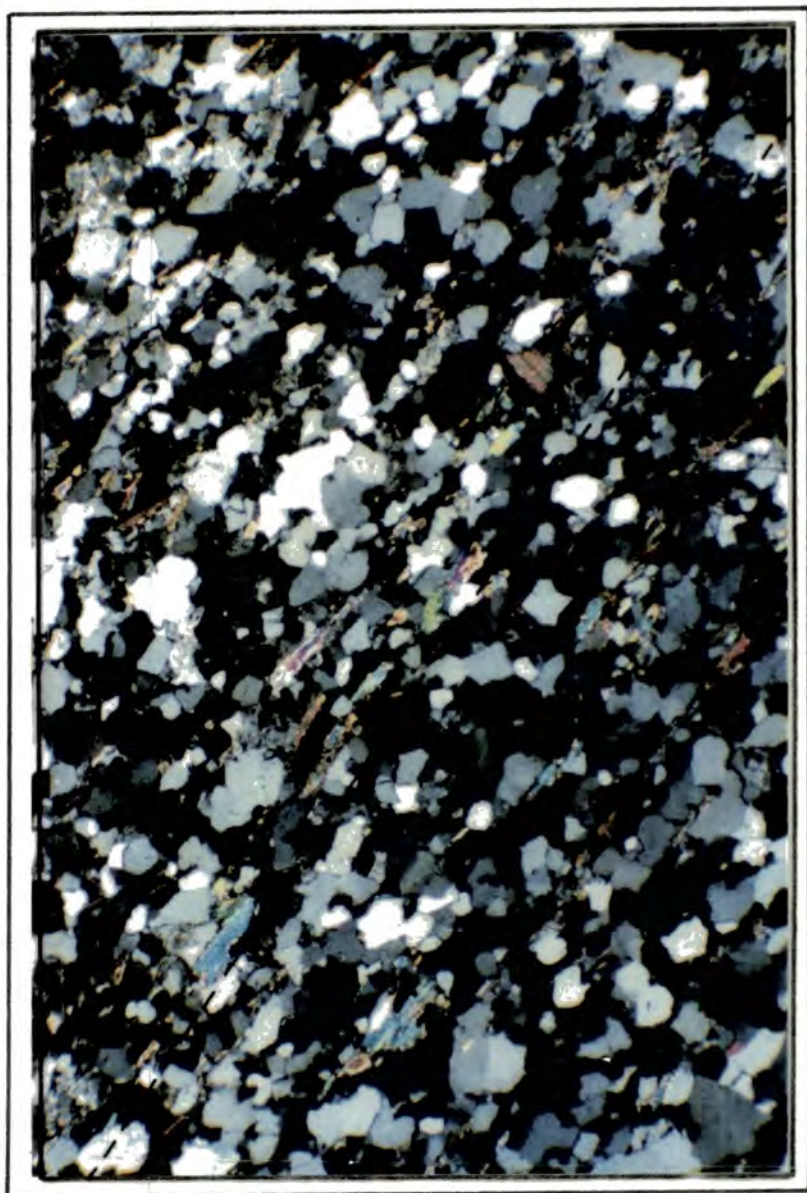
Intense extensional crenulations developed within the quartzitic variety of tectonic schist, and related to the third deformation (S3 - E) (outlined on the overlay). These structures are related to the oblique dextral overthrusting towards the south associated with the D3 Ballybofey slide.

a.



b.





a.

**PLATE 23a.**

**Locality** - Clogher South (G 964946), 20m South of the Gaugin Quartzite / Tectonic schist contact (within the Gaugin Quartzite).

Photomicrograph taken under crossed polars with a length<sup>t</sup> of field of view of 4 mm. Within the Gaugin Quartzite, muscovite and biotite are aligned and define the moderately well developed S2 fabric (the orientation of which is shown on the overlay). Occasional oblique and cross cutting biotites are developed (top - middle right of photograph).

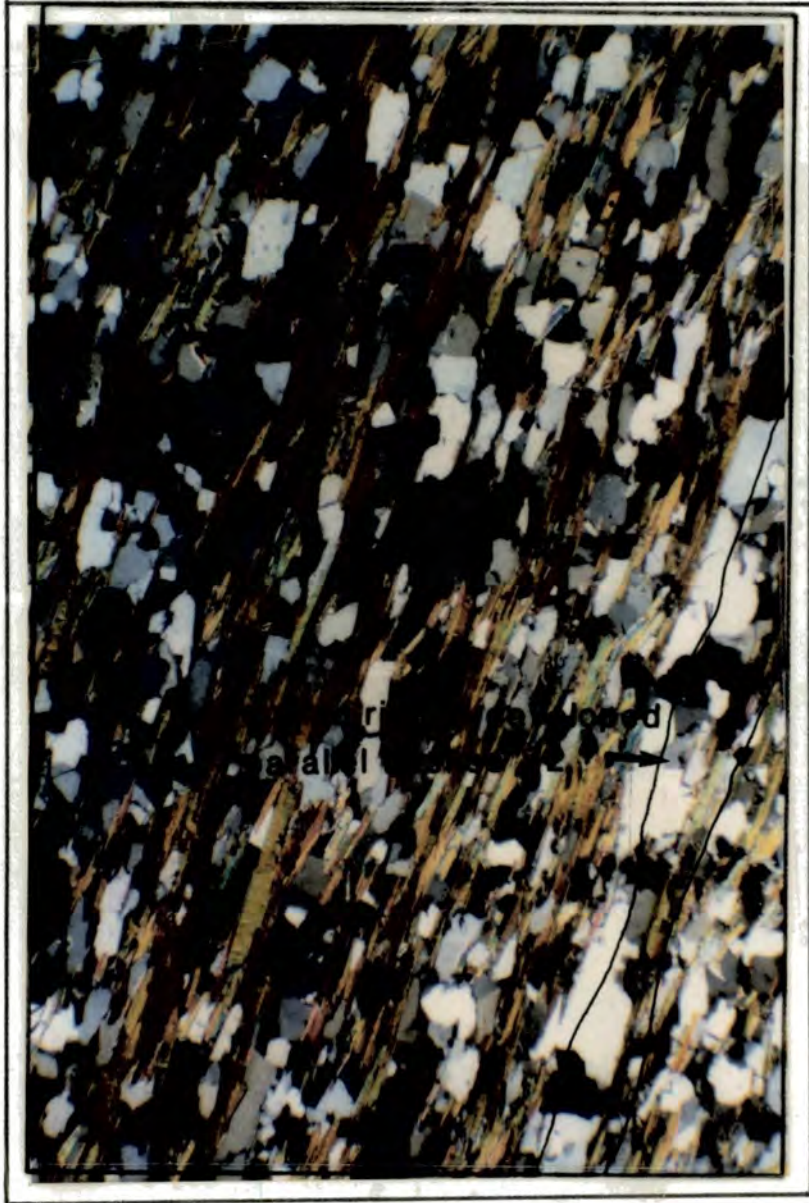


b.

**PLATE 23b.**

**Locality** - Clogher South (G 964947), at the Gaugin Quartzite / Tectonic schist junction.

Photomicrograph taken under crossed polars, with a length of field of view of 4 mm. Biotites are becoming larger and clearly parallel the intensifying S<sub>2</sub> fabric (marked on the overlay). These biotite porphyroblasts are cross cut by later MP5 biotites (shown on the overlay). Quartz ribbons are preserved.

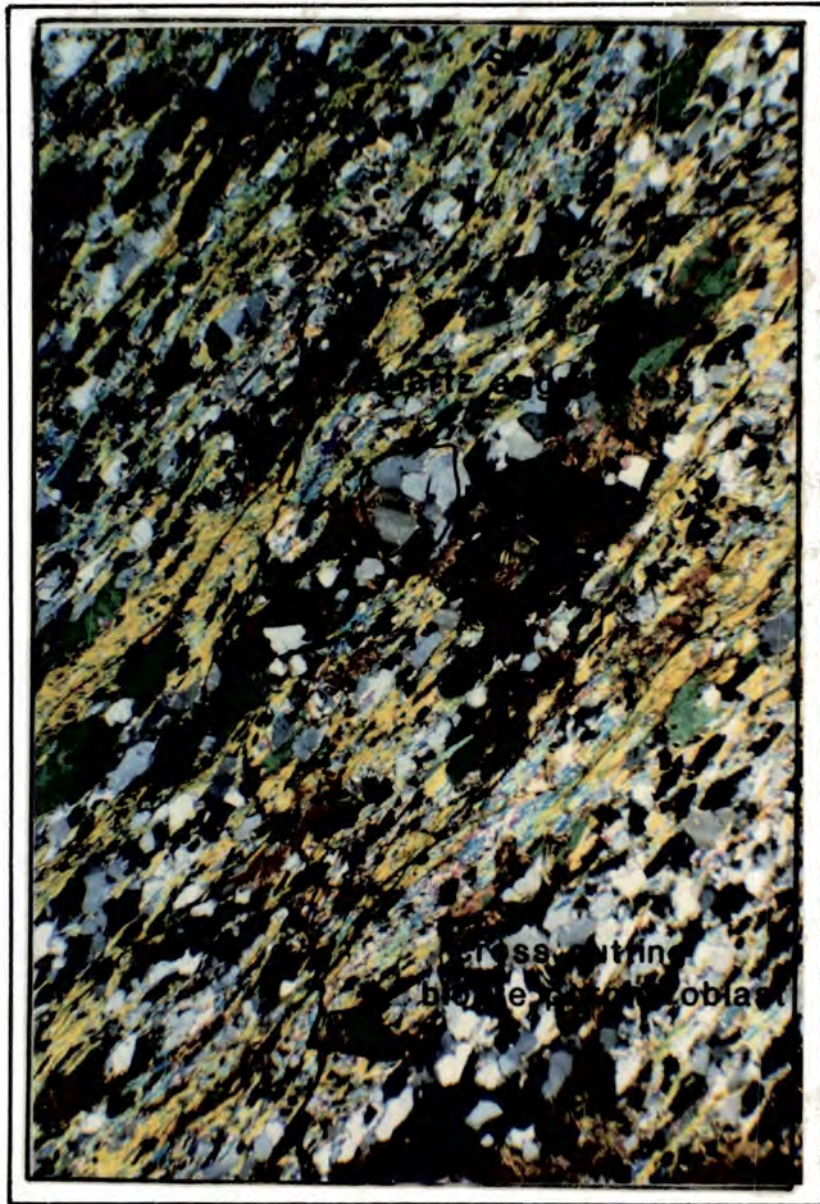


C.

PLATE 23c.

**Locality** - Clogher South (G 963947), 25m North of the Gaugin Quartzite / Tectonic schist junction (within Tectonic schists).

Photomicrograph taken under crossed polars, with a length of field of 4 mm. Development of the S2 mylonitic fabric, and continued formation of quartz ribbons (outlined on the overlay). Biotite porphyroblasts have become extremely well aligned.



d.

**PLATE 23d.**

**Locality** - Clogher South (G 964948), 25m North of the Tectonic schist / Croaghubbrid Pelite junction (within Croaghubbrid Pelites).

Photomicrograph taken under crossed polars, with a length of field of view of 4mm. Graphitic pelites contain a higher percentage of quartz than is typical, which may occasionally form small quartz ribbons which parallel the intense S2 fabric. MP5 biotite porphyroblasts cross cut the S2 fabric, and are slightly more common within the high strain zone.

KEY TO OPPOSING PAGE



BOULTYPATRICK GRITS



CROAGHUBBRID PELITES



CENTRAL DONEGAL SLIDE



REELAN FORMATION



GAUGIN QUARTZITE (WITH TILLITE AT BASE)



CROVEENANANTA FORMATION



DIRECTION OF YOUNGING



TECTONIC PACKAGE B



TECTONIC SCHIST



TECTONIC PACKAGE A



PLATE 24

Schematic block diagram showing D2 sheath fold geometry (slight vertical exaggeration)

D2 sheath folds 'intrude' towards the south east (relative shear sense shown on the overlay) producing reactivation of the Central Donegal slide. The X, Y, and Z axis of one of the sheath folds, the Commeen Fold is marked on the overlay. The sheath fold of similar geometry above the Commeen Fold represents the Altnapaste / Gorey sheath, whilst that below is representative of the supposed deeper structure suggested by geometries to the west of the Carnaween Fault.

**CHAPTER 4**  
**THE BALLYBOFEY ANTIFORMAL COMPLEX.**

## CHAPTER 4

## 4.1) An outline of the D3 Ballybofey Antiformal complex. (Map 3 -map box)

The gross structure relating to the third deformation is a broad overturned antiformal complex with an across strike hinge zone width of upto 5 km. This northward dipping antiform overthrust towards the south east in a oblique dextral sense. The complementary synformal hinge is preserved to the south. Prior to a detailed description of the overall D3 fold geometry, an account of the related minor structures in each of the sub-areas will be given. Throughout the area, S3 is defined by a grain shape and alignment fabric of quartz, muscovite, biotite and opaques, which is clearly a crenulation cleavage in the hinge and northern limb of the Ballybofey Antiform. (Plate 23)

## 4.2) D3 Area 1

As noted in 3.3b), with the increased intensity of D3 shear, S2 and S3 fabrics can only be differentiated on rare occasions on the lower inverted limb of the D3 Ballybofey Antiform. As such, the main fabric in this southern area (sub-area 1b) has been identified and mapped as a composite cleavage (S2-S3) fully described in section 3.3b). The instances where D3 structures can be satisfactorily distinguished eg. the Silver Hill Synformal complex (G 910915), indicate that major D3 structures plunge gently towards the west (Map 3 map box). Only structures of definite D3 age are shown on map 3 for sub-area 1b.

Apart from the northern flanks of Gaugin Mountain (G 980950), S3 dips consistently steeply towards the north north west throughout area 1 (Figure 4.1a.). The exception noted above is due to S3 fanning around the Gaugin Quartzite mass in the hinge of the D3 Gaugin Synform. <sup>a fold which clearly folds the regional S<sub>2</sub> fabric (Plate 15a).</sup> The D3 folding in the Gaugin Mountain area (Figure 4.2.), (Maps 3 and 14 map box) is the dominant control on the orientation of S0 and S2 in this district (Figures 4.3b., 3.4b.). Indeed throughout the whole of area 1, S0 and S2 are approximately coplanar, their orientation being determined by D3 folding (Figures 4.3a., 3.4a.). Poles

**Figure 4.1a.**

**S3 - Area 1.**  $n = 1659$ , maximum concentration of data points = 095/67N, mean = 072/82S. Distribution is related to fanning of S3 surfaces around the quartzite mass in the hinge of the F3 Gaugin Synform.

**Figure 4.1b.**

**B3 Lineations - Area 1.**  $n = 191$ , maximum concentration of data points = 22/118, mean = 23/093. Distribution is related to refolding by F7 and F9 folds.

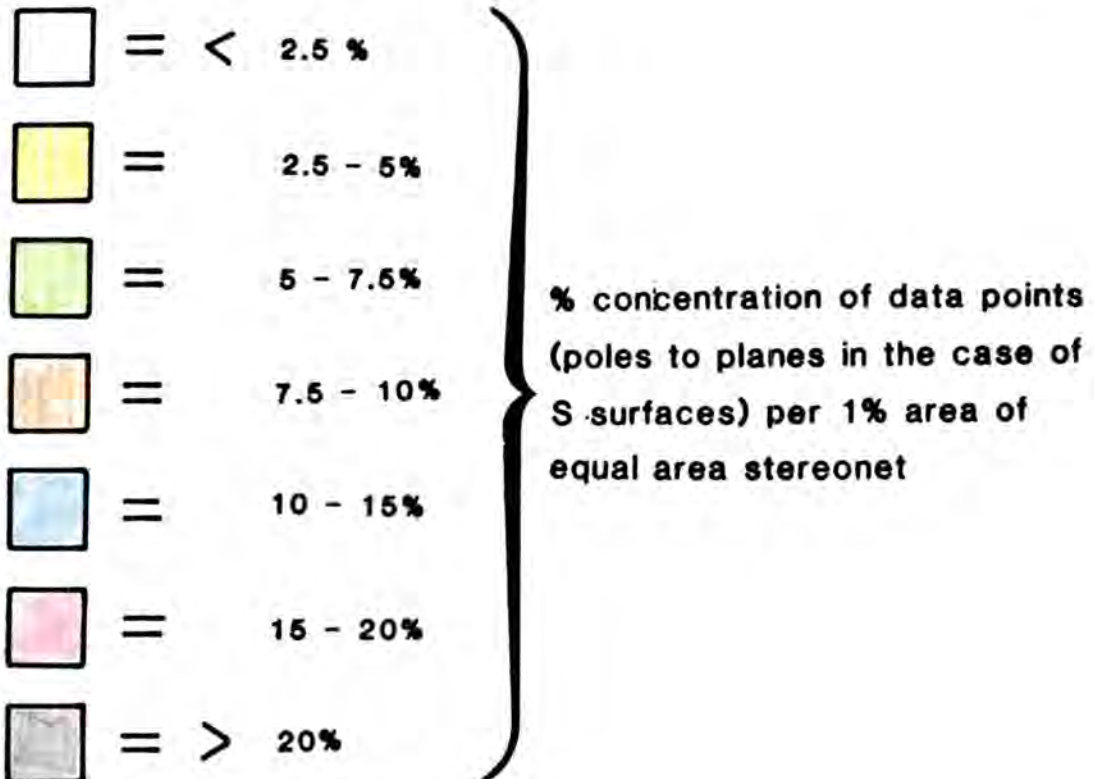
**Figure 4.1c.**

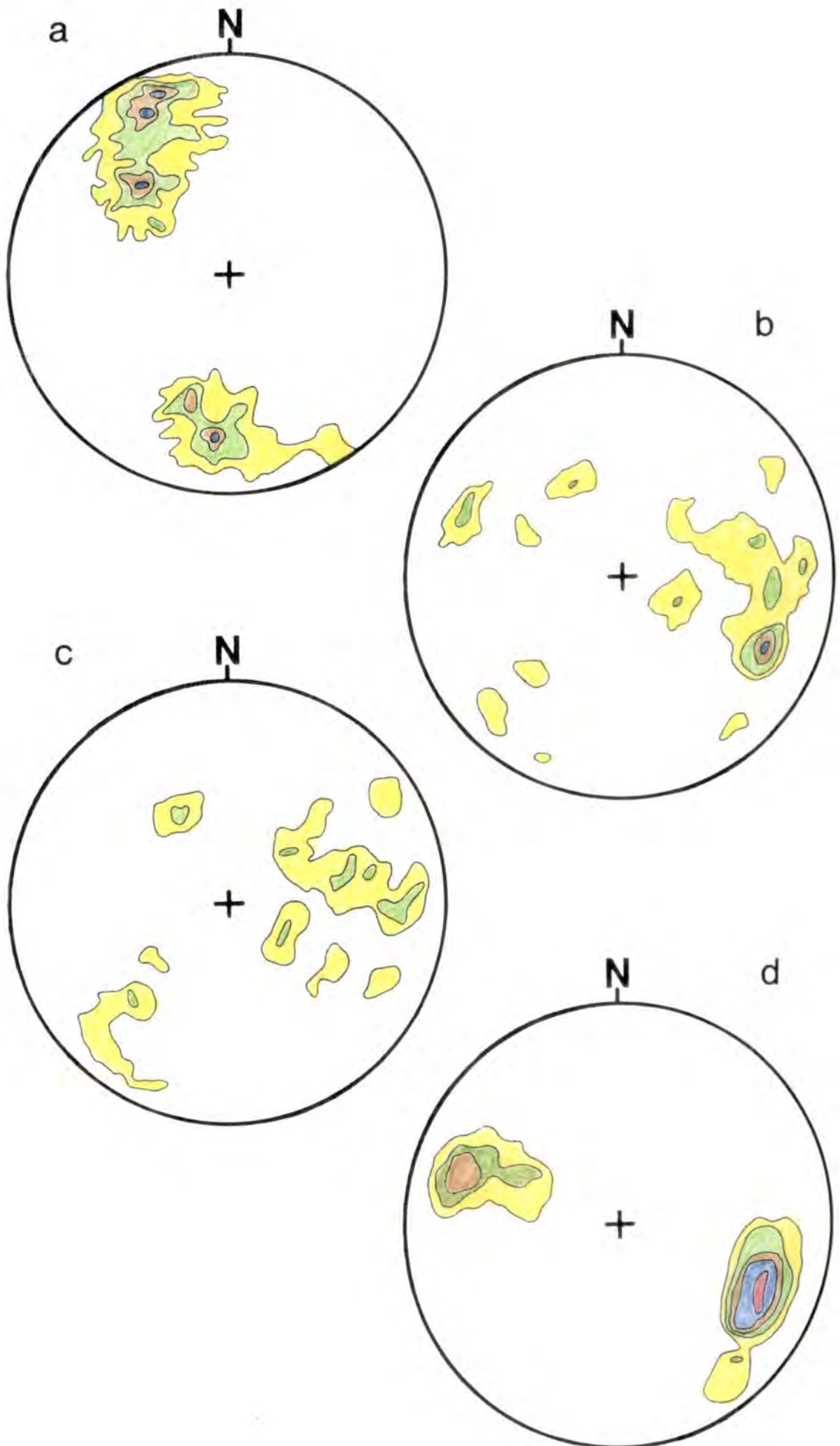
**B3 Lineations - Area 1a.**  $n = 130$ , maximum concentration of data points = 50/332, mean = 34/070. Distribution is related to refolding by F7 and F9 folds.

**Figure 4.1d.**

**B3 Lineations - Area 1b.**  $n = 61$ , maximum concentration of data points = 27/115, mean = 7/113. Bimodal distribution is related to F7 and F9 refolding together with rotations along D3 slide planes.

**Contour intervals on equal area stereograms shown on facing page**





## GEOLOGICAL MAP OF GAUGIN MOUNTAIN

## DALRADIAN SUPERGROUP

## STRUCTURAL SYMBOLS



Boulypatrick Grit



D1/D2 Tectonic slide



Croaghubbrid Pelite



D1/D2/D3 Tectonic slide



Gaugin Quartzite



Tectonic schist



Tillite



Younging



Limestone bands

Bedding  
(compositional layering  
in tectonic schist)

Metadolerite



F3 Axial trace (Antiform)

124 m  
contour

F3 Axial trace (Synform)



townland boundary



Fault



wall

N



250 m



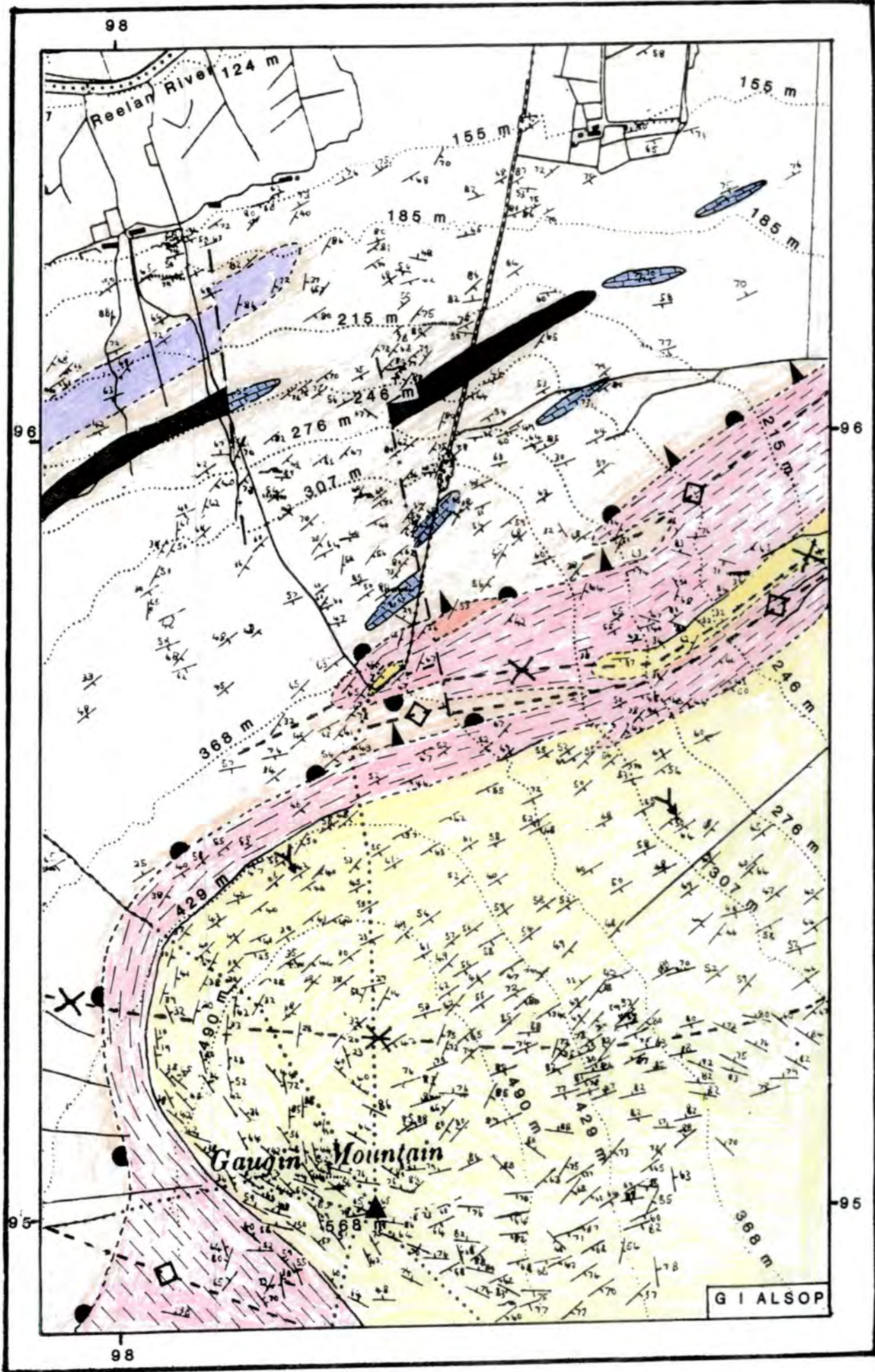


FIGURE 4.2.

to S0 and S2 for area 1 define great circles, whose pole point plunges gently to moderately towards the east. This coincides with the orientation of F3 fold axes and S3 / S1-S2 intersection lineations (B3 lineations collectively) which parallel one another (Figure 4.1b.), (Map 3 map box). Mesoscopic F3 folds frequently have short middle limbs less than 1 m long and are associated with an axial planar S3 cleavage which clearly crenulates S2. They are upright, close folds in areas of lower D3 strain on the upper normal limb of the D3 Ballybofey Antiformal complex (Plate 25b.), and become overturned and tight in areas of more intense D3 shear on the lower inverted limb of this major fold (Plate 25a.). It can thus be concluded from observational (S3 deforming S2) and geometric grounds (stereogram analysis), that D3 is the major refolding influence in area 1.

There is no new stretching lineation developed in association with the third deformation and it is apparent that the D2 and D3 X directions were sub-parallel, (see 3.3b). Indeed in the Croaghbrid area (G 910930), the mineral elongation lineation L2 - L3 (defined by stretched quartz and feldspar grains) is developed on mylonitic surfaces at right angles to the intersection of D3 extensional crenulation cleavages (Berthè et al 1979). Such a relationship would be anticipated if the structures were of the same generation, or if the later deformation had been coaxial with the earlier and had experienced parallel stretching. Figure 3.8d. shows the orientation of the stretching lineation throughout the mapped area. It is also interesting to note that within the same area, the D3 Croaghbrid Synform and its associated minor folds plunge gently towards the east (Map 3 and 10, map box). This is in the opposite plunge sense to the F3 fold axes observed to the east of the Carnaween Fault. Such F3 fold axes to the north of the Central Donegal slide, and to the east of the Carnaween Fault are thought to have been reoriented by a north - south trending D9 antiform adjacent to the Reelan River (G 965940) eg. Croveenananta (G 945945) (Maps 3 and 13, map box).

**Figure 4.3a.**

**S0 - Area 1. (excludes Gaugin Sub-Area)**  $n = 1338$ , maximum concentration of data points = 106/60N, mean = 096/72N. Pole to great circle = 30/086 (corresponds to folding by the D3 Ballybofey Antiformal complex).

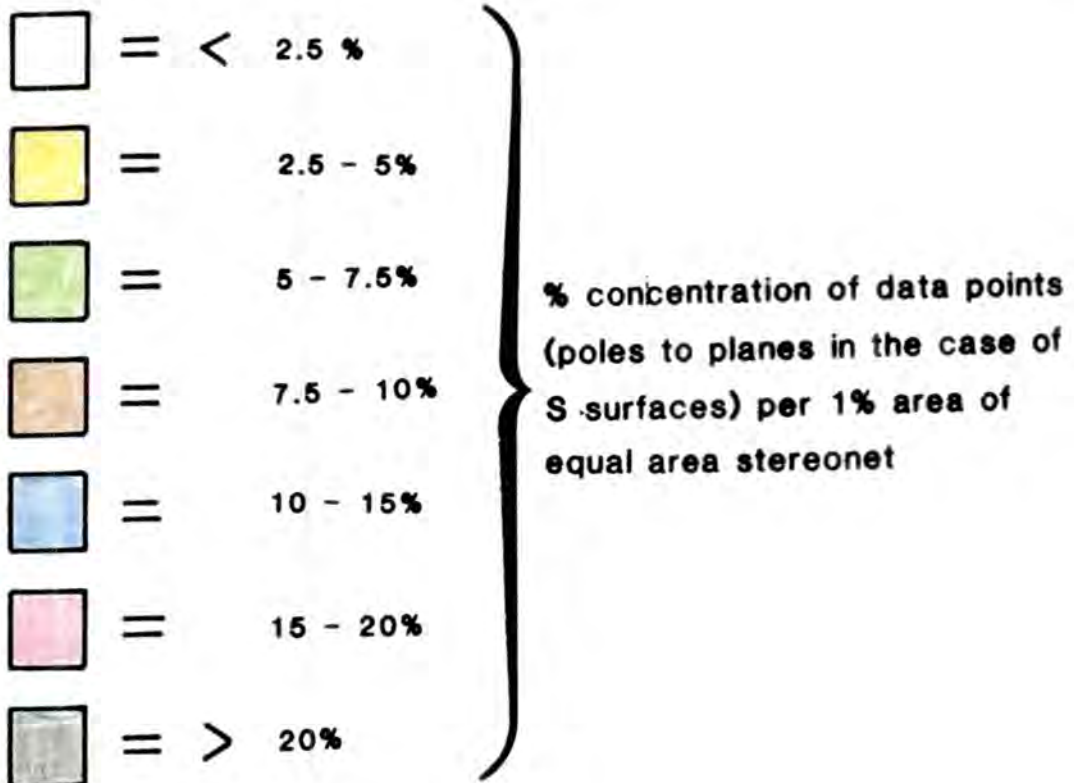
**Figure 4.3b.**

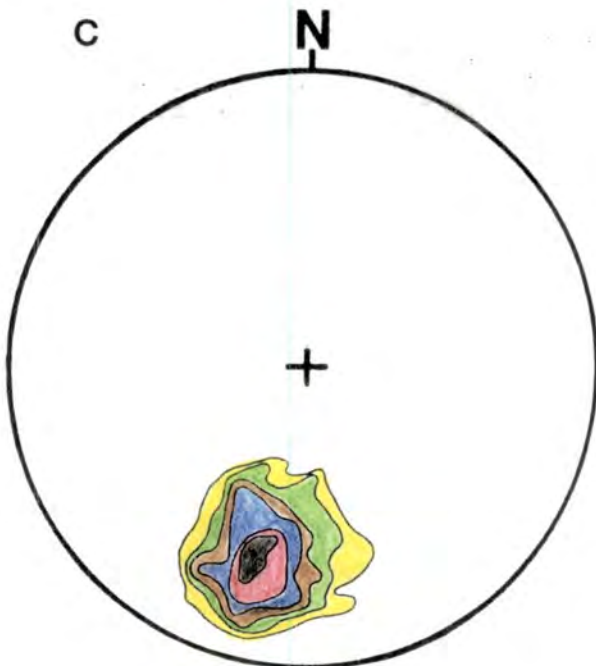
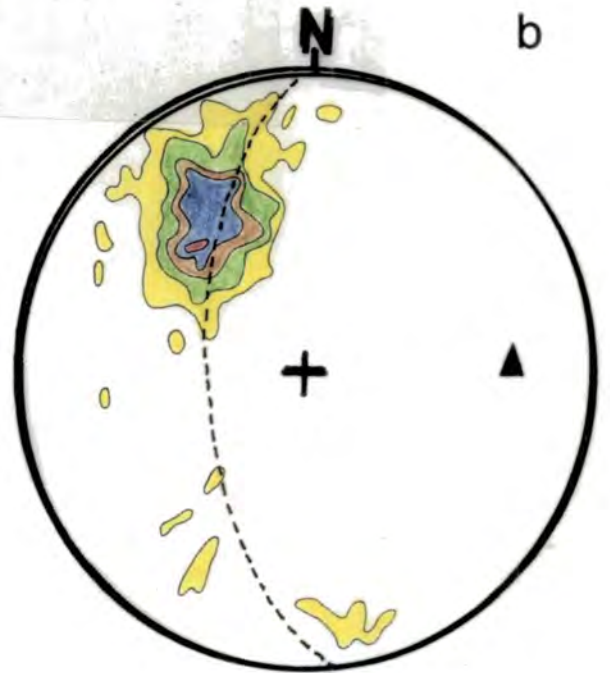
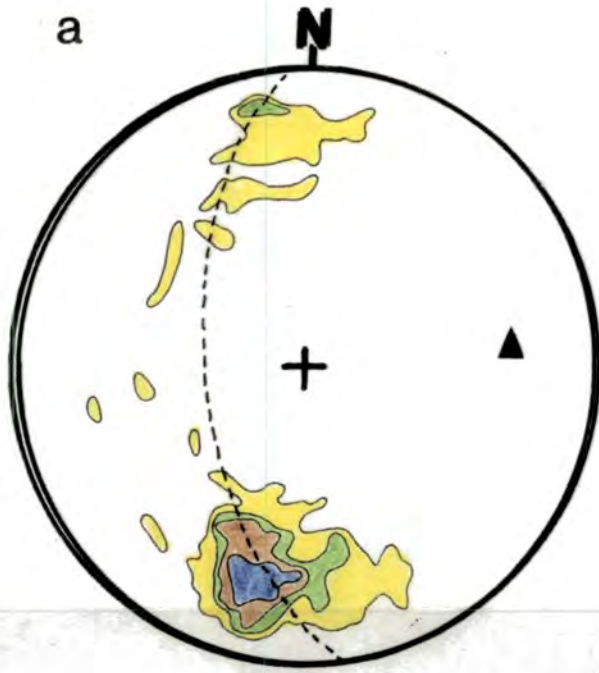
**S0 - Gaugin Sub-Area**  $n = 1735$ , maximum concentration of data points = 045/49SE, mean = 056/60SE. Pole to great circle = 30/086 (corresponds to folding by the D3 Ballybofey Antiformal complex).

**Figure 4.3c.**

**S0 - Sub-Area 1b.**  $n = 2008$ , maximum concentration of data points = 106/64N, mean = 102/59N.

**Contour intervals on equal area stereograms shown on facing page**





Vergence of D3 structures in the Croaghbrid Pelites to the north of Croveenanata (G 945945) clearly suggest the presence of a D3 fold pair (the Ballybofey Antiform and the Gaugin Synform) (Maps 3 and 13 map box). Throughout area 1, the vergence of D3 structures support the major F3 folds proposed on Map 3 (map box).

As noted in 3.3b), a late D3 clockwise rotation of  $30^{\circ}$  (looking north) across the Central Donegal slide would account for the variation in plunge direction of B3 lineations and L2 - L3 lineations seen adjacent to this structure in the Croveenananta area (G 950940). This will be discussed fully in section 4.6), whilst the gross D3 geometry of area 1 will be described in 4.5).

#### 4.3) D3 Area 2.

Sub-area 2 lies entirely on the upper normal limb of the D3 Ballybofey Antiformal complex. As such, the state of D3 strain is lower than that in area 1 on the inverted limb of this fold. Area 2 is relatively unaffected by the D7 Ballard Antiform (Map 10 map box), bedding dipping gently towards the east, as it does in the general eastern portion of the mapped area (Map 1 map box).

Both S2 and S3 are clearly distinguishable throughout area 2. S3 crenulations and associated minor F3 folds are seen to deform volcanogenic clasts in which an S2 fabric is preserved, and to which the clast is parallel (Elatagh River (C 025010)) (Plate 26). S3 is a zonal crenulation cleavage of the spaced S2 fabric (Plate 27b.) and dips at shallow angles to the east north east (Figure 4.5a.). Throughout area 2, the associated minor D3 structures verge consistently towards the Ballybofey Antiformal complex to the south east (Map 3 map box). Mesoscopic recumbent F3 folds clearly deform the S2 fabric, have short middle limbs upto 1 m long and have a well developed axial planar S3 fabric. F3 fold axes and minor D3 crenulation axes parallel the S3 / S1-S2 intersection lineation and have collectively been termed B3 lineations. In the southern portion of area 2, B3 lineations (Map 3 map box), and the L2 - L3 mineral elongation lineation

**Figure 4.4a.**

**S0 - Area 2.**  $n = 850$ , maximum concentration of data points = 138/34NE, mean = 133/28NE.

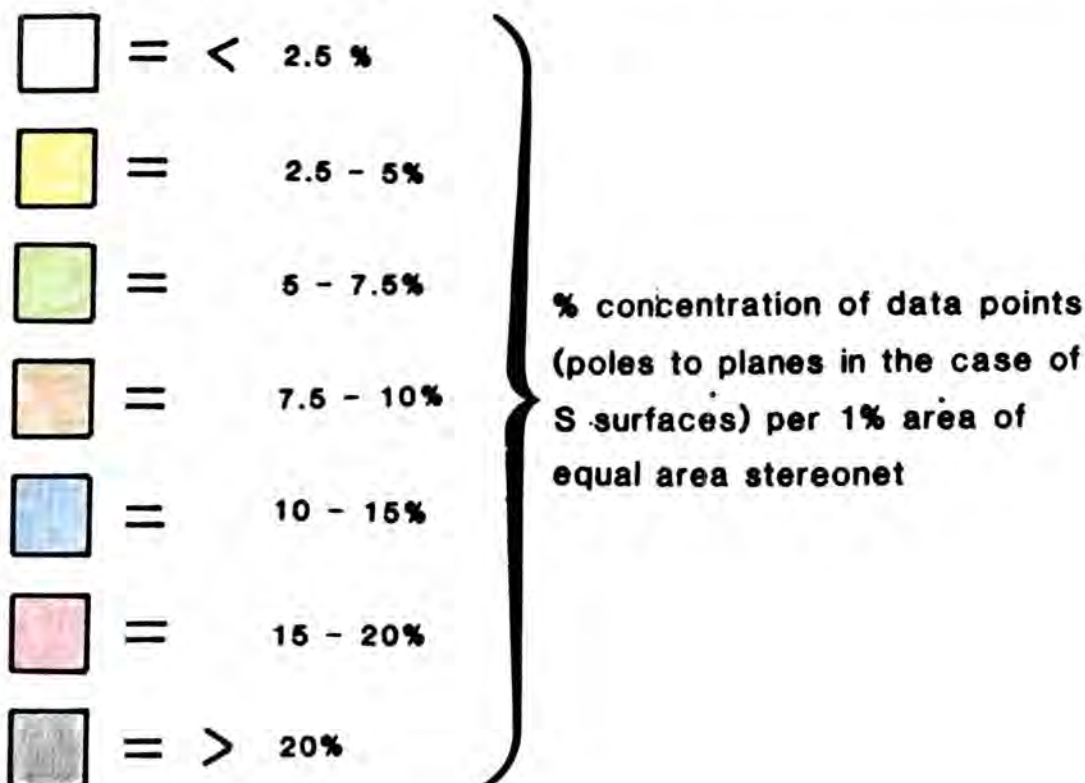
**Figure 4.4b.**

**S0 - Area 3.**  $n = 2227$ , maximum concentration of data points = 164/40NE, mean = 165/39NE.

**Figure 4.4c.**

**S0 - Altnapaste / Gorey Hill Sub-Area**  $n = 293$ , maximum concentration of data points = 140/58NE, mean = 140/60NE. Pole to the great circle = 35/118 and corresponds to folding by the D3 Ballybofey Antiform.

**Contour intervals on equal area stereograms shown on facing page**



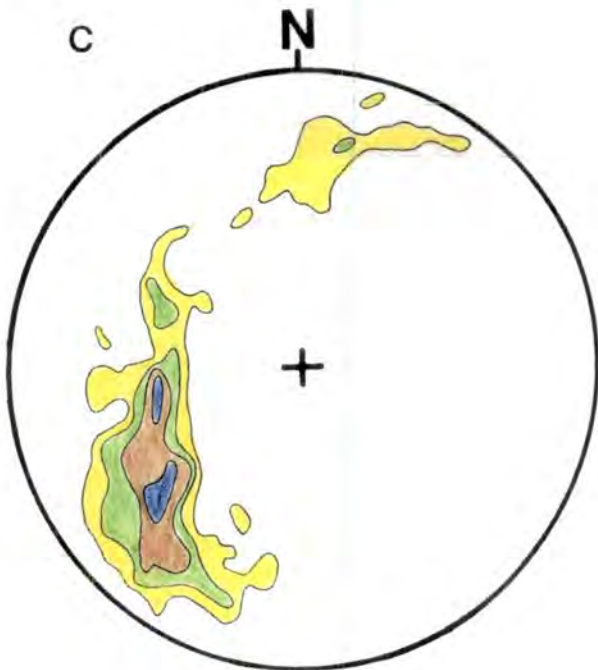
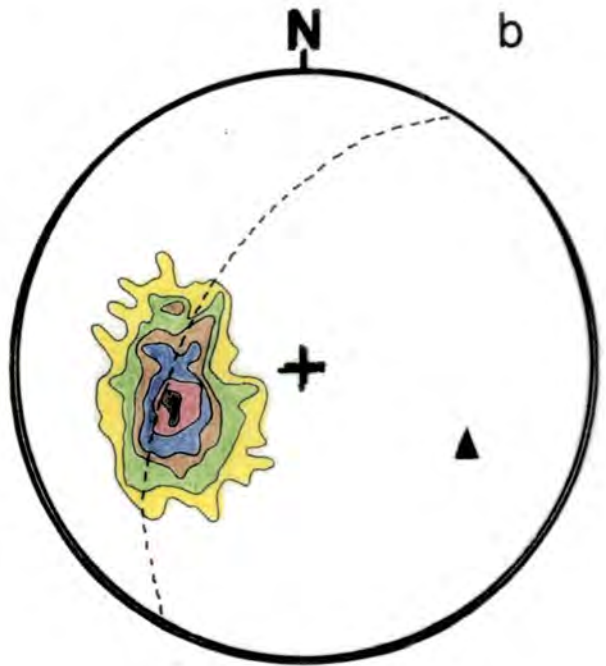
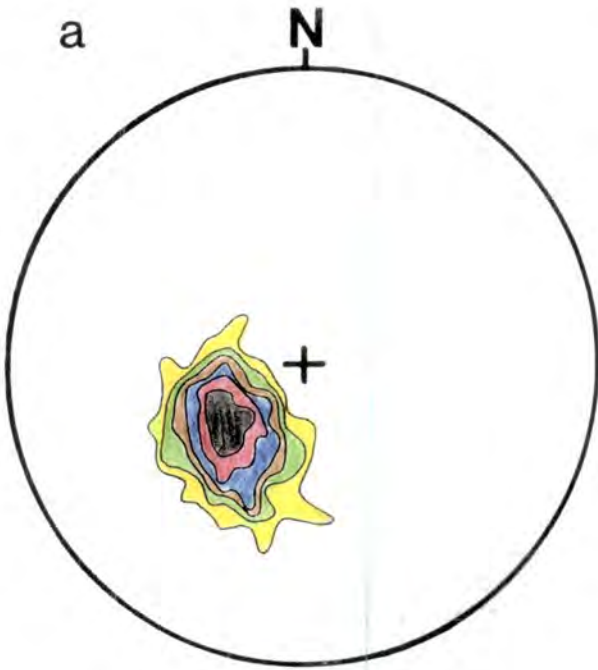


Figure 4.5a.

**S3 - Area 2.**  $n = 129$ , maximum concentration of data points = 158/19NE, mean = 152/21NE.

Figure 4.5b.

**B3 Lineations - Area 2.**  $n = 81$ , maximum concentration of data points = 13/053, mean = 17/068. Best fit great circle to data girdle = 160/18NE. Thus, there is an apparent rotation of B3 Lineations within the plane of S3.

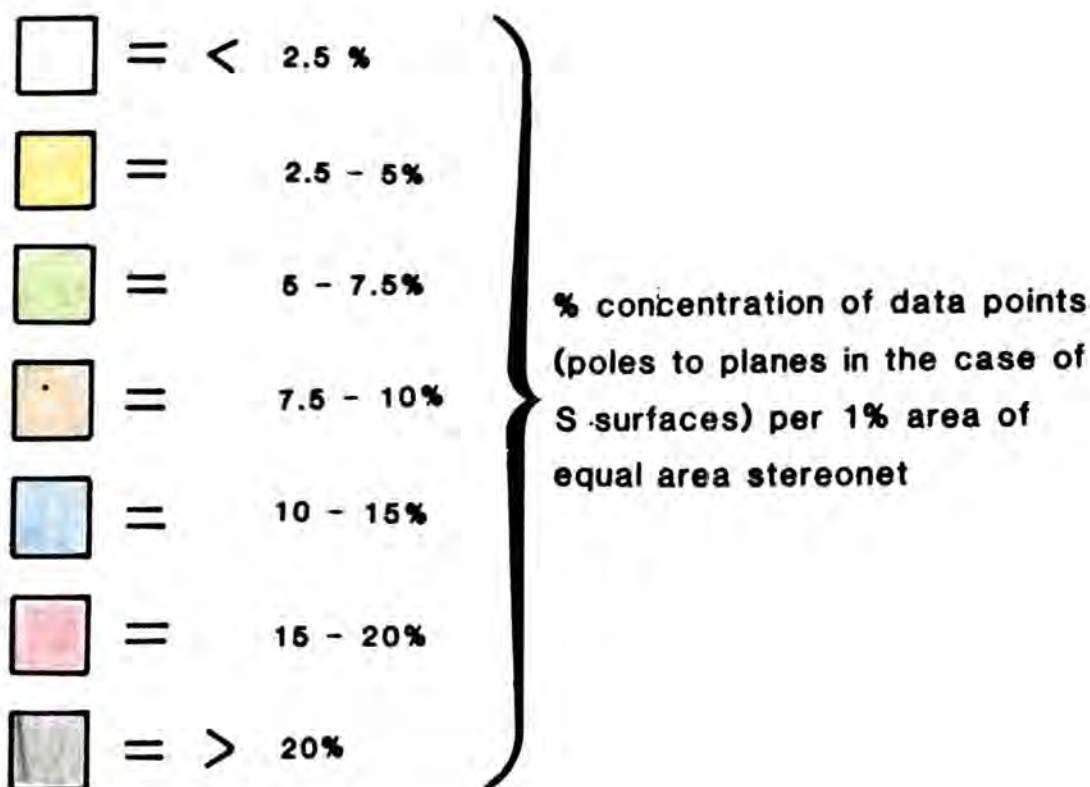
Figure 4.5c.

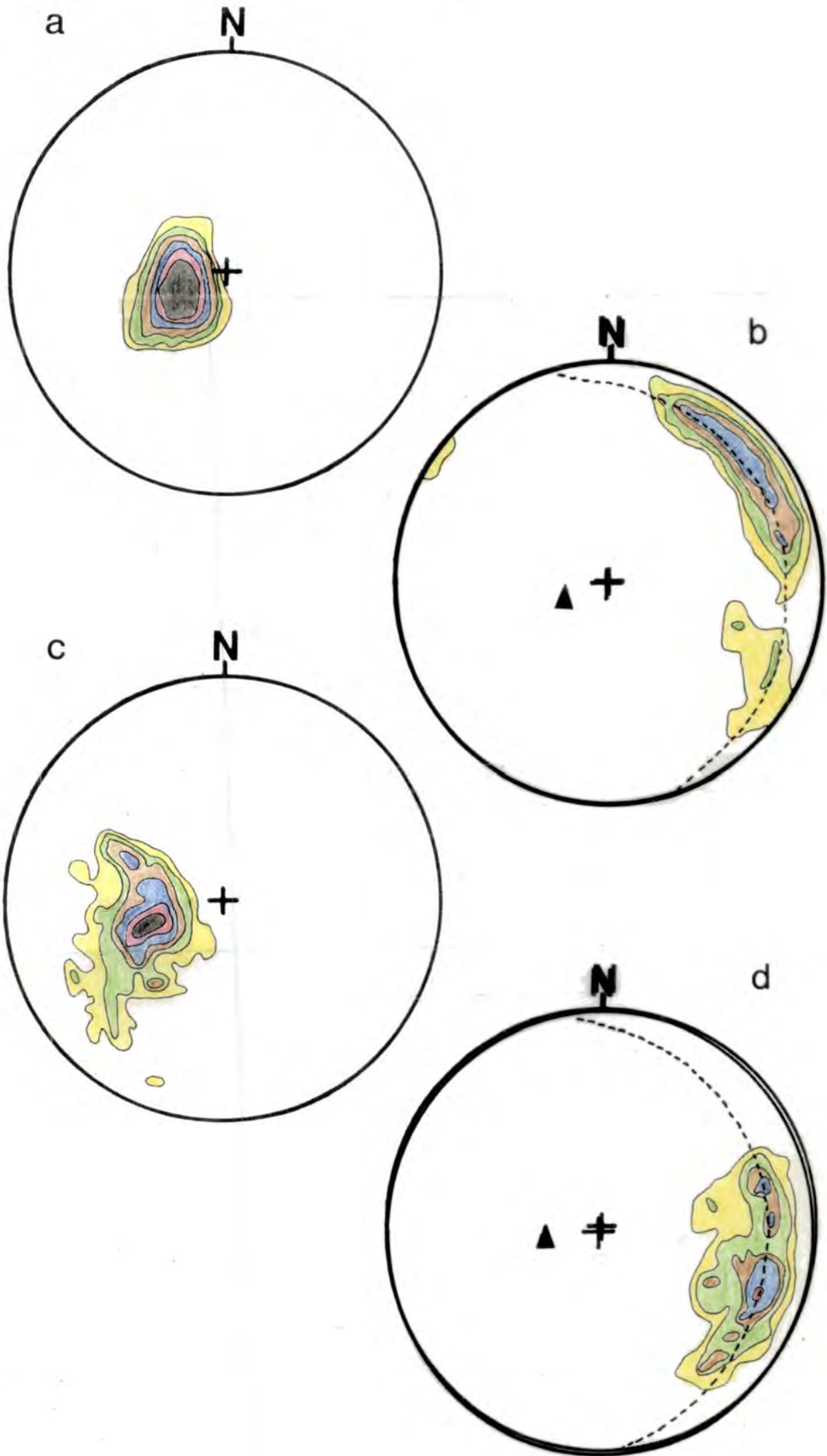
**S3 - Area 3.**  $n = 612$ , maximum concentration of data points = 161/34NE, mean = 162/36NE.

Figure 4.5d.

**B3 Lineations - Area 3.**  $n = 111$ , maximum concentration of data points = 16/113, mean = 27/105. Best fit great circle to data girdle = 172/22NE. There is an apparent rotation of B3 lineations within the approximate plane of S3.

Contour intervals on equal area stereograms shown on facing page





(Map 9 map box) are parallel. The elongation lineation is defined by stretched quartz and feldspar grains within the plane of S2 and plunges gently towards the south east. Towards the north and east of area 2, the mineral elongation lineation, although difficult to identify at all outcrops (due to the pelitic nature of the lithologies), plunges consistently towards the south east. The L2 - L3 mineral elongation lineation for the whole of area 2 is shown on Figure 3.8a.. B3 lineations towards the northern and eastern portions of area 2 undergo a gradual rotation (Map 3 map box). As noted previously, B3 lineations in the southern portion of area 2 plunge gently towards the south east. In the northern portion of area 2 this plunge direction gradually rotates in an anticlockwise sense and in the plane of S3 away from the mineral elongation lineation (Map 3 map box). Thus, at Three Tops (C 070010), B3 lineations plunge gently towards the east north east, and moving northwards to Meentycat (C 090040), they plunge gently and consistently towards the north east. This rotation within the plane of S3 of B3 lineations throughout area 2 is clearly depicted on Figure 4.5b.. There would thus appear to be a north east - south west D3 strain gradient over approximately 10 km in area 2. This could be regarded as increasing D3 strain into the D3 slide zone on the inverted limb of the D3 Ballybofey Antiform. Thus, lower D3 strains existed in the northern portions of area 2 where B3 lineations and the L2 - L3 mineral elongation lineation are most oblique. D3 strain increased towards the south where B3 lineations and L2 - L3 mineral elongation lineations are sub-parallel in the hinge and inverted limb of the D3 Ballybofey Antiformal complex. Quantitative analysis of oblique folds and fold rotation towards stretching lineations with increasing strain have been undertaken by Sanderson (1973), Roberts and Sanderson (1974) and Borradaile (1972).

#### 4.4) D3 Area 3

Throughout area 3, D3 is the major control on the orientation of S0 and S2. As area 3 encompasses both the upper normal limb and the lower inverted limb of the D3 Ballybofey Antiform, a range of strains and therefore structures relating

to the third deformation are observed. Area 3 is positioned entirely on the eastern limb of the D7 Ballard Antiform and is therefore relatively unaffected by this late fold (Map 10 map box). Within the area, S2 and S3 are clearly distinguishable fabrics on both the upper and lower limbs of the D3 Ballybofey Antiform.

S3 is a well defined zonal crenulation of S2 and dips gently to the east north east on the upper limb of the D3 Ballybofey Antiform (Map 3 map box). It is a fabric axial planar to mesoscopic F3 folds, which are recumbent, have short middle limbs less than 1 m long and which clearly deform the spaced S2 fabric. Mesoscopic F3 fold axes and S3 / S1-S2 intersection lineations are parallel. Such B3 lineations have undergone a similar rotation within the plane of S3 and towards the L2 - L3 mineral elongation lineation as described in 4.3) (Map 3 map box). The rotation within area 3 is not as pronounced due to the proximity of the D3 Ballybofey Antiformal trace. F3 folds verge consistently towards the south and east i.e. the D3 Ballybofey Antiform. The L2 - L3 mineral elongation lineation plunges gently towards the south east throughout the upper normal limb of the D3 Ballybofey Antiform (Map 9 map box).

To the south west of the axial trace of the Ballybofey Antiform, the rocks are steeply dipping towards the north east and are inverted (Map 1 map box). The two limbs of the D3 Ballybofey Antiform are clearly expressed in the general orientation of the folded S0 and S2 fabric throughout area 3 (Figures 3.7b. , 4.4b.). S3 remains a well developed crenulation cleavage throughout the inverted limb, but increases in intensity and becomes steeper dipping and more closely spaced ( 4 mm average )there (Plate 27a.). Associated with this steepening and change of character of S3 is a change in vergence towards the north east towards the Ballybofey Antiform (Map 3 map box). Mesoscopic F3 folds in this southern portion of area 3 clearly deform S2 and are slightly tighter than the F3 folds on the upper limb of the D3 Ballybofey Antiform. Mesoscopic F3 folds and S3 / S1-S2 intersection lineations are parallel. These B3 lineations consistently par-

allel the L2 - L3 mineral elongation lineation, both structures plunging gently towards the south east (Maps 3 and 9, map box). Thus, throughout area 3, S3 dips gently towards the east (Figure 4.5c.), B3 lineations plunge to the south east or east north east depending on the state of D3 strain (Figure 4.5d.), and the L2 - L3 mineral elongation lineation gently plunges consistently towards the south east (Figure 3.8b.).

This overall picture is consistent with D3 observations in area 2 (see 4.3). The combination of D3 data from both area 2 and area 3 presents a comprehensive view of D3 tectonics, as it includes samples from the higher D3 strain zones on the southern inverted limb of the Ballybofey Antiform. Thus, S3 changes strike and dip only slightly (becoming steeper towards the south) throughout areas 2 and 3 (Figure 4.6a.). Within the plane of S3, B3 lineations now more clearly define a rotation towards the L2 - L3 mineral elongation lineation (Figure 4.6b.). This is due to the sample population containing a larger percentage of highly strained (D3) rocks.

Within the hinge zone of the D3 Ballybofey Antiform, in the Gaugin Quartzite bodies of Altnapaste (H 045960), and Gorey Hill (H 085975), a well developed upright S3 cleavage is developed (Maps 3 and 16 map box). This S3 cleavage clearly crenulates the earlier S2 fabric, especially in the surrounding pelites and grits of tectonic package B (Plate 28). The north west - south east trending S3 fabric is moderately dipping to the north east (Figure 4.6c.), and is axial planar to recumbent, commonly tight mesoscopic F3 folds which clearly fold the S1-S2 fabric and have short limbs less than 1 m long (Plates 29a., 29b.). These mesoscopic F3 fold axes within the D3 Ballybofey Antiformal hinge zone parallel the S3 / S1-S2 intersection lineation (all collectively termed B3 lineations) and plunge moderately to the south east (Figure 4.6d.). B3 lineations within the hinge zone are sub-parallel to the L2 - L3 mineral elongation lineation well developed within the Gaugin Quartzite of Altnapaste and Gorey Hill (Map 16 map box) (Figure 3.8c.). The effects of the D3 folding within

Figure 4.6a.

**S3 - Areas 2 and 3 combined.**  $n = 741$ , maximum concentration of data points = 159/30NE, mean = 161/33NE.

Figure 4.6b.

**B3 Lineations - Areas 2 and 3 combined.**  $n = 192$ , maximum concentration of data points = 16/113, mean = 24/089. Best fit great circle to data girdle = 172/23NE. There is an apparent rotation of B3 Lineations within the approximate plane of S3.

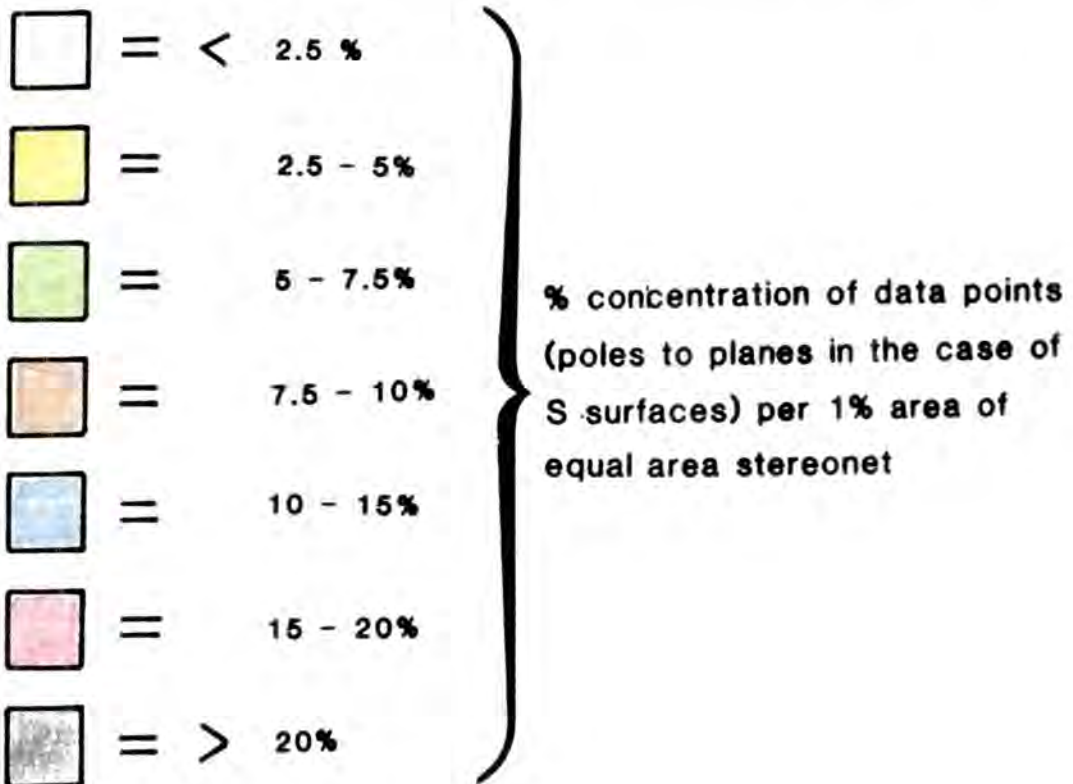
Figure 4.6c.

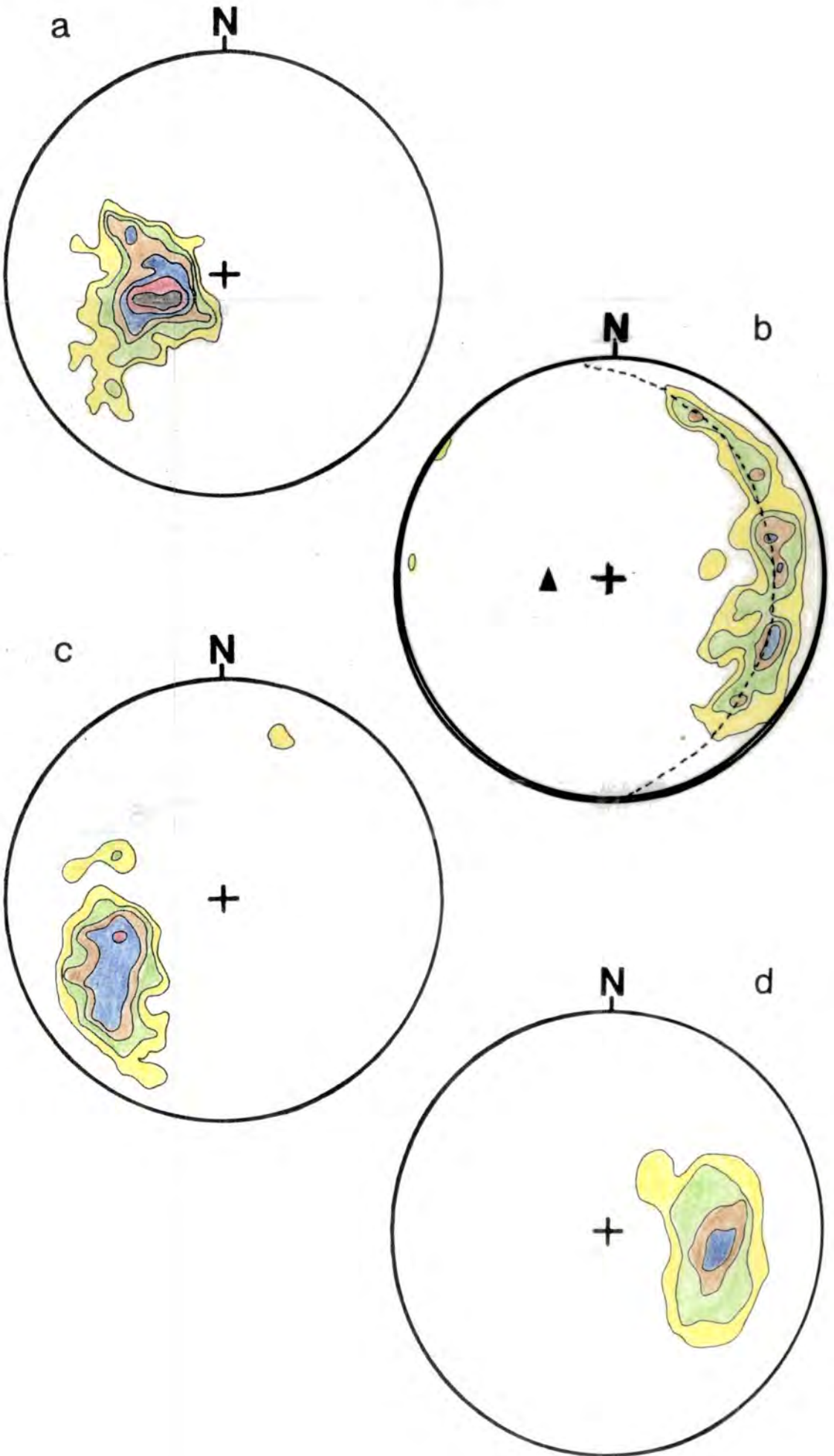
**S3 - Altnapaste / Gorey Hill Sub-Area.**  $n = 206$ , maximum concentration of data points = 160/44NE, mean = 145/55NE.

Figure 4.6d.

**B3 Lineations - Altnapaste / Gorey Hill Sub-Area.**  $n = 22$ , maximum concentration of data points = 48/104, mean = 47/095.

**Contour intervals on equal area stereograms shown on facing page**





the hinge zone of the Ballybofey Antiform are very obviously shown by equal area stereograms of S0 and S2 orientations within the Altnapaste / Gorey Hill quartzite bodies (Fig ures 4.4c., 3.7c.). The attitude of these earlier surfaces is clearly a product of D3 folding, the geometrically predicted fold axis and the measured D3 fold axes broadly corresponding, *plunging gently to the S.E.*

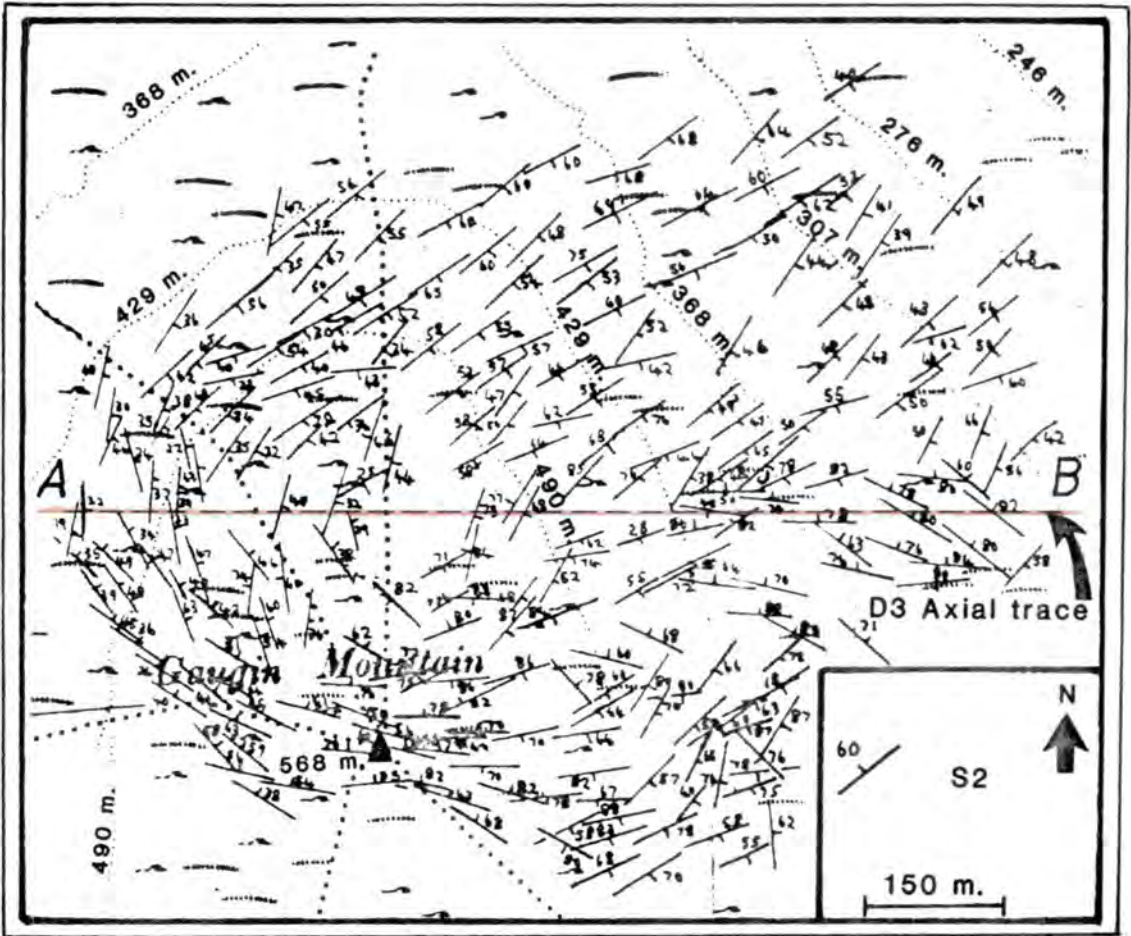
#### 4.5) Regional D3 synthesis

On the gross scale, the refolding effects of the D3 Ballybofey Antiformal complex on the Central Donegal slide and the major D2 structures (see 3.3 e) are obvious (Maps 3 and 10, <sup>Sections 1,2,3</sup> map box).

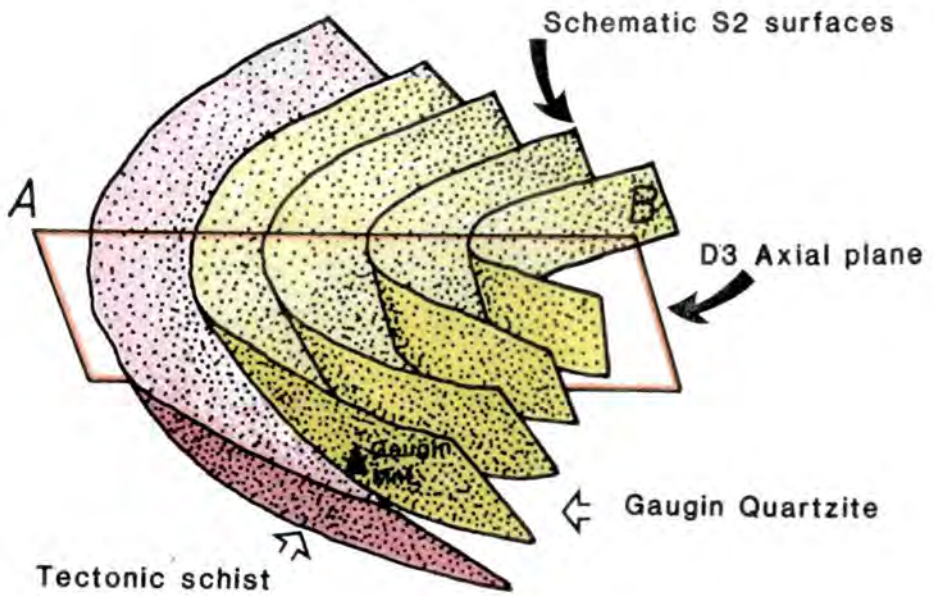
In the southeastern portion of the mapped area, the folding of the Croaghbrid Pelites and Boultypatrick Grits of tectonic package B is apparent. Also folded are the tectonic schists of the Central Donegal slide, further verifying the pre-D3 age of this structure (Map 3 map box). D2 mylonites of the Central Donegal slide are clearly folded around the hinge of the D3 Ballybofey Antiform to the south east of Gorey Hill (G 095960) (see 3.3f). In the extreme north eastern portion of the map at Meenalaban (C 100020), an easterly plunging D3 fold pair verge towards the Ballybofey Antiform in the south (Map 3, Section 3 map box).

The large scale refolding effects of the D7 Ballard Antiform on the D3 Ballybofey Antiform are shown on Map 10, as well as Maps 15 and 16 (map box). Minor D3 structures (S3, B3) have obviously been reoriented by this later D7 fold. The orientation of B3 lineations for the whole of the mapped area are shown on Figure 4.9b.. Maps 3 and 10 (Map box) show that the refolding effects of the Ballard Antiform are concentrated primarily on the lower inverted limb of the D3 Ballybofey Antiform, to the west of the D7 axial trace (Figure 4.1c.). The preexisting structural geometry relating to the second and third deformations may have controlled the configuration of the D7 folding.

The D3 Crocknahamid Antiform in the central portion of the mapped area



**a.** S2 map Gaugin Mnt.



**b.** Schematic diagram of S2 surfaces in the Gaugin synform (D3)

FIGURE 4.7.

appears to die out towards the east, having no equivalent on the eastern limb of the D7 Ballard Fold (Map 3 map box). This D3 fold is the major structure responsible for upfolding the inverted sequence of Croaghbrid Pelites and Boultypatrick Grits adjacent to the Leannan Fault (see 3.3e), (Map 3, Section 2, map box). Farther to the south, the complementary Gaugin Synform (D3) can be traced eastwards from the Carnaween Fault towards Gaugin Mountain (G 980950), where it folds tectonic schists and associated S2 fabrics of the central Donegal slide (Figure 4.7.) (Maps 3 and 14, map box). The D3 Gaugin Synform clearly refolds the D2 Commeen Fold (see 3.3c) (Map 10 map box), prior to fading in the hinge zone of the D7 Ballard Fold (Section 2 map box).

To the south of the D3 Gaugin synform, the D3 Ballybofey Antiform is the major structure controlling structural geometry throughout eastern Donegal and western Tyrone (Pitcher, Shackleton and Wood 1971, Pitcher and Berger 1972) (Figure 4.8.) (see chapter 6). It should be noted that although this fold has been named the Ballybofey Antiform and can be traced for distances in excess of 40 km (opp. cit.), it is only a component in the complicated multiple hinge of the Ballybofey Antiformal complex. To the west of the D7 Ballard Antiform, the D3 Ballybofey Antiform has an east - west axial trace, and plunges gently to the east (see 4.2), its axial plane dipping moderately / steeply towards the north (Maps 3, 12, 13, 14, map box). In the vicinity of the hinge of the D7 Ballard Antiform, the D3 Ballybofey Antiform axial trace in tandem with its related minor structures (S3, B3, L2 - L3), is refolded to a East-North-East, West-South- West trend. The S3 axial planar fabric within this area becomes steeply dipping / sub-vertical towards the north and west (Figure 4.9a.), (Maps 3, 10, 15 map box). The structure of the central portion of the map is clearly related to multiple refolding about approximately orthogonal axes (Map 10 map box). The refolding effects of the D7 Ballard Antiform are, due to the nature of its steep northerly plunging axis, best viewed on the plane of the map (Map 10 map box). The refolding effects of the D3 Ballybofey Antiformal complex on

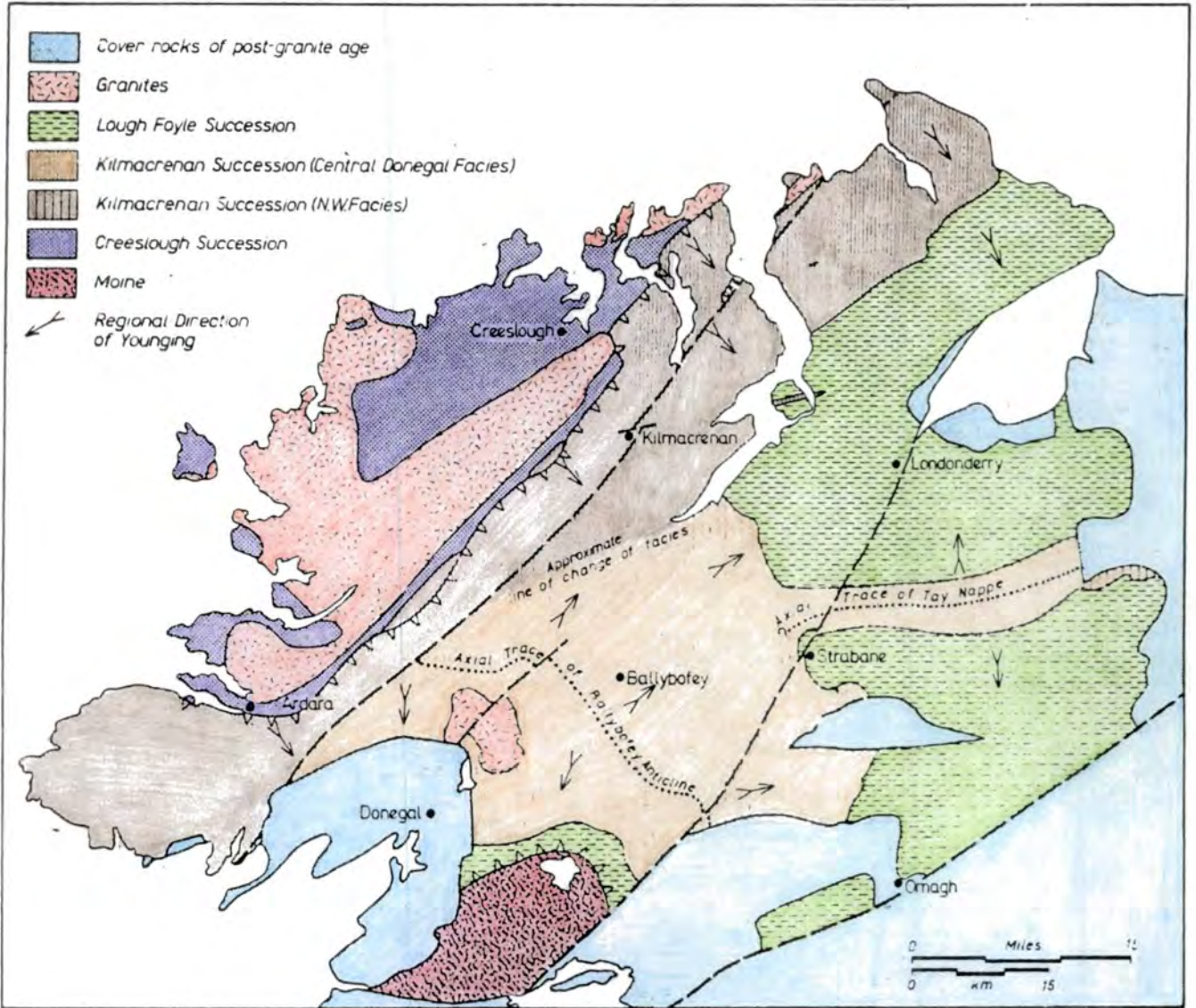


FIGURE 4.8.  
GEOLOGICAL MAP  
OF NW IRELAND  
(FROM PITCHER  
et al 1971)

the D2 sheath fold complex are better observed in section (Section 2 map box).

To the south of the D3 Ballybofey Antiform the complementary synformal hinge, the Silver Hill Synformal complex is developed. These two multiple hinges are separated by the D3 Ballybofey slide which is located on the lower inverted limb of the antiformal complex. This slide overthrusts towards the south east in an oblique dextral sense (see 4.6). The Silver Hill Synformal complex is best developed in the Lough Eske Psammities (see 2.5c) adjacent to the Carnaween Fault. Quartzite units within the steep, northerly dipping psammities aid in the definition of the D3 folding (Map 3 map box). Farther to the north, a synformal axis is clearly developed in the Croaghubbrid area (G 915930), (the D3 Croaghubbrid Synform). To the west of the Carnaween Fault, the D3 Croaghubbrid Synform repeats the Gaugin Quartzite on either margin of the older Croveenananta Formation (see 3.3a). The rapid variation of outcrop width of the southern band of Gaugin Quartzite across the Leannan Fault (Map 3 map box), has previously been interpreted in various ways. Cambray (1964) states that "parts of the same succession originally widely spaced and of different thickness must have been brought together by these faults" (Carnaween Fault). Pitcher et. al. (1964) in their regional synthesis of the Leannan Fault system state that the Carnaween Fault "shifts the base of the Croaghubbrid Dark Schists one mile and, if a strike slip fault, would be sinistral; on the other hand the way in which a long strip of quartzite, north east from Binbane is brought against granulite (Lough Eske Psammite) would seem to require considerable dip slip movement". The author believes that there has been appreciable downthrow to the south east in an oblique sinistral sense on this fault. Such a hypothesis can not be tested directly in the field as the Carnaween Fault plane is very poorly exposed along its length. Therefore no slickenslide observations have been made in either the present study or by previous workers (opp. cit.). However a downthrow to the south east in tandem with a sinistral displacement along the Carnaween Fault (possibly resulting in a scissor motion opening towards the

south) would integrate with similar motions based on slickenside observations seen throughout the Leannan Fault system (Pitcher et. al. 1964), (Cambray 1969a).

The large outcrop width of inverted Gaugin Quartzite exposed to the west of the Carnaween Fault (Map 3 map box), therefore probably represents a deeper structural level of the Silver Hill Synformal complex. The exposed quartzite dips gently towards the north and thus completes an overall synformal geometry with the steep northerly dipping D3 Ballybofey Antiform to the north (Section 1 map box). The extreme variation in outcrop width of the Gaugin Quartzite across the Carnaween Fault can therefore be attributed to the quartzite west of the fault having a shallow northerly dip, as well as being less strained than its counterpart to the east. Gaugin Quartzite immediately east of the Carnaween Fault at (G 920930) has started to thicken in the hinge of the D3 Croaghubbrid Synform.

In order for the Gaugin Quartzite / Lough Eske Psammite D3 tectonic slide junction to be exposed at Binbane (G 8388700) (beyond the south western corner of the map) (Section 1 map box), a return D3 antiformal hinge to the south of the Silver Hill Synformal complex must exist. To the west of the Carnaween Fault, evidence for such a hinge is found in the Gaugin Quartzite at Carnaween (G 875890), where southerly dipping rocks are exposed and where Cambray (1964) believed there to be large scale folding. Thus, the D3 Carnaween Antiform (Section 1 map box) folds the D3 tectonic slide junction between the Lough Eske Psammites and the Gaugin Quartzite. This suggests a certain degree of diachronous deformation during F3 folding.

In summary, the overall D3 geometry is dominated by the Ballybofey Antiformal complex overthrusting in an oblique dextral sense towards the south east (see 4.6). The Ballybofey Antiform has attenuated and sheared on its inverted southern limb, cutting out stratigraphy and producing the Ballybofey slide (see 4.6). To the south, the D3 Silver Hill Synformal complex is the complementary

return hinge to the Ballybofey Antiform and clearly folds the D3 Ballybofey slide junction between Gaugin Quartzite and Lough Eske Psammities. This D3 slide reappears to the south of the D3 Carnaween Antiform at Binbane (G 838870). The folding of the D3 slide by structures of the same 'generation' is indicative of a certain degree of diachroneity and progressive shear zone - related strain during the overall D3 event. Plate 30 shows a block diagram representing the gross D3 geometry of Central Donegal, the attitudes of the structures being displayed in relation to the steep western limb of the refolding D7 Ballard Antiform.

#### 4.6) The D3 Ballybofey tectonic slide

The Ballybofey tectonic slide is a major D3 dislocation which has developed south of, and sub-parallel to the northward dipping axial plane of the D3 Ballybofey Antiformal complex (Map 3 map box). This slide was originally described by Pitcher, Shackleton and Wood (1971) based on the stratigraphic discontinuities it produces and it extends from Ballard (H 020945) in the east, to the Carnaween Fault in the west (G 920930). To the west of the Carnaween Fault it can be traced towards the Leannan Fault at Binbane (G 838870). Throughout the western portion of the slide, Gaugin Quartzite (tectonic package A) and Lough Eske Psammities (tectonic package B) (Chapter 2) are juxtaposed (Map 3 map box). Only in the extreme eastern portion of the Ballybofey slide are tectonic cut offs against the slide plane observed (Map 3 map box).

To the south of Slievemullagh (H 010940), Gaugin Quartzite enclosing Reelan Formation calcareous Pelites within the hinge of the D2 Commeen Fold (see 3.3e.), has been clearly breached and cut out in the hangingwall of the northerly dipping slide (Map 3 map box). This excision causes the Lough Eske Psammite to be directly juxtaposed against the Reelan Formation. Towards the east at Stroangibbagh (H 022940), a strip of Gaugin Quartzite and tectonic schists of the D1 - D2 Central Donegal slide are cut out in the hangingwall of the D3 Ballybofey slide. This illustrates the point made in 3.6 , that unfavourably oriented early slides and associated tectonic schists may act as part of the de-

formed stratigraphy and be cut out against later dislocations. However, towards the east in the vicinity of the D7 Ballard Antiformal hinge the D1 - D2 Central Donegal slide has presumably been favourably oriented in relation to the D3 stress field and has been utilised by D3 shear. Thus, the tectonic schists of the Central Donegal slide are, at this juncture, representative of polyphase reactivation during D1, D2 and D3. This point will be returned to later.

As noted earlier, the footwall of the Ballybofey slide is, in the western portion of the mapped area, entirely occupied by the Lough Eske Psammities (Map 3 map box). However, towards the east in the Ballard area (H 025940), footwall cutoffs relating to D3 shear become evident. Croaghubbrid Pelites (tectonic package B) which are found adjacent to the D1 - D2 tectonic schists of the Central Donegal slide throughout its entire exposed length are cut out against the footwall of the D3 Ballybofey slide, as are the structurally underlying Boultypatrick Grits (Map 3 map box). The cutting out of the Croaghubbrid Pelites and the Boultypatrick Grits permits the Lough Eske Psammities in the footwall of the D3 Ballybofey slide to be juxtaposed against the Gaugin Quartzite in the hangingwall. Thus, the Ballard region of the D3 Ballybofey slide would appear, due to the cut offs noted, to represent some form of thrust ramp structure.

Along the entire length of the D3 Ballybofey slide, there are relatively few localities where the slide junction is actually exposed. Such localities eg. Croveenananta (G 945934), indicate that in the mapped area there was no major development of tectonic schists along the D3 Ballybofey slide. This may largely be related to and controlled by the quartzite / psammite lithologies on either margin of the tectonic slide (see 3.3f.). However, it should be noted that in some instances eg. Stroangarrow (G 985939), the Lough Eske Psammite contains slightly more biotite adjacent to the D3 Ballybofey slide. Although clearly not a tectonic schist, this slight mineralogical variation may have been tectonically induced. At Binbane (G 838870) however, beyond the south western portion of the mapped area D3 tectonic schists have developed between Gau-

gin Quartzite to the north and Lough Eske Psammites to the south. There is an increased platiness and an intensified mineral elongation lineation in both the psammite and the quartzite on either margin of the tectonic junction. The tectonic schists are very similar to those developed along the D1 - D2 Central Donegal slide in the area (see 3.3f.), indeed they are displayed as the same rock type by Pitcher and Berger (1972 map 1). The tectonic schists are a quartz rich, strongly foliated rock with quartz ribbons upto 30 cm in length paralleling the main fabric. Also present within the schists are large biotite porphyroblasts upto 4 mm long as well as garnets (which have since been chloritised) and staurolite. This tectonic schist occupies a width of approximately 15 m on the summit of Binbane (G 838870) (Section 1 map box).

There appear to be no mineralogical changes in the Gaugin Quartzite in the hangingwall of the D3 Ballybofey slide. There are however textural and structural changes within the quartzite which include an increasing platiness within the quartzite upto 20 m from the slide, with bedding and the composite S2 - S3 fabric becoming coplanar. The spacing between beds diminishes to approximately 25 cm and a stronger mineral elongation lineation, defined by stretched quartz and feldspar grains, is developed. The structural changes described from within the quartzites adjacent to the D3 Ballybofey slide are not as well developed within the adjoining Lough Eske Psammites. D3 mylonites developed along the Ballybofey slide are shown in Plates 31a., 31b. .

In summary, the northerly dipping Ballybofey slide is a zone of more localised discrete D3 displacement within an area of regional D3 shear on the lower inverted limb of the Ballybofey Antiform. It cuts out the Croaghubbrid Pelite and Boulypatrick Grits of tectonic package B along its footwall, and occasionally breaches through the Gaugin Quartzite in its hangingwall (Stroangibbagh (G 022940)). The eastern 'termination' of the Ballybofey slide can be regarded as the point in its hangingwall at which it ceases to cut through the rocks of tectonic package A and the tectonic schists of the D1 - D2 Central

Figure 4.9a.

**S3 - Slievemullagh (H 005950) (within Area 1.)**  $n = 216$ , maximum concentration of data points = 109/53N, mean = 093/61N. Distribution of data corresponds to refolding by the D7 Ballard Antiform.

Figure 4.9b.

**B3 Lineations - whole of map area.**  $n = 383$ , maximum concentration of data points = 20/117, mean = 23/090. Distribution of data corresponds to refolding by F7 and F9 folds, together with rotations of B3 lineations (towards the mineral elongation lineation) within the plane of S3.

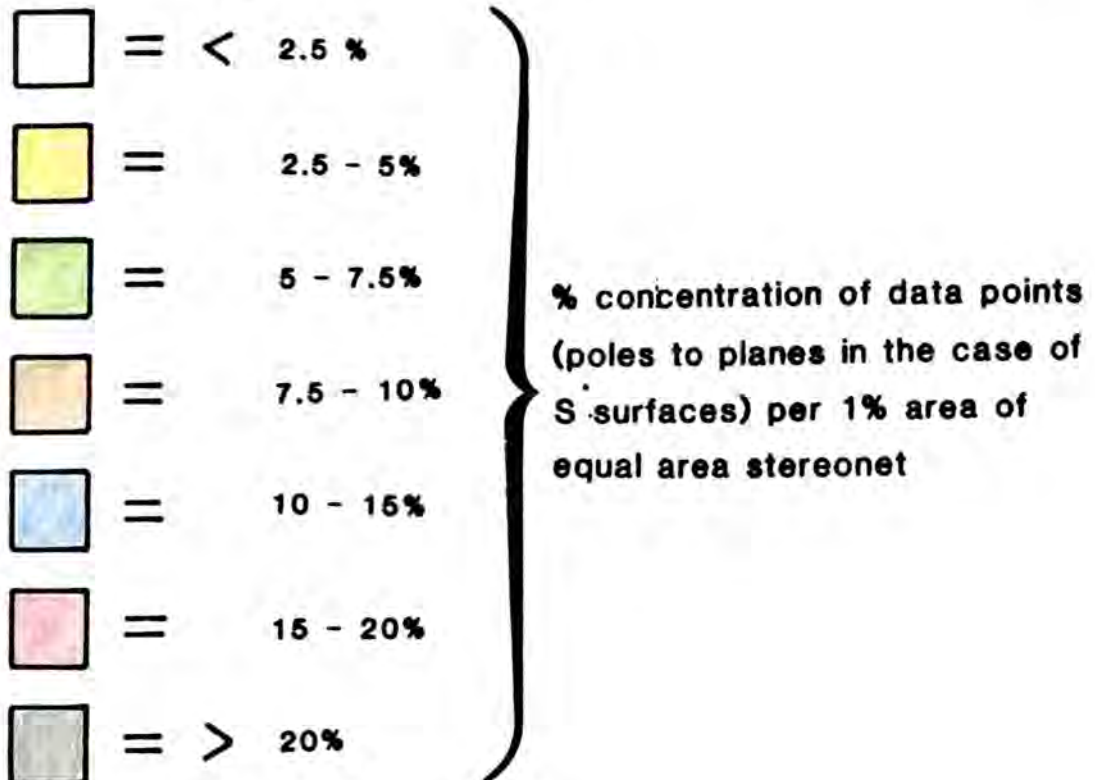
Figure 4.9c.

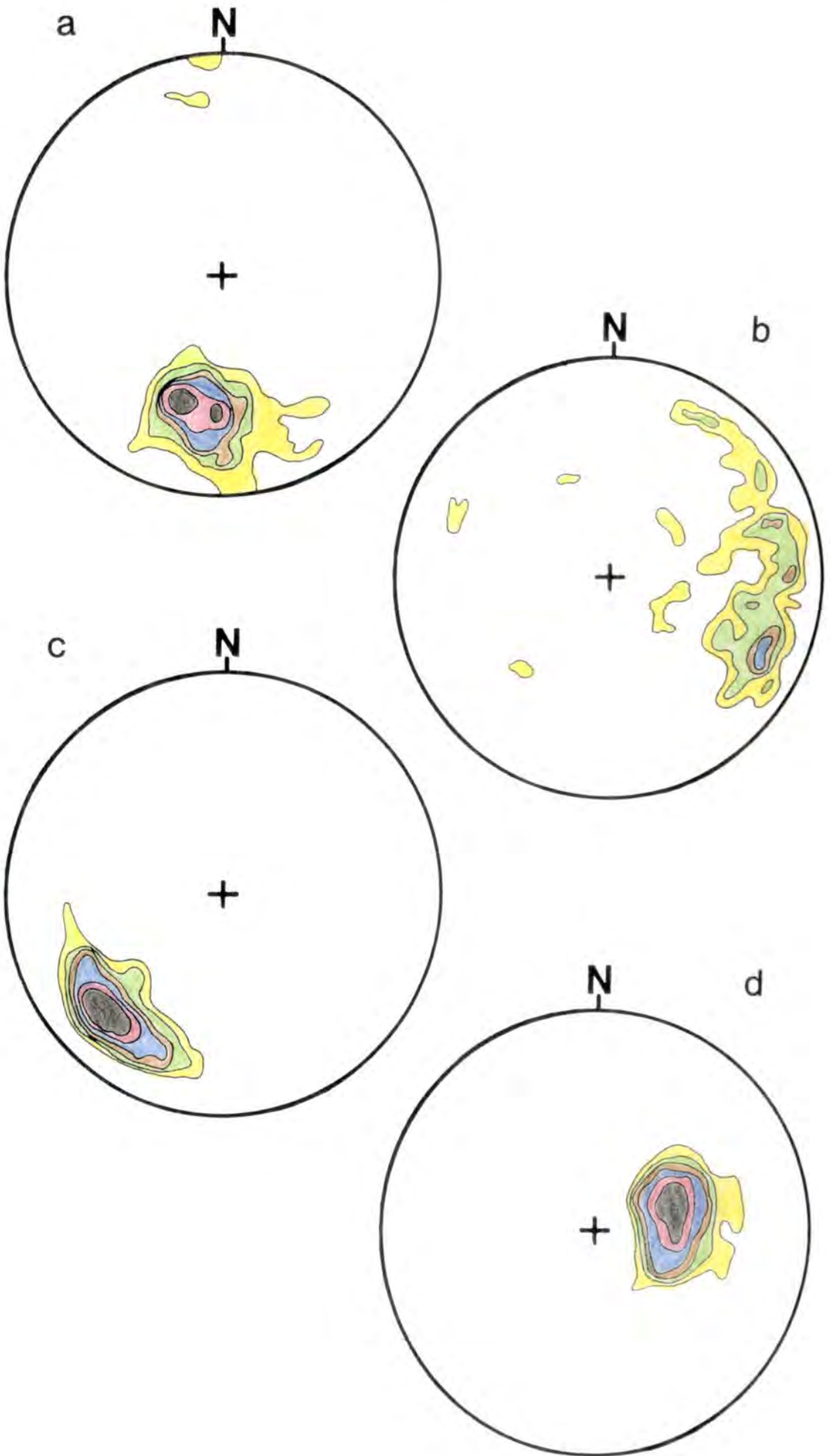
**S3-E - Croaghbrid (G 910930) (within Sub-Area 1b.)**  $n = 127$ , maximum concentration of data points = 139/67NE, mean = 133/65NE. The slight girdle shape corresponds to a rotation into parallelism with the Carnaween and Leannan Faults (shown on Map 12, map box).

Figure 4.9d.

**B3-E Lineations - Croaghbrid (G 910930) (within Sub-Area 1b.)**  
 $n = 73$ , maximum concentration of data points = 56/066, mean = 56/086.

**Contour intervals on equal area stereograms shown on facing page**





Donegal slide. At this point, D3 strain is accommodated along the reactivated Central Donegal slide, a polyphase D1 - D2 - D3 structure in this area. The D3 Ballybofey slide is clearly folded by the D7 Ballard Antiform, by D5 folds at Croveenananta (G 950940), and to the south by the major D3 folds of the Silver Hill Synformal complex and the Carnaween Antiform. Folding of the slide plane by structures belonging to the same 'deformation' indicates clear structural diachroneity within a single 'event'.

#### 4.7) D3 kinematics of the Ballybofey slide and associated reactivation of the Central Donegal slide.

There are a variety of kinematic indicators developed within the mapped area that can be directly related to movement on the D3 Ballybofey slide, and D3 reactivation of the D1 - D2 Central Donegal slide. Zones of more intense D3 shear may be recognised in a number of ways.

On the gross scale, zones of more discrete D3 shear can be recognised on the inverted limb of the D3 Ballybofey Antiform, where the composite S2-S3 fabric swings towards parallelism with the D3 Ballybofey slide (Lavagh More (G 940920)). As noted in 4.6), reactivation of the Central Donegal slide during D3 is seen in some instances. In the hinge of the D3 Ballybofey Antiform at Ballard (H 035960) (Map 15 map box), Gaugin Quartzite on the upper limb of the D2 Commeen Fold (see 3.3f.) has been preserved, whilst on the limbs of the D3 Ballybofey Antiform it has been sheared out along the tectonic schists of the reactivated Central Donegal slide (Maps 3 and 15, map box). The 10 km wide zone of clockwise rotation of B3 lineations towards the mineral elongation lineation can be regarded as being indicative of increasing D3 strain towards the inverted limb of the Ballybofey Antiform. Within this inverted limb in the zone of intense regional D3 shear, more discrete localised displacement surfaces such as the D3 Ballybofey slide occur.

D3 extensional crenulations (Berthé et al.1979, Platt and Vissers 1980, White

et al 1980, Passchier 1984) have been identified along the Central Donegal and Ballybofey slides, as have a symmetrical pressure shadows (Simpson and Schmidt 1983). These D3 kinematic indicators give a consistent sense of D3 over shear towards the south (Shown on Map 3 map box). Adjacent to the western section of the Central Donegal slide between the Carnaween Fault and the Leannan Fault (Croaghbrid (G 915930)), there is exposed a highly attenuated sequence of calcareous pelites (Croveenananta Formation) and Gaugin Quartzite (see 2:2) (Maps 3 and 12, map box). Within the Gaugin Quartzite, and the tectonic schists of the Central Donegal slide which form the northern boundary to the quartzite, are a well developed set of extensional crenulations. These extensional crenulations (S3-E) are consistently developed in a clockwise sense to, and dip at shallower angles towards the north east than, the S2-S3 mylonitic fabric (Figure 4.9c.), (Map 12 map box). Only one set of extensional crenulations appears to have been developed and preserved within the S2-S3 mylonite, any opposing or conjugate sets are not present. Extensional crenulation axes (B3-E) plunge moderately to the east north east within the plane of the S2-S3 mylonitic fabric (Fig. 4.9d.), and are orthogonal to the westerly plunging L2 - L3 mineral elongation lineation developed within the same plane (Plate 32b.) (Map 12 map box). This is the anticipated relationship if the westerly plunging L2 - L3 stretching lineation noted above is indicative of the local D3 transport direction associated with shear band development. Thus, B3-E lineations may be regarded as forming at approximate right angles to the coeval transport direction. B3-E lineations include not only minor crenulation axes, but sheared a symmetrical folds with short limbs upto 1 m long and which are clearly deforming the mylonitic S2-S3 fabric. These larger folds are developed in the same orientation as the minor extensional crenulation axes and also suggest the same sense of shear. Throughout this section of the Central Donegal slide, every D3 extensional crenulation noted (S3-E), and its associated fold axis (B3-E) are indicative of D3 overthrusting towards the south in a pronounced oblique dextral sense.

In most instances, S3-E fabrics are planar surfaces developed at less than  $45^\circ$  to the S2-S3 mylonitic fabric (Plates 32a., 33b.). On some occasions however, the S3-E fabric is seen to become asymptotic in relation to the mylonitic fabric. As the angle between the extensional crenulations (S3-E) and the mylonitic fabric (S2-S3) diminishes, the width between S3-E surfaces also reduces (Plate 33a.). This rotation of the extensional crenulation surface appears to develop parallel<sup>t</sup> the local transport direction. It may be related to compositional variations within the rock, and / or localised strain gradients culminating in discrete shears where the extensional crenulations have rotated into parallelism with the mylonitic fabric. If related to increasing strain, it would be interesting to note whether the extensional crenulation axis rotated within the plane of the shear band as it became asymptotic to the mylonitic fabric. Thus, this hypothesis suggests that increasing strain would lead to a rotation (within the plane of the shear band) of extensional crenulation axes towards the local transport direction (defined by the mineral elongation lineation), as the extensional crenulation surface became asymptotic to the mylonitic fabric. Such a hypothesis is obviously very similar to models proposed for the generation of sheath folds in simple shear regimes (see 3.3a.), both concepts being governed by the necessity of the original axes having developed at approximate right angles to the transport direction, with a statistical bimodal distribution about the transport direction being required for sheath fold generation. Although poor exposure did not permit such observations, (and therefore testing of the model) in the present study, possible small-scale analogues relating to the hypothesis described may be beneficial in interpreting large scale sheath fold generation and geometries.

The timing and development of D3 extensional crenulations in relation to major F3 folds such as the Ballybofey Antiform has<sup>v</sup> been closely bracketed within the area of the present study. Detailed observation of S3-E extensional crenulation cleavages reveals that they deform the mylonitic S2-S3 fabric and therefore post-date its formation in their immediate vicinity (Plates 34a., 34b.). B3-E lin-

eations also clearly deform the S2-S3 fabric, this is especially well seen on the flat mylonitic surfaces (Plate 35a.). Rotation of S3-E towards the mylonitic fabric (S2-S3) in some instances (mentioned above), suggests that the S2-S3 fabric is composed of earlier formed, rotated and sheared S3-E crenulations. This leads to the concept of a progressively formed mylonitic fabric that may, if developing spatially as well as temporally, pre-date a 'set' of structures in one area and post-date them in another. It must be remembered that the observed and mapped extensional crenulations and associated axes (Map 12 map box) represent the last 'generation' of such structures to have developed, and have thus been preserved. It is an assumption that all previously formed extensional crenulation cleavages and associated axes were originally parallel and displayed the same movement sense i.e. there was no rotational axis perpendicular to the slide plane during progressive deformation. From observations of tectonic slides, both in the present study and elsewhere (Borradaile 1974), it appears that major rotations can and do develop along and within the plane of tectonic slide zones. The syn-metamorphic nature of tectonic slides together with in some instances a polyphase history, may in many cases prevent the preservation of an earlier formed mineral elongation lineation. Thus, one must not oversimplify tectonic movement zones by suggesting that the presently observed shear structures and deduced movement directions were typical throughout a deformational 'event'. Indeed, the observed extensional crenulations (S3-E) and associated axes (B3-E) not only post-date the mylonitic S2-S3 fabric within their immediate vicinity, but also clearly deform compressional crenulations relating to the D3 Ballybofey Antiform (Croaghbrid (G 908930)). D3 fold axes and associated crenulations (collectively termed B3 lineations) clearly do not have the same orientation as extensional crenulation axes (B3-E) (Figures 4.1d., 4.9d.). Thus, if a fold hinge is regarded as forming perpendicular to, or sub-perpendicular to the transport direction (defined as the mineral elongation or 'stretching' lineation), then movement directions must have varied with the evolution of the third deformational 'event'. In some instances along the D3

Ballybofey slide (Lacroagh (G 927937), a steep westerly plunging mineral elongation lineation defined by stretched quartz and feldspar is preserved within the mylonitic S2-S3 surfaces. This is clearly more orthogonal to F3 fold axes related to the Ballybofey Antiform and Silver Hill Synformal complex, and may be a remnant of an earlier movement direction along the Ballybofey slide associated with D3 folding. This earlier shear direction would approximate to an overthrust towards the south with a limited component of dextral shear. From these observations, it can be suggested that the latter phases of discrete D3 movement relating to the observed extensional crenulation development (S3-E, B3-E), were at a slightly different orientation to and post-dated the initiation of the Ballybofey slide.

As noted in 3.3b.), major D3 folds together with the L2 - L3 mineral elongation lineation plunge gently in opposing directions on either side of the Central Donegal / Ballybofey D3 slide zones at Croveenananta (G 940935). Such a variation in the plunge direction of both D2 and D3 structures has been related to a D3 rotation along the Central Donegal slide, which must post-date the initiation of major D3 folds. However, in order for the D3 Ballybofey slide to be exposed at Binbane (G 838870) to the south of the D3 Carnaween Antiform and Silver Hill Synformal complex, the slide must have been folded by these D3 structures. Thus, the picture emerges where a major D3 fold complex (Ballybofey Antiform, Silver Hill Synformal complex, Carnaween Antiform) was related to dip slip overthrusting towards the south with only a limited component of oblique dextral shear. D3 slides developed almost synchronously with the formation of the Ballybofey Antiform and towards the south (the transport direction), were deformed by slightly later folds of the same D3 'generation'. Towards the latter stages of D3 fold formation, the stress system on the inverted limb of the already formed Ballybofey Antiform is believed to have altered slightly leading to pronounced oblique dextral overthrusting towards the south. This shear sense is clearly shown by extensional crenulations (S3-E) and a 30° clockwise rotation<sup>of</sup> B3

axes along the Central Donegal and Ballybofey slides. The westerly plunging mineral elongation lineation (representing finite stretching) developed at right angles to the B3-E lineations. This will obviously have a large component of late D3 stretching relating to dextral oblique shear preserved within it. In summary, the D3 Ballybofey Antiform and the complementary D3 Silver Hill Synformal complex, developed prior to the latter stages of pronounced oblique dextral shear on more discrete, localised movement surfaces such as the Central Donegal and Ballybofey slides which separate them. Discrete D3 movements along the Central Donegal and Ballybofey slides can be regarded as having ceased prior to D4 and D5 (see 5.1., 5.2.). D4 structures clearly overprint Ballybofey slide fabrics at Stroangibbagh (G 990935). Major F5 folds and S5 fabrics clearly overprint both the S2-S3 mylonitic surfaces and the associated S3-E extensional fabrics (Maps 12 and 13, map box).

**PLATE 25a.**

**Locality** - Stroangarrow (G 992946)

Tight, overturned F3 fold of bedding (S0) and the S1-S2 fabric developed in Gaugin Quartzite on the inverted southern limb of the D3 Ballybofey Antiform.

**PLATE 25b.**

**Locality** - Bindoo (H 031970)

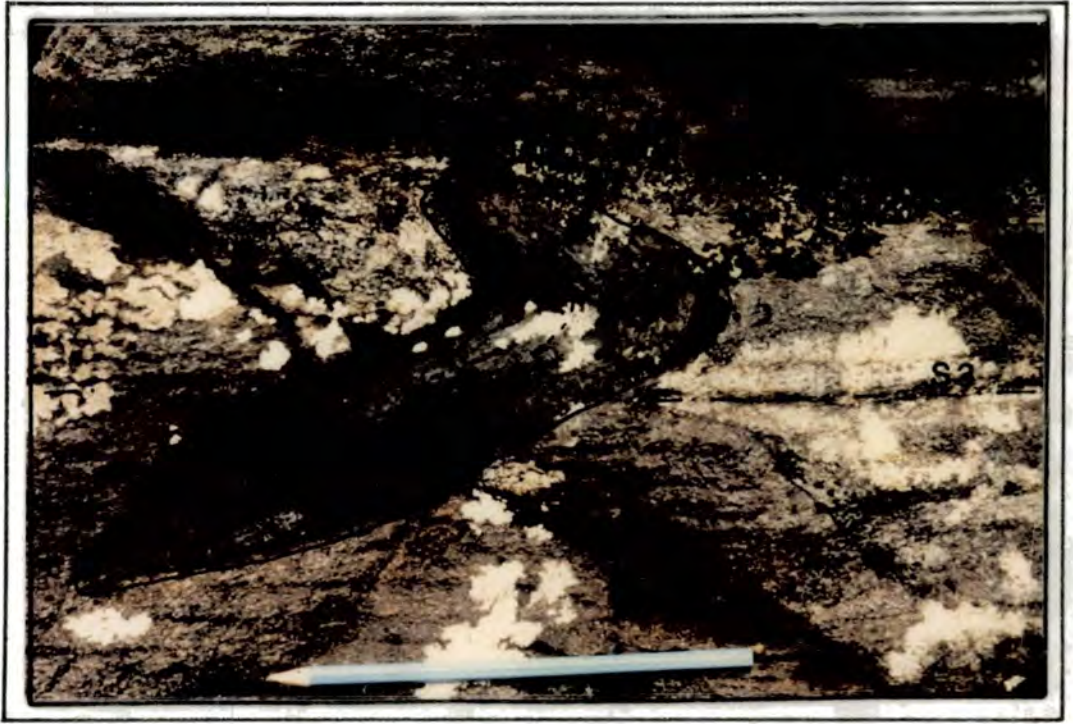
Close, slightly overturned F3 fold of bedding (S0) and the S1 - S2 fabric developed in Gaugin Quartzite on the upper normal limb of the D3 Ballybofey Antiform.



a.



b.



a.

### PLATE 26

**Locality** - Atlahan (C 025011)

This volcanogenic clast has been deposited within the Boulypatrick Grits. The clast has preserved within it the S2 fabric, which the long axis of the clast originally paralleled. Refolding by B3 crenulations is apparent, and outlined on the overlay.

**PLATE 27a.**

**Locality** - Garranbane Hill (H 062931)

Intense S3 crenulation cleavage of a spaced S2 fabric developed on the higher strained inverted lower limb of the D3 Ballybofey Antiform. The S3 cleavage has been later deformed by the S5 crenulation cleavage (outlined on the overlay).

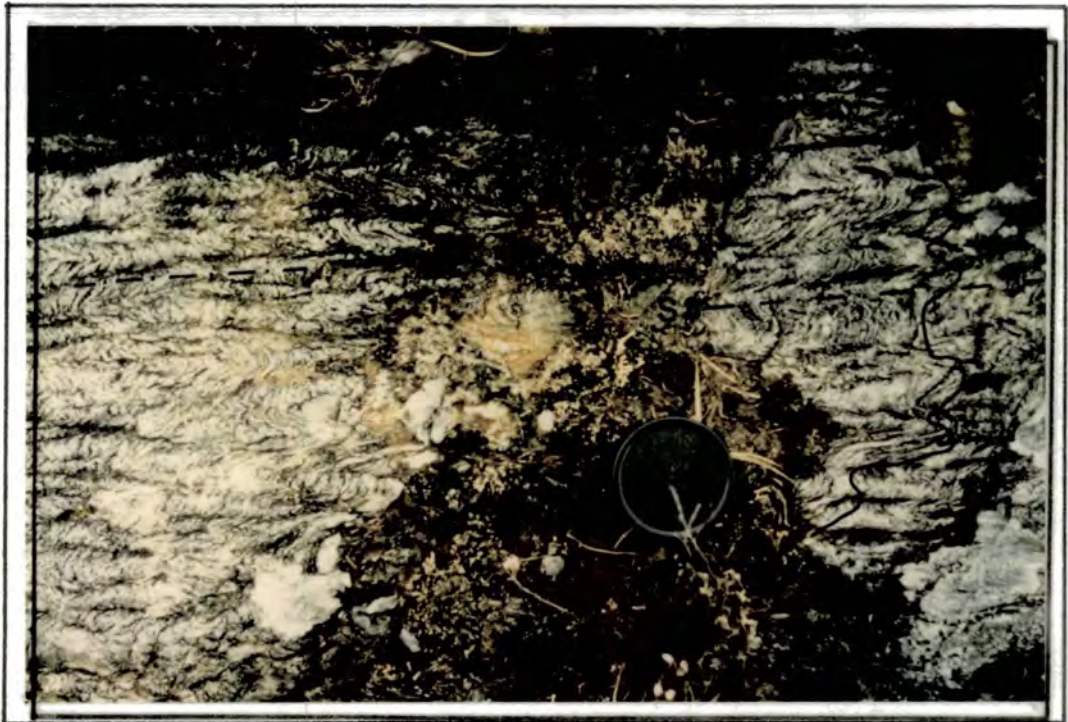
**PLATE 27b.**

**Locality** - Abermaddy (H 066995)

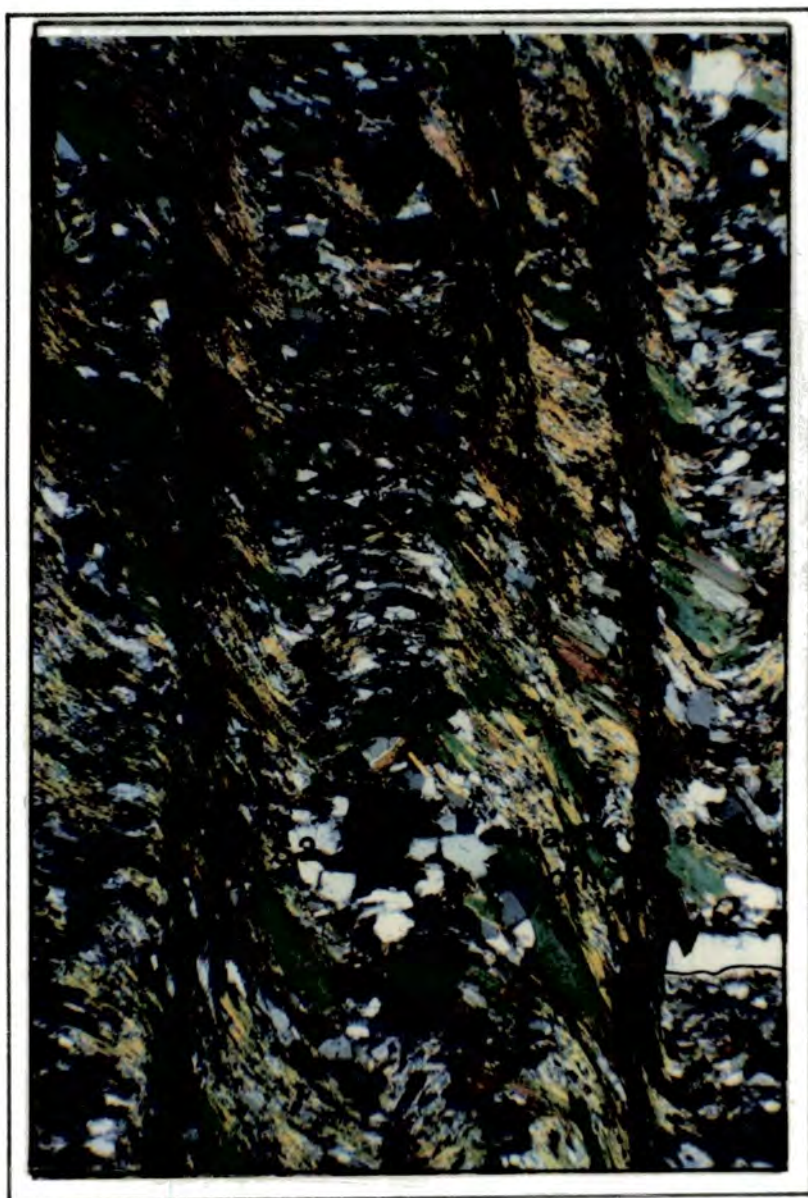
Open crenulations of a spaced S2 fabric developed on the lower strained upper normal limb of the D3 Ballybofey Antiform. The S3 crenulation cleavage is clearly contractional, the compressional folds of S2 being outlined on the overlay.



a.



b.



a .

## PLATE 28

**Locality** - Ballynatone (H 100965)

Photomicrograph taken under crossed polars. The length of field of view is 4 mm. An S3 crenulation of the S2 fabric (outlined on the overlay) is clearly developed within the Boultypatrick Grits, in the hinge zone of the D3 Ballybofey Antiform. Clasts of quartz and feldspar are contained within the grit.

**PLATE 29a.**

**Locality** - Altnapaste (H 043958)

Photograph of the hinge zone of a recumbent mesoscopic F3 fold developed in Gaugin Quartzite towards the hinge of the D3 Ballybofey Antiform. An intense axial planar S3 crenulation cleavage of a spaced S2 fabric is outlined on the overlay. Pencil in the mid - foreground for scale.

**PLATE 29b.**

**Locality** - Altnapaste (H 043958)

A photograph of a recumbent, mesoscopic F3 fold developed in Gaugin Quartzite in the hinge zone of the D3 Ballybofey Antiform. An intense axial planar S3 crenulation cleavage is outlined on the overlay.



a.



b.

KEY TO OPPOSING PAGE



BOULTYPATRICK GRITS



CROAGHUBBRID PELITES



CENTRAL DONEGAL SLIDE



REELAN FORMATION



GAUGIN QUARTZITE (WITH TILLITE AT BASE)



GROVEENANANTA FORMATION



DIRECTION OF YOUNGING



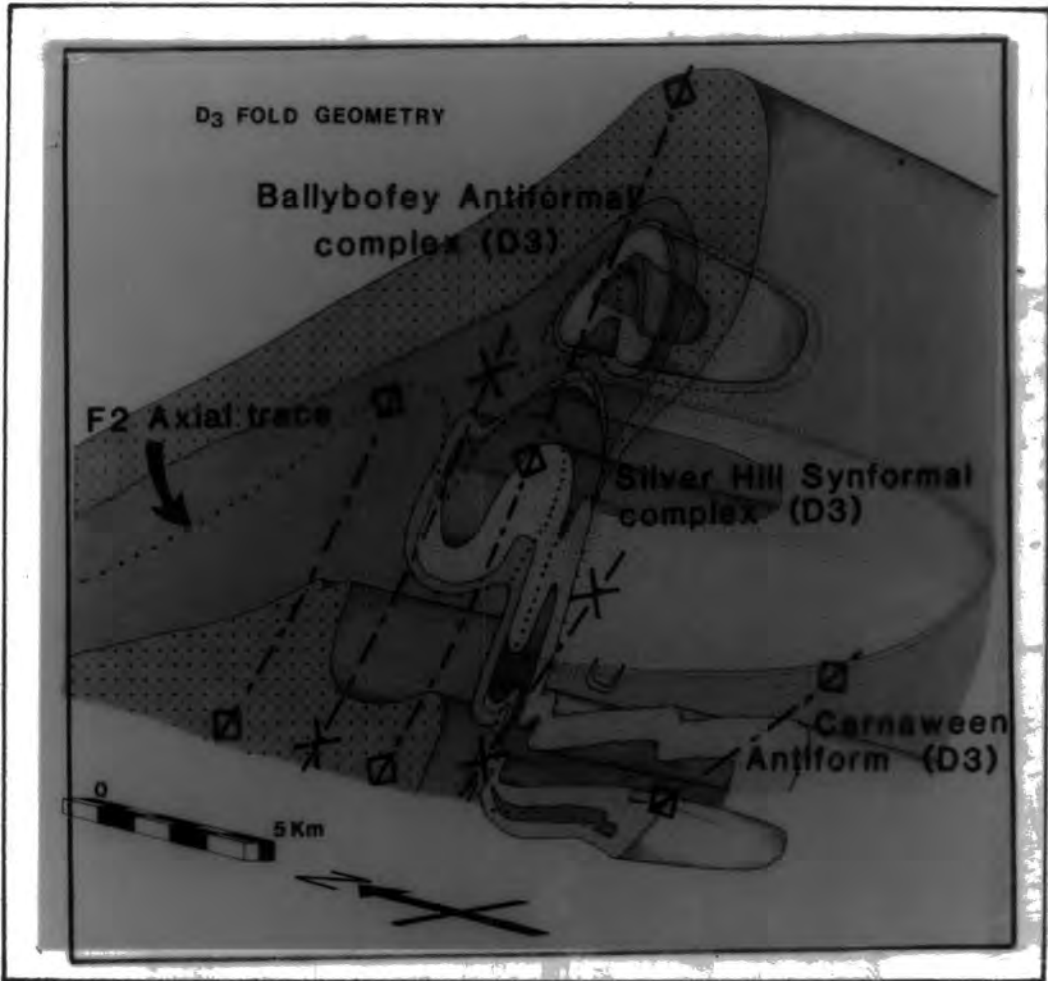
TECTONIC PACKAGE B



TECTONIC SCHIST



TECTONIC PACKAGE A



### PLATE 30

Schematic block diagram showing the gross D<sub>3</sub> fold geometry (re-oriented to the western limb of the D<sub>7</sub> Ballard Antiform).

This schematic diagram shows the refolding effects of the D<sub>3</sub> Ballybofey Antiformal complex, and the complementary Silver Hill Synformal complex on the D<sub>2</sub> Central Donegal sheath folds. Major fold axes are marked on the overlay, and a key to the stratigraphy is given on the opposing page.

**PLATE 31a.**

**Locality** - Croaghbrid (G 927937)

D3 mylonites developed along the Ballybofey slide, which juxtaposes Gaugin Quartzite and Lough Eske Psammities. Quartz veins have been sheared (foreground) parallel<sup>to</sup> the extremely planar fabric.

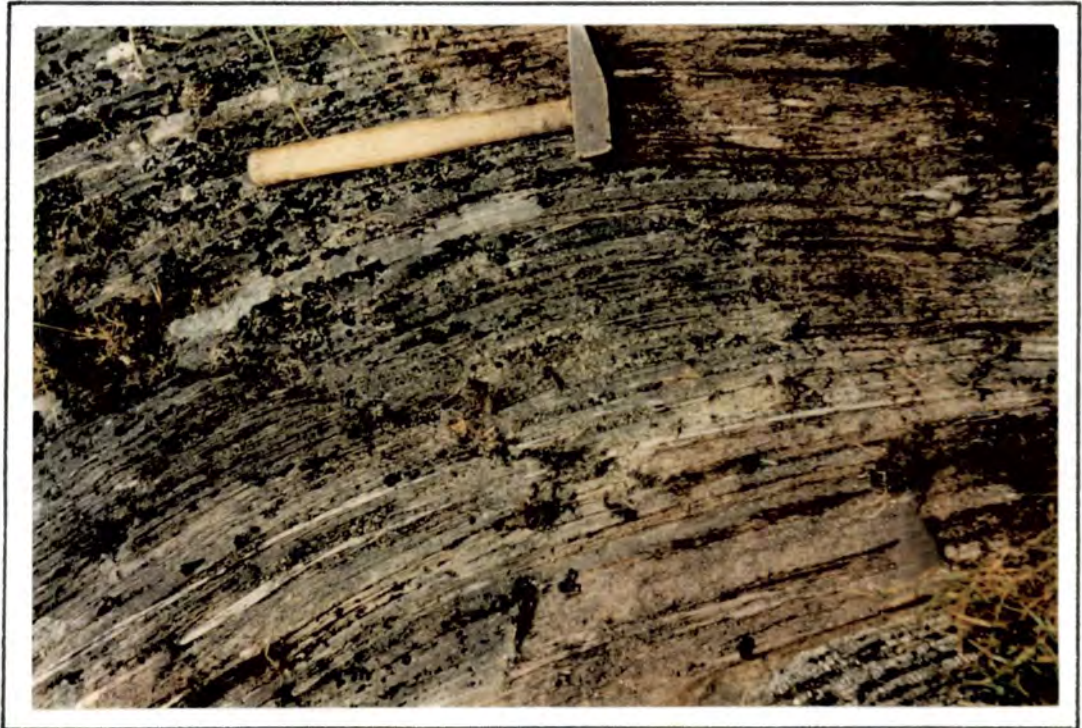
**PLATE 31b.**

**Locality** - Clogher South (G 963947)

Composite D2 - D3 mylonites developed along the Central Donegal slide (within the tectonic schist zone), between Croaghbrid Pelites (graphitic) and Gaugin Quartzite. Quartz veins have been sheared into parallelism with the planar fabric.



a.



b.

**PLATE 32a.**

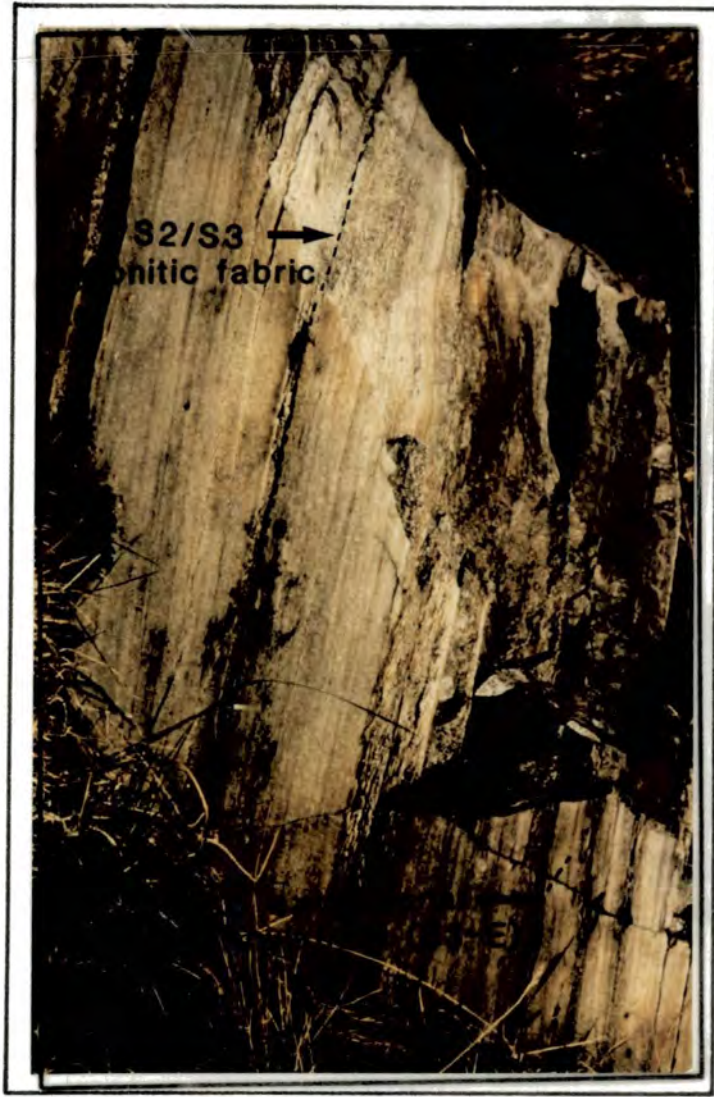
**Locality** - Croaghbrid (G 912932)

D2 - D3 mylonites developed within the Gaugin Quartzite adjacent to the Central Donegal slide. Extensional crenulations related to the third deformation suggest oblique dextral overshear towards the south and are associated with the D3 Ballybofey Antiform (outlined on overlay).

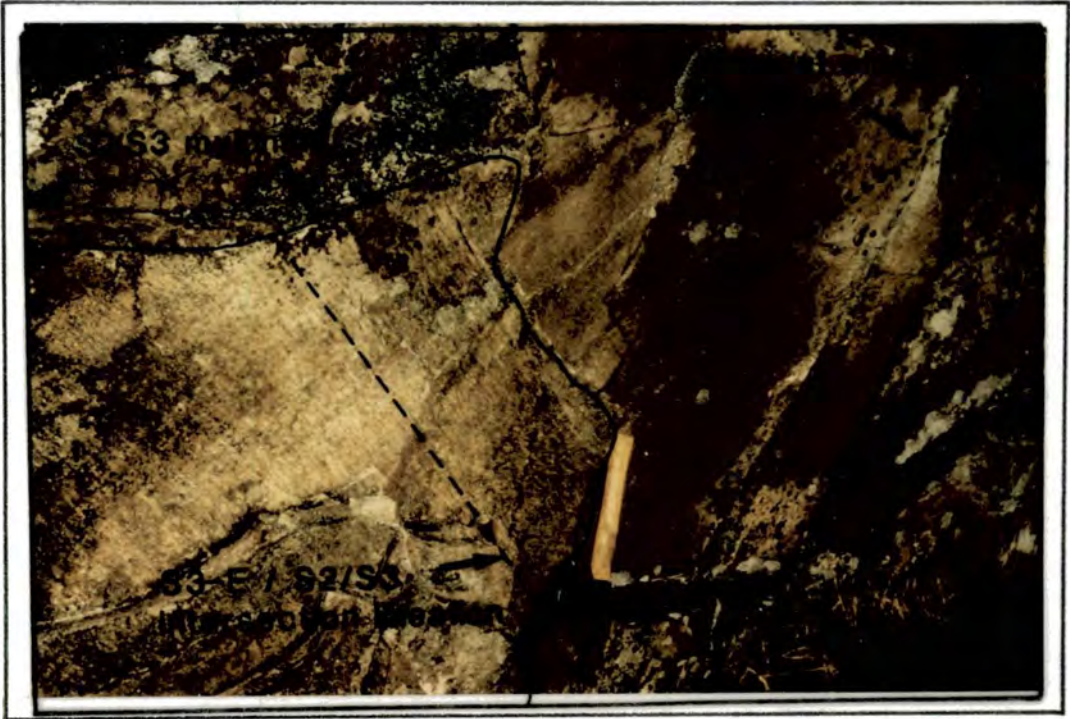
**PLATE 32b.**

**Locality** - Croaghbrid (G 908934)

D2 - D3 mylonitic surface with an intense mineral elongation lineation plunging towards the bottom left of the photograph (towards the west) and outlined on the overlay. The intersection of the extensional crenulation cleavage related to the third deformation (S3 - E) with the S2 - S3 mylonitic fabric produces an intersection lineation at right angles to the stretching direction (outlined on the overlay).



a.



b.

**PLATE 33a.**

**Locality** - Croaghubbrid (G 904935)

Asymptotic extensional crenulations developed within the Gaugin Quartzite adjacent to the Central Donegal slide. These structures are representative of the third deformation and suggest dextral oblique overshear towards the south.

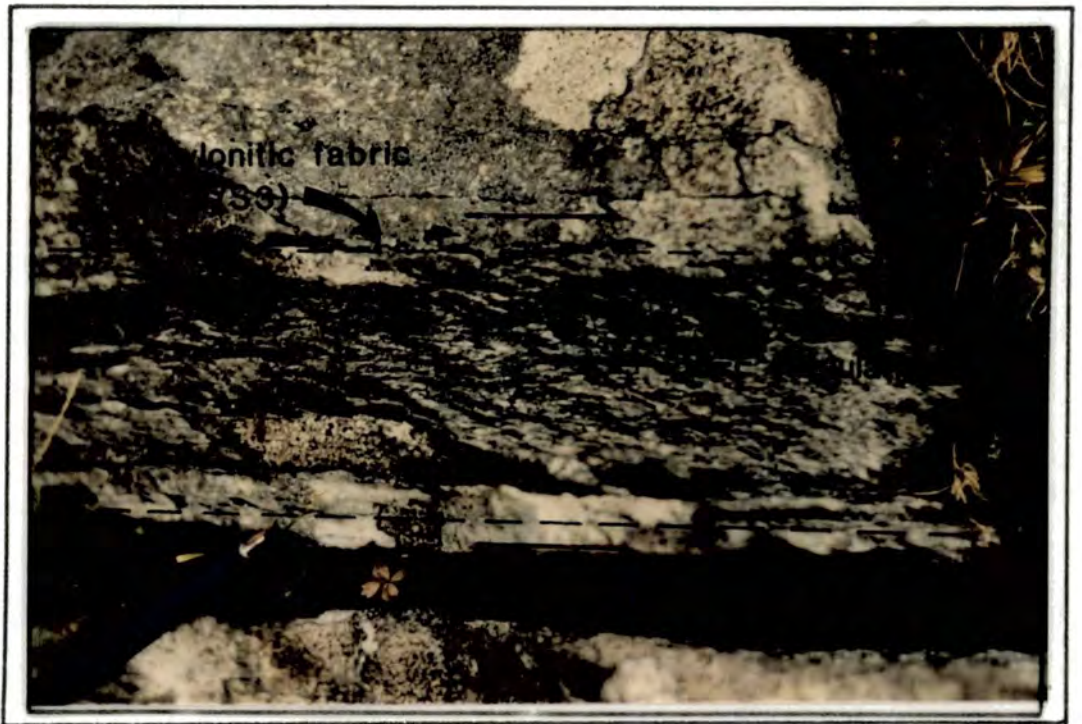
**PLATE 33b.**

**Locality** - Croaghubbrid (G 906934)

Planar extensional crenulation cleavage developed in the Gaugin Quartzite adjacent to the Central Donegal slide. Such structures appear to be concentrated in the slightly more schistose horizons within the massive quartzite, and give consistent shear sense for the third deformation as noted above (Plate 33a.).



a.



b.

**PLATE 34a.**

**Locality** - Croaghubbrid (G 914933)

Hand specimen of Gaugin Quartzite displaying planar extensional crenulation cleavages related to the third deformation (S3 - E). These structures are preserved at approximately 45° to the mylonitic S2 - S3 fabric, which they clearly deform. Shear sense related to the extensional crenulations is displayed on the overlay,

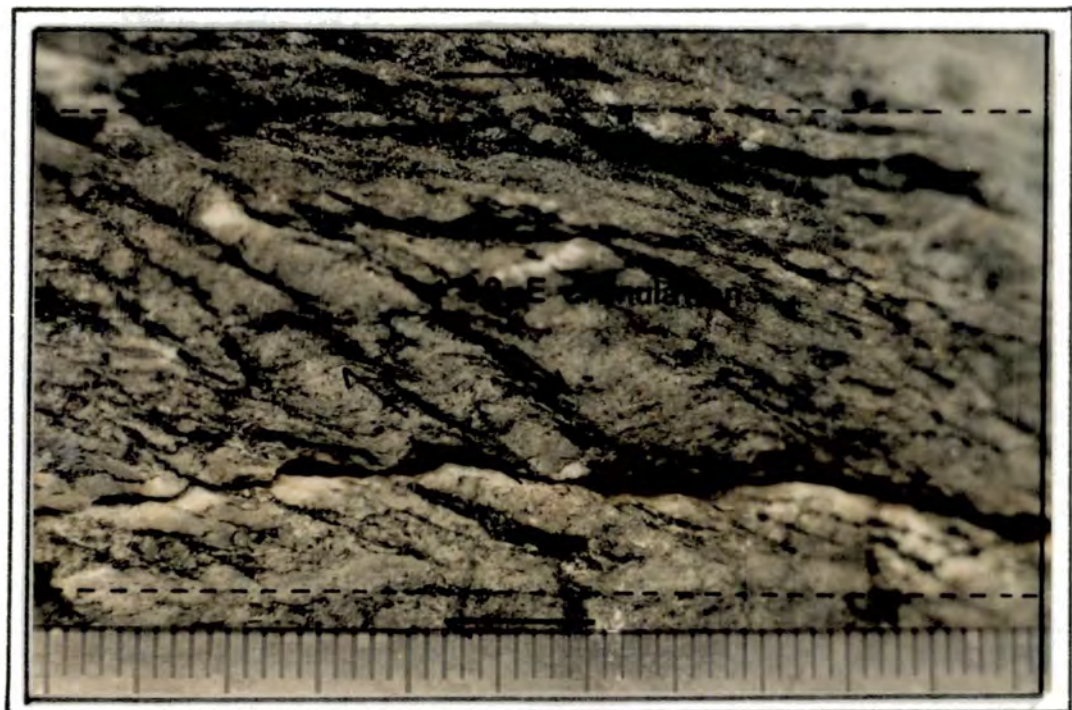
**PLATE 34b.**

**Locality** - Croaghubbrid (G 914933)

Close up photograph of the hand specimen described above (Plate 34a.). The S3 - E extensional crenulations are clearly deforming the S2 - S3 mylonitic fabric, and are most obviously developed in the more schistose horizon of the specimen. Gradations on the scale are at 1mm intervals. •



a.



b.

**PLATE 35a.**

**Locality** - Croaghubbrid (G 914933)

Extensional crenulations related to the third deformation (S3 - E) clearly deform the S2 - S3 mylonitic surface, producing an intersection lineation at right angles to the mineral elongation lineation.

**PLATE 35b.**

**Locality** - Altnapaste (H 041958)

Hand specimen of Port Askaig Tillite Formation psammite with small (less than 3 cm) clasts of leucogranite. Biotite, quartz and feldspar are apparent within the clasts which have been deformed during shearing along the adjacent Central Donegal slide.



a.



b.

**CHAPTER 5**  
**THE LATER DEFORMATIONS.**

CHAPTER 5  
THE LATER DEFORMATIONS.

5.1) The fourth deformation (D4). (Map 4, map box)

No major folds relating to the fourth deformation have been observed in the mapped area. Typically, S4 is a cross cutting contractional crenulation cleavage which dips gently / moderately towards the south depending on its position relative to the D7 Ballard Antiform. It is associated with an approximate East - West sub-horizontal B4 lineation, the orientation of which is also controlled by D7 folding.

5.1a) D4 - Area 1

On the gross scale, D4 structures clearly overprint, and therefore post-date, the D3 Gaugin Synform and Ballybofey Antiform shown on Map 4 (map box). S4 is one of the most obvious 'late' contractional crenulations observed within this area, typically trending North East - South West and dipping gently towards the south (Figure 5.1a.) (Map 4 map box). B4 crenulation axes plunge gently towards the south west, whilst larger F4 folds with middle limbs upto 0.5 m long generally plunge gently to the east (Figure 5.1b.). This variation in plunge direction is related to the orientation and scale of the deformed surfaces which define B4 crenulation axes and F4 fold axes. B4 crenulation axes have usually been measured deforming S2 and S3 fabrics, whilst the F4 folds are defined by, and therefore measured in relation to bedding (S0). Slight obliquity between S0 and S2 or S3 fabrics will result in the observed variation in plunge direction. S4 is axial planar to the tight, recumbent F4 folds of S1-S2 and S3, and is also seen to overprint F3 folds (Croveenananta (G 940942)).

To the south east of Slievemullagh (G 005946), D4 structures are rotated to a North East - South West trend by large scale folding relating to the D7 Ballard Antiform (Map 4 map box). This refolding is clearly portrayed in Figure 5.1b., where B4 lineations are seen to form a slight girdle. Throughout area 1, D4

**Figure 5.1a.**

**S4 - Area 1.**  $n = 496$ , maximum concentration of data points = 058/36SE, mean = 062/33SE.

**Figure 5.1b.**

**B4 Lineations - Area 1.**  $n = 345$ , maximum concentration of data points = 23/081, mean = 4/080. Bimodal distribution of data points corresponds to refolding by F7 and F9 folds, together with minor B4 crenulation axes being measured folding earlier cleavage surfaces, whilst larger F4 fold axes have been measured folding S0. Slight obliquity between bedding and the main cleavage results in a bimodal distribution.

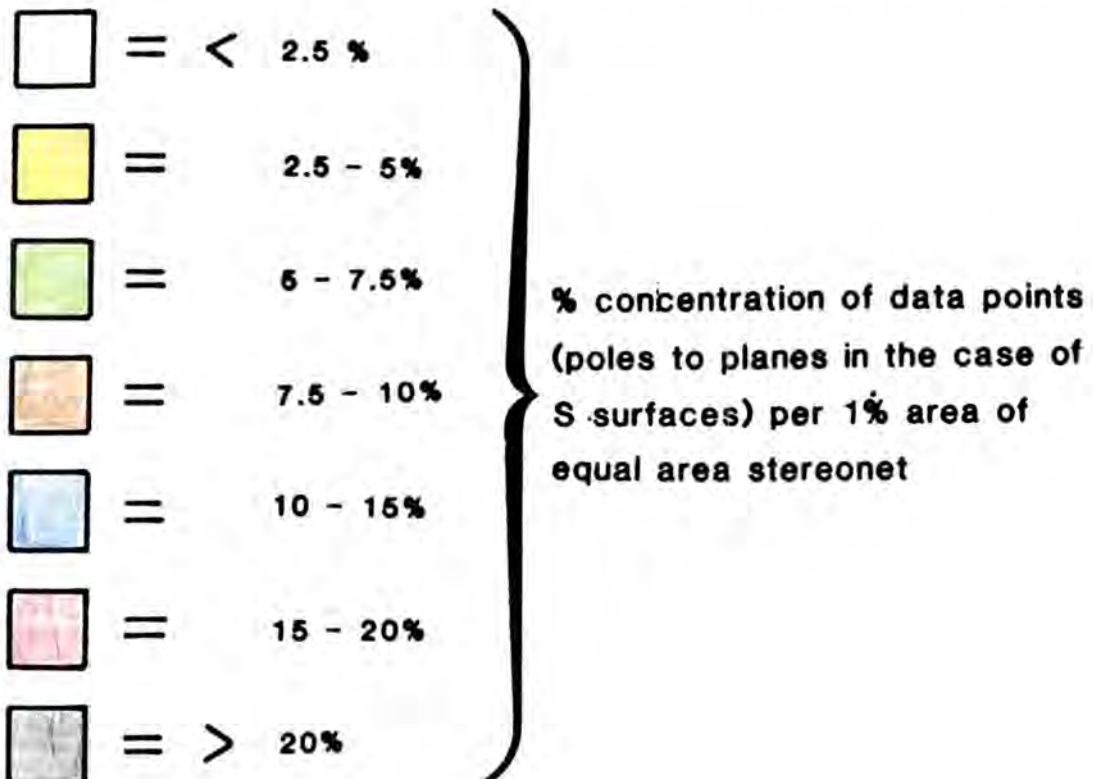
**Figure 5.1c.**

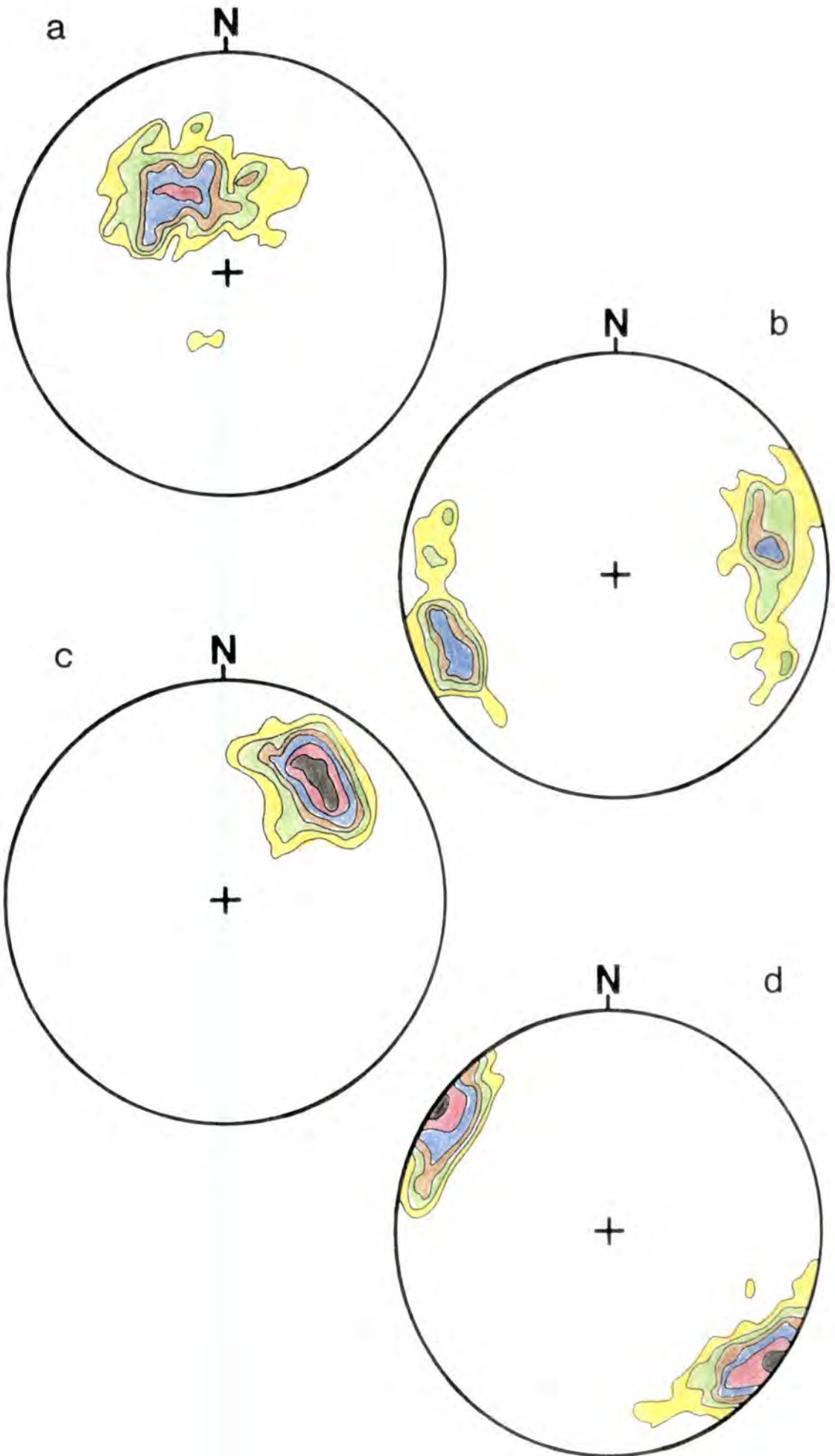
**S4 - Area 2.**  $n = 120$ , maximum concentration of data points = 130/60S, mean = 129/62S.

**Figure 5.1d.**

**B4 Lineations - Area 2.**  $n = 141$ , maximum concentration of data points = 1/126, mean = 2/129.

**Contour intervals on equal area stereograms shown on facing page**





structures cross cut major D2 and D3 folds at high angles, and have a consistent southerly vergence in relation to bedding (S0) and the main fabric (S2 or S2-S3).

#### 5.1b) D4 - Area 2

As noted in 4.3), area 2 appears to be largely unaffected by the D7 Ballard Antiform (see Map 10 map box). The orientation of D4 structures should therefore differ in relation to those of area 1, which are developed on the down-bent western limb of this D7 fold. Throughout area 2, S4 trends North West - South East and dips moderately towards the south west (Figure 5.1c.) (Map 4 map box). The strike of the S4 contractional crenulation is sub-parallel to the strike of bedding (S0) and 2, S2, as is the case in area 1. B4 lineations are sub-horizontal and trend North West - South East (Figure 5.1d.) (Map 4 map box). Thus, there is a definite reorientation of D4 structures in area 2 in relation to those observed in area 1. This reorientation is related to the approximate North - South steeply plunging D7 Ballard Antiform (see 5.4). Throughout area 2, S4 is a consistently well developed crenulation cleavage clearly overprinting D3 crenulations of S2 at Cullagh (C 030069). Few F4 folds have been observed in area 2, the vast majority of the B4 lineation measurements relating to small (less than 1 cm) crenulations of S2. Larger F4 folds are close / tight structures with middle limbs less than 0.5 m long. Structures relating to the fourth deformation verge consistently towards the south west in area 2.

#### 5.1c) D4 - Area 3

Area 3 is positioned entirely to the east of the axial trace of the Ballard Antiform, and as such is relatively unaffected by this structure. The orientation of D4 structures developed within this area should therefore broadly correspond to those developed in area 2 (see 5.1b). S4 within area 3 generally trends North West - South East and dips at moderate angles towards the south west (Figure 5.2a.) (Map 4 map box). As in area 2, the strike of S4 on the upper normal limb of the D3 Ballybofey Antiform approximately parallels the strike of bedding (S0)

**Figure 5.2a.**

**S4 - Area 3.**  $n = 67$ , maximum concentration of data points = 122/59S, mean = 123/60S.

**Figure 5.2b.**

**B4 Lineations - Area 3.**  $n = 62$ , maximum concentration of data points = 13/129, mean = 15/129.

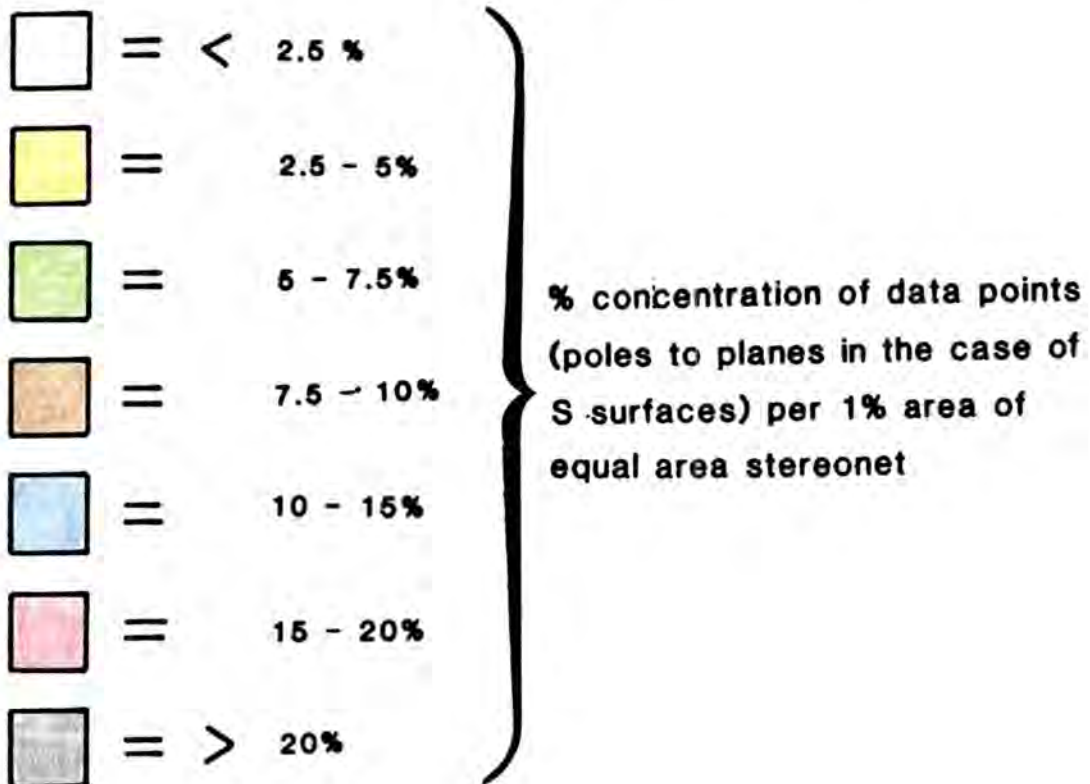
**Figure 5.2c.**

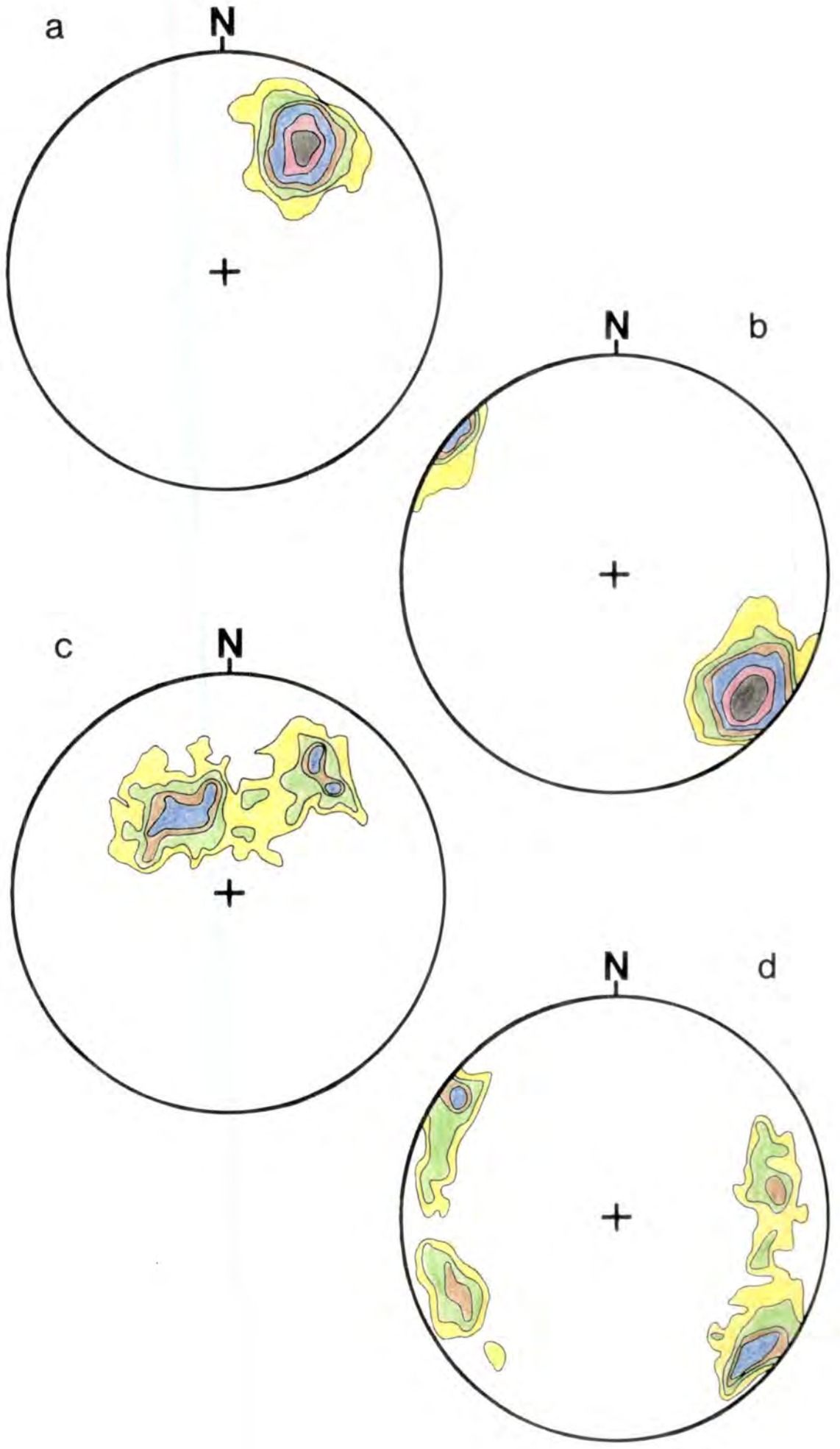
**S4 - whole of map area.**  $n = 683$ , maximum concentration of data points = 122/67S, mean = 085/35S. The bimodal distribution of data points corresponds to regional refolding by the D7 Ballard Antiform.

**Figure 5.2d.**

**B4 Lineations - whole of map area.**  $n = 548$ , maximum concentration of data points = 9/130, mean = 6/099. The distribution of data points corresponds to regional refolding by the D7 Ballard Antiform, together with the scale of B4 Lineations measured (as noted in Figure 5.1b.).

**Contour intervals on equal area stereograms shown on facing page**





and S2. However on the inverted limb of this D3 structure, S4 and B4 lineations are consistently developed in a anticlockwise sense to the strike of S0 and S2 eg. Garranbane Hill (H 055 930). Once again, this accentuates the cross-cutting nature of D4 on both D2 and D3 folds. On an outcrop scale, S4 crenulations clearly overprint a shallow easterly dipping S3 crenulation cleavage of S2 at Creggan (H 123977). B4 lineations plunge gently towards the south east (Figure 5.2b.), and are shown on Map 4 (map box). F4 folds are once again rare, with middle limbs less than 0.5 m long. Comparison of Figures 5.1c. and 5.1d. with 5.2a. and 5.2b. together with inspection of Map 4 (map box), demonstrates the similarity in orientation of D4 structures in areas 2 and 3. Throughout area 3, D4 structures verge consistently towards the south on bedding (S0) and S2, across the axial trace of the D3 Ballybofey Antiform.

#### 5.1d) D4 synopsis

From the foregoing account, it is apparent that D4 crosscuts the major D2 and D3 folds, and is itself refolded by the D7 Ballard Antiform. Stereograms portraying S4 and B4 lineations throughout the mapped area clearly show the refolding effect of this D7 fold (Figures 5.2c., 5.2d.). Map 4 (map box) shows the gradual rotation of D4 structures around the hinge of this later fold (Ballard (H 030955)), and also their reorientation south of Crocknahamid (G 990980), towards the western limb of the Ballard Fold. Throughout the mapped area, D4 is represented by obvious cross cutting contractional structures which verge consistently south, and which cannot directly be related to any major folds.

#### 5.2) The fifth deformation (D5) (Map 5 - map box)

The only significant D5 folds within the mapped area are developed south east of Croveenananta (G 940935). These folds deform and therefore post-date the D1-D2-D3 Central Donegal slide and the D3 Ballybofey slide (see 4.b) (Maps 5 and 13 map box).

**Figure 5.3a.**

**S5 - Area 1.**  $n = 748$ , maximum concentration of data points = 113/72N, mean = 105/82N. Pole to great circle = 40/095 and corresponds to the fanning of S5 surfaces about the Gaugin Quartzite in the hinge of the D3 Gaugin Synform, as well as refolding by F7 and F9 folds.

**Figure 5.3b.**

**B5 Lineations - Area 1.**  $n = 307$ , maximum concentration of data points = 41/093, mean = 15/099. Bimodal distribution of data points corresponds to refolding about the North - South trending F7 and F9 folds.

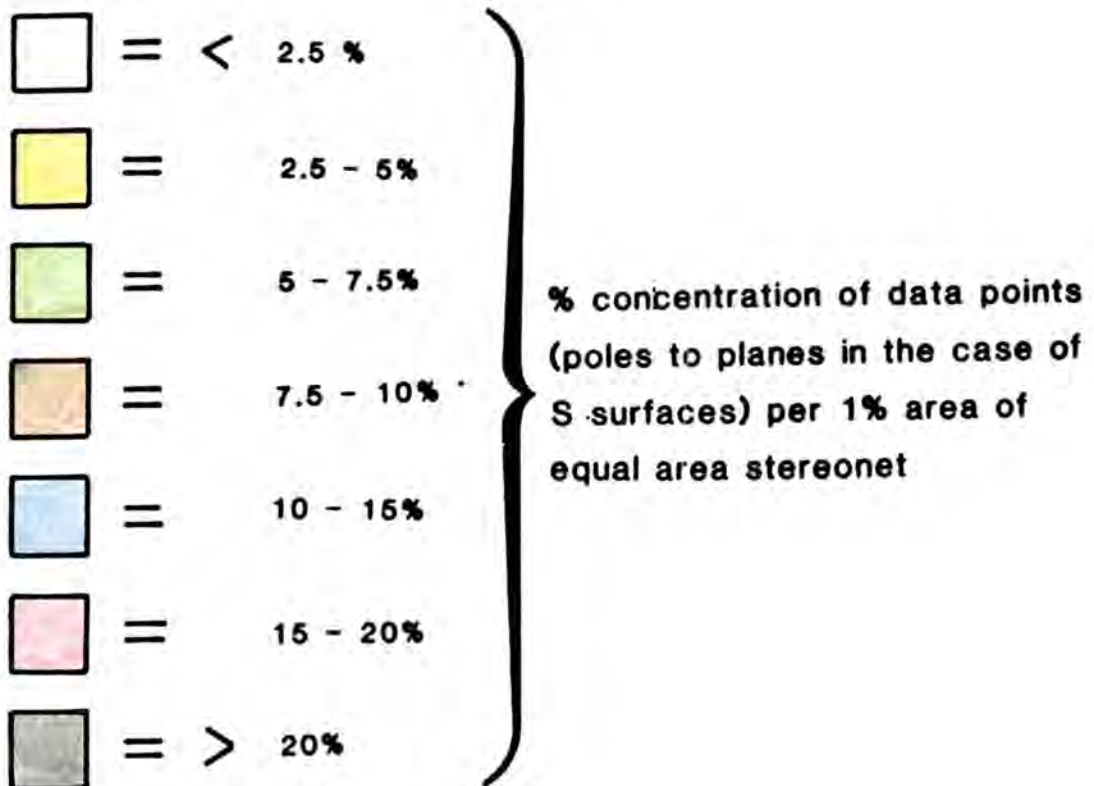
**Figure 5.3c.**

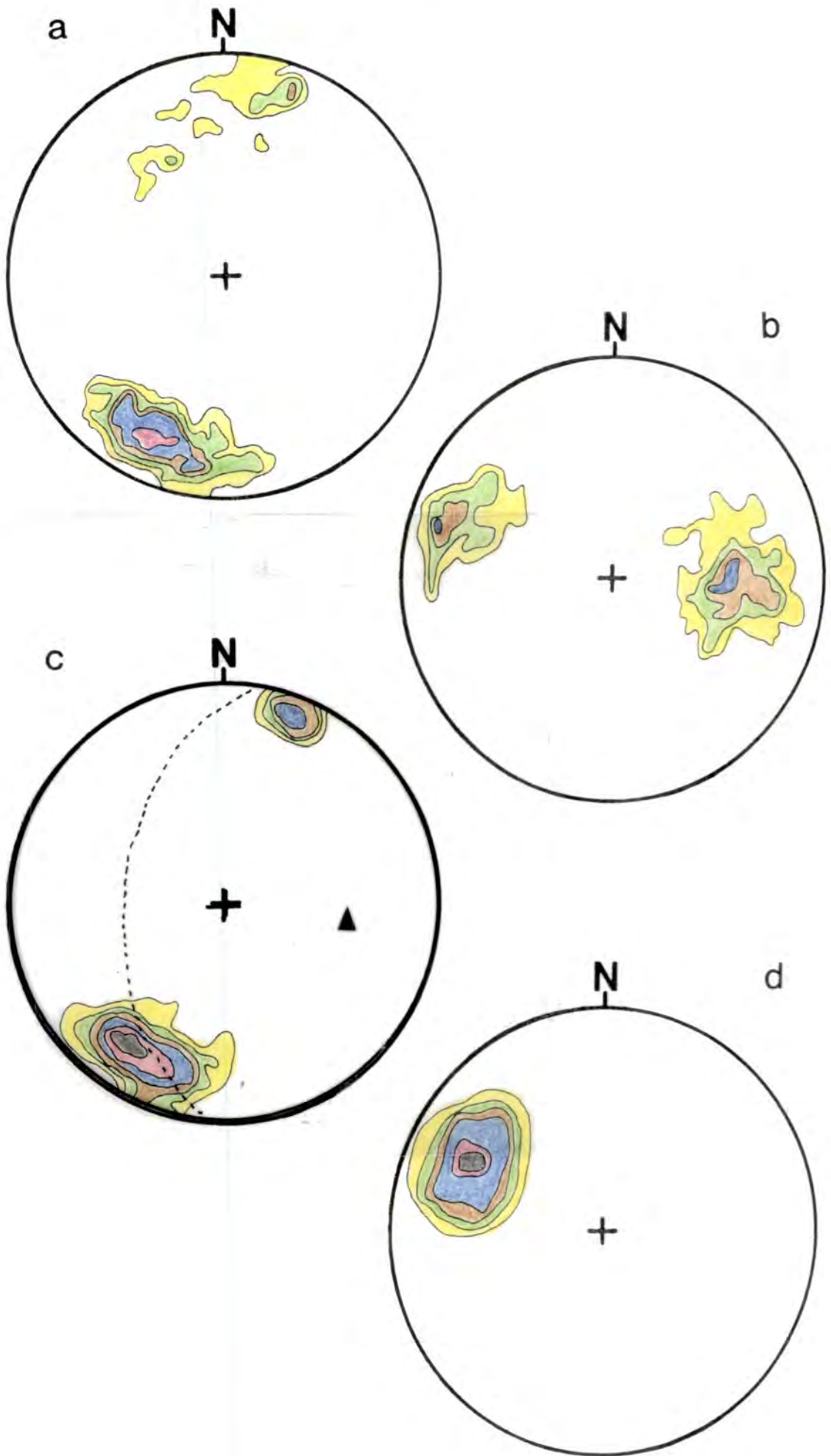
**S5 - Area 1b.**  $n = 103$ , maximum concentration of data points = 125/71N, mean = 116/74N.

**Figure 5.3d.**

**B5 Lineations - Area 1b.**  $n = 30$ , maximum concentration of data points = 30/297, mean = 27/294.

**Contour intervals on equal area stereograms shown on facing page**





## 5.2a) D5 - Area 1

S5 is an obvious and often intense crenulation developed preferentially within and adjacent to, the hangingwall of the D3 Ballybofey slide (see 4.6) (Maps 5 and 13 map box). It typically trends West North West - East South East and dips steeply towards the north, occasionally passing through the vertical and dipping south (Figure 5.3a.) (Map 5 map box). Excluding the area to the south of the Central Donegal slide at Croveenananta (G 940935) (sub-area 1b, see below), F5 folds are commonly close, angular structures with short limbs upto 0.5 m long, and axes plunging moderately towards the east. B5 crenulation axes parallel the F5 fold axes, the B5 lineation orientation for the whole of area 1 being shown on Figure 5.3b. S5 is axial planar to F5 folds, and clearly overprints S4 crenulations at Gaugin Mountain (G 978956). S5 post-dates small F3 hinges to the south of Slievemullagh at Stroangibbagh (G 008943), (Plate 36a.). On the gross scale, D5 structures obviously overprint D2 and D3 folds (Map 5 map box), and are themselves clearly reoriented in the hinge zone of the D7 Ballard Antiform.

As previously mentioned, the nature of the D5 structures in the vicinity of the Central Donegal slide and the D3 Ballybofey slide undergoes modification. In the zone of rocks which are bounded to the north by the Central Donegal slide and in the south by the Ballybofey slide, D5 structures become increasingly asymmetric and representative of shearing. Within this area, S5 is consistently developed in a clockwise strike direction, and dips steeper towards the north than the S2-S3 fabric (Figure 5.3c.). Only in one instance was a conjugate cleavage developed in S5 (Plate 36b.) (see below). F5 folds clearly deform the S2-S3 fabric and consistently plunge at shallow angles towards the north west (Figure 5.3d.). F5 folds are close, have short limbs upto 1 m long, and sheared long limbs which suggest top to the north shear, and in an oblique dextral sense (on the northward dipping S5) ie. opposing shear senses to D3 (Plates 37a., 37b.). The S5 cleavage, although clearly not extensional due to it being developed at angles greater than

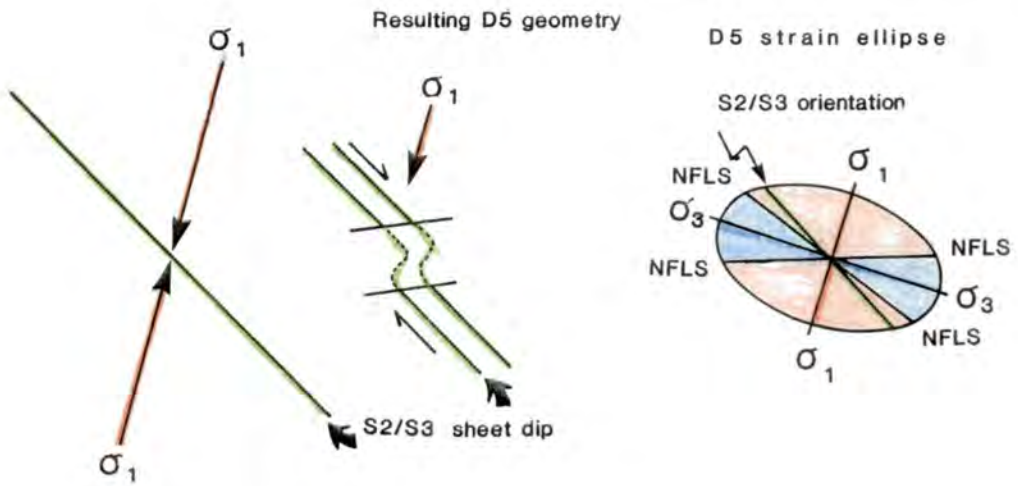
45° to S2-S3, and on occasion containing contractional geometries, also has a strong sense of shear (Figure 5.4b.). As noted earlier, D5 structures obviously deform the D3 Ballybofey slide south of Croveenananta at (G 955935), and also overprint D3 extensional crenulations (S3-E) at Croaghubbrid (G 907934). These cross cutting relationships clearly indicate that D5 entirely post-dated the D3 deformation on the inverted limb of the Ballybofey Antiform.

Thus, the lithologies immediately adjacent to the Central Donegal slide and the Ballybofey slide contain D5 structures which entirely post-date movement on these slides, and whose asymmetry suggests top to the north shear on the northward dipping S5 crenulation cleavage. To both the north and south of this zone of D5 shear, compressional structures verging towards the south are representative of the fifth deformation. Throughout the mapped area, late biotite porphyroblasts (Mp5) commonly lie parallel to the S5 crenulations (occasionally cutting B5 crenulation axes), thus aiding in their definition and correlation.

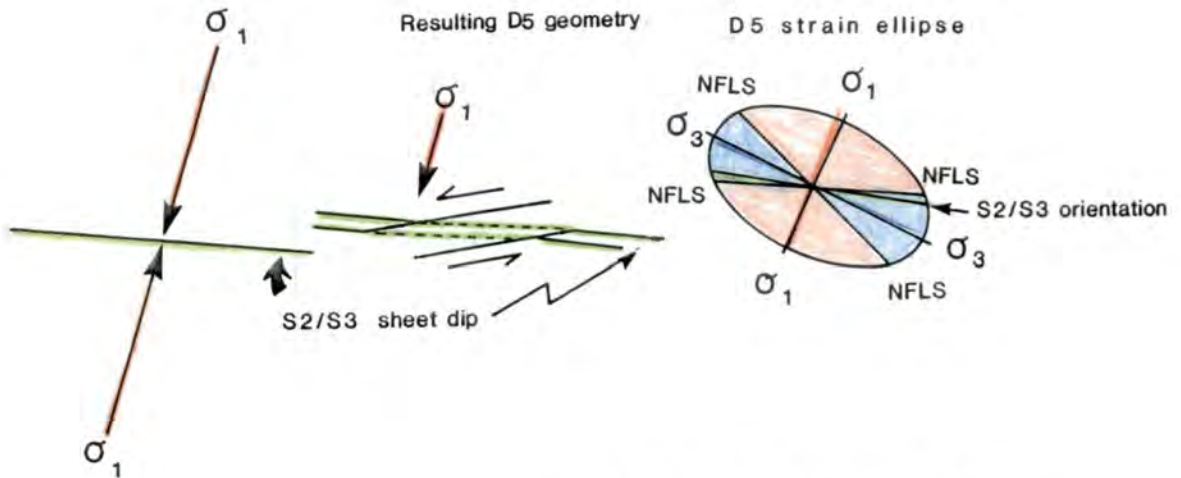
There are a number of models which may explain the extensional D5 zone being bounded by compressional D5 geometries. Varying amounts of synchronous D3 shear on the Ballybofey and Central Donegal slides may have led to the development of a shear couple. A greater amount of displacement on the Ballybofey slide would produce structures of similar geometry to those labelled D5. However, D5 structures clearly post date D3 movement and also cross cut both slide zones, rendering this model inadequate. The timing relationships noted above also discredit a 'domino collapse' mechanism of producing the observed reversal in shear sense. (ie. as 'blocks' rotate towards the simple shear plane, an apparent counter sense of shear is initiated between adjacent blocks). A simple model relates to differences in the orientation of the S2-S3 composite fabric within the area. The D1-D2-D3 Central Donegal slide and the D3 Ballybofey slide are closely spaced dislocations (less than 1 km) in the zone of asymmetric D5 structures. As such, it is expected that the S2-S3 fabric with intensification

D5 Geometry (D3 Ballybofey slide rotated to horizontal)

a. North of Ballybofey slide



b. Ballybofey slide zone



c. South of Ballybofey slide

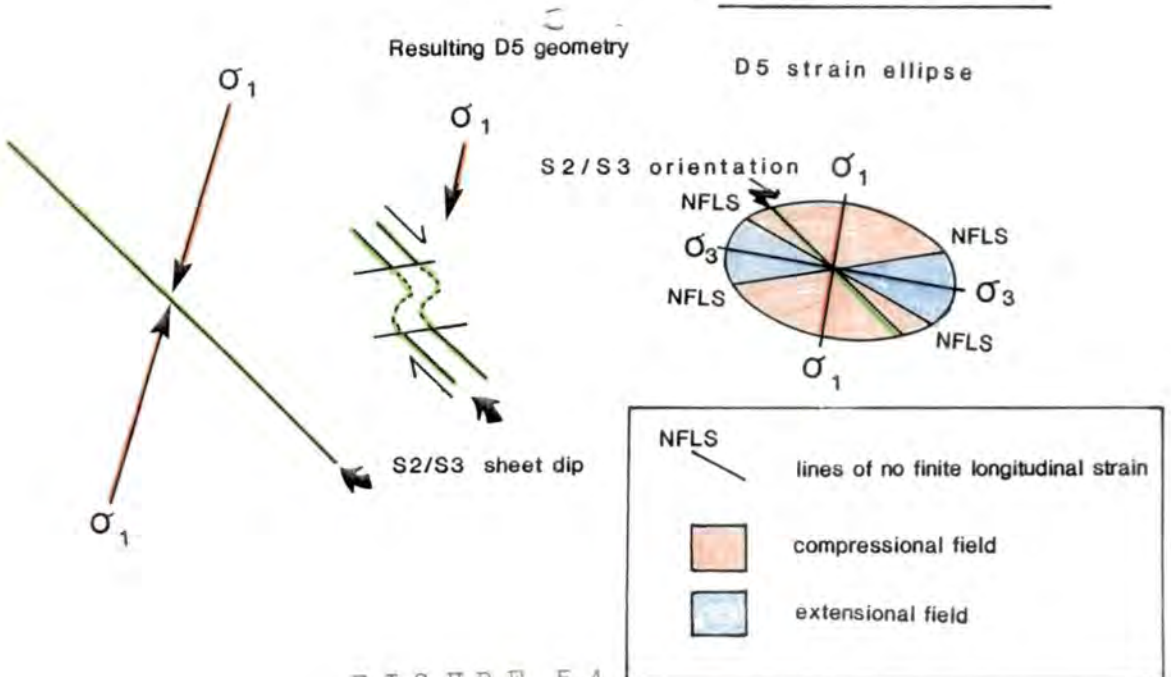


FIGURE 5.4

of D3 strain would become parallel to the slides, and at greater distances from the zone of intense D3 shear, the obliquity of the fabric to the slides would increase. Thus, the present D5 geometries appear to reflect the original variations in the state of D3 strain. The reorientation of S2-S3 fabrics will affect the way in which the D5 stress system may deform these surfaces. Compressional D5 folds of the S2-S3 surfaces indicate that they were oriented within the compressional field of the D5 strain ellipsoid (Figure 5.4 a and c), whilst S2-S3 fabrics in the zone of asymmetric extensional D5 shear were oriented in the extensional field of this ellipsoid (Figure 5.4b.). Map 13 (map box) shows the strike swing in the S2-S3 fabric of the Lough Eske Psammities towards the D3 Ballybofey slide. This reorientation of the S2-S3 surfaces is the dominant factor controlling the nature of D5 structures in the proposed model. Also implicit within the model is the requirement of a pure shear (irrotational) strain component within the area. The highly deformed and mobile rocks contained in the zone of extensional D5 shear may have been more susceptible to pure shear, as witnessed by the conjugate S5 crenulations at Croveenananta (G 947 936). The presence of a pure shear component does not exclude a simple shear component also occurring.

Thus, area 1 contains two varieties of D5 structures, which in the proposed model are inherently related to the pre-D5 orientation and nature of the second and third deformations which preceded them. This model is simple, and one of a number which conform to the observed structures.

#### 5.2b) D5 - Area 2

The fifth deformation produces obvious 'late' structures which are common throughout area 2, especially so in its southern portion. As noted previously, area 2 appears to be largely unaffected by the D7 Ballard Antiform. The orientation of D5 structures should therefore differ in relation to those of area 1, which are developed on the western limb of this D7 fold. Throughout area 2, S5 trends North West - South East and dips steeply towards the north east (Fig-

**Figure 5.5a.**

**S5 - Area 2.**  $n = 60$ , maximum concentration of data points = 107/74N,  
mean = 107/70N.

**Figure 5.5b.**

**B5 Lineations - Area 2.**  $n = 41$ , maximum concentration of data points  
= 12/115, mean = 5/112.

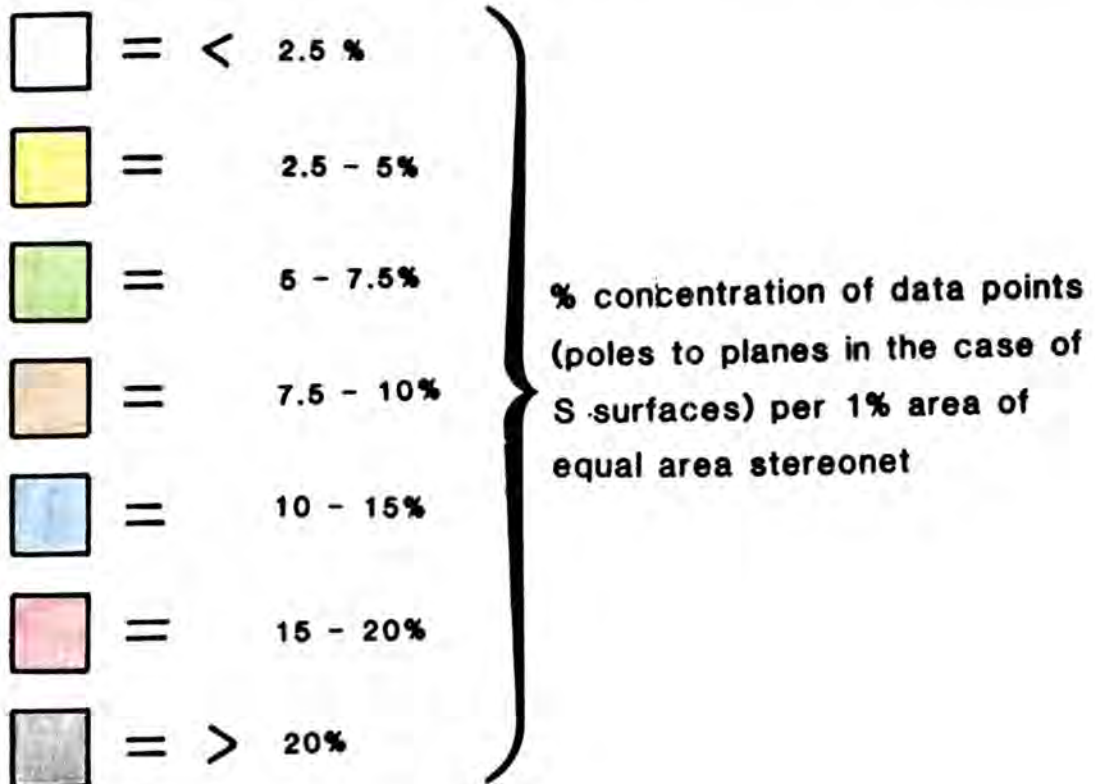
**Figure 5.5c.**

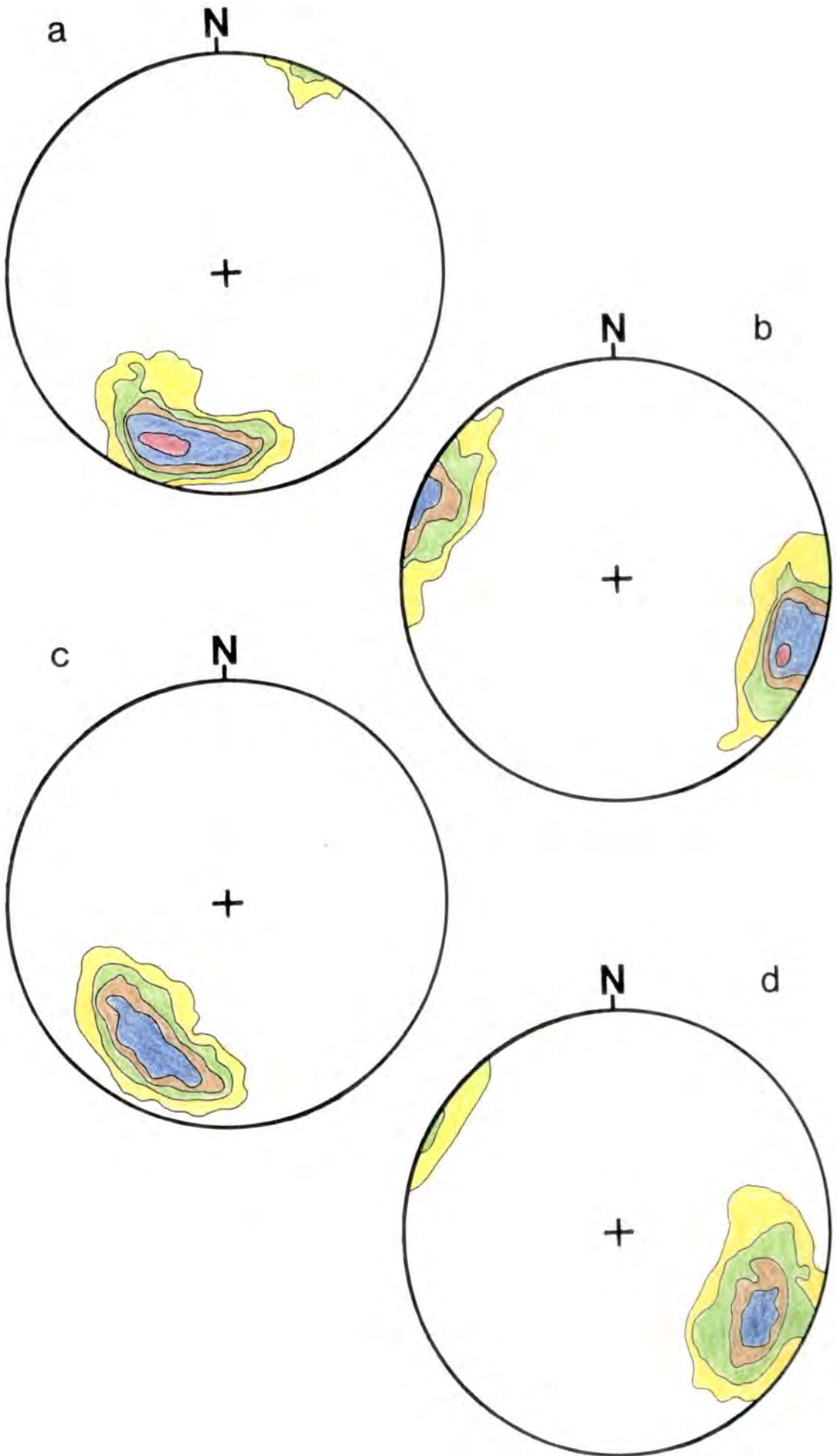
**S5 - Area 3.**  $n = 46$ , maximum concentration of data points = 131/62NE,  
mean = 117/64NE.

**Figure 5.5d.**

**B5 Lineations - Area 3.**  $n = 15$ , maximum concentration of data points  
= 24/117, mean = 21/117.

**Contour intervals on equal area stereograms shown on facing page**





ure 5.5a.), (Map 5 map box). B5 lineations (B5 crenulation axes and F5 fold axes) are sub-horizontal, plunging gently towards the south east (Figure 5.5b.) (Map 5 map box). Thus, a reorientation of D5 structures in relation to those of area 1 obviously exists. Compared to area 1, S5 in area 2 has a slightly more North West - South East strike and dips at shallow angles towards the north east, whilst B5 lineations in area 2 also have a more obvious North West - South East trend. These effects, although not as pronounced as the reorientation of D4 structures may be attributed to refolding by the Ballard Antiform.

Within area 2, S5 is a consistently well developed crenulation, clearly overprinting S4 fabrics at Letterbrick (C 017018). F5 folds are close compressional structures with short limbs upto 0.5 m long which generally suggest vergence towards the south. B5 crenulation axes deform the S2 fabric and have short limbs upto 1 cm across. They parallel the larger F5 fold axes and represent the majority of B5 lineations shown on Figure 5.5b. S5 may be differentiated with ease from the other late crenulation cleavages by its relationship to MP5 biotite porphyroblasts (classification of Sturt and Harris 1961). These porphyroblasts are frequently seen to parallel S5, occasionally cross cutting B5 crenulation axes (See 6.3a.).

### 5.2c) D5 - Area 3

Area 3 is positioned entirely to the east of the axial trace of the Ballard Antiform, and as such is relatively unaffected by this fold. The orientation of D5 structures within this area should therefore broadly correspond to those developed in area 2 (see 5.2b). D5 structures in area 3 are not developed as frequently as in areas 1 and 2. This may be related to either the predominance of gritty and psammitic lithologies within area 3 (which do not preserve minor late crenulations as readily as pelites) , or to original spatial variations in D5 strain. It may equally be associated with differences in orientation of S2 fabrics in the D3 Ballybofey hinge zone.

Within area 3, S5 typically trends North West - South East and dips at steep angles towards the north east (Figure 5.5c.) (Map 5 map box). B5 lineations plunge gently towards the south east (Figure 5.5d.) and are also shown on Map 5 (Map box). Examination of Figures 5.5a. and 5.5b. with 5.5c. and 5.5d. together with inspection of Map 5 (Map box) demonstrates the similarity in orientation of D5 structures in areas 2 and 3. S5 is a moderately developed zonal crenulation of S2 with no new discrete planes of mica and is axial planar to rare close F5 folds with middle limbs upto 0.5 m long. The majority of B5 lineations shown on Figure 5.5d. and Map 5 are B5 crenulation axes with short middle limbs upto 1.5 cm across which parallel the larger F5 fold axes. Throughout area 3, D5 vergence is towards the south, clearly cross-cutting the D3 Ballybofey Antiformal hinge. On the upper normal limb of this D3 fold, D5 structures are sub-parallel to bedding (S0), whereas on the lower inverted limb they overprint S0 at quite high angles. S5 is frequently seen to deform S3 (Plate 27a.), eg. Garranbane Hill (H 063962).

#### 5.2d) D5 Synopsis

From the preceding accounts, it is obvious that D5 cross cuts the major D2 and D3 folds, as well as overprinting the D4 fabrics described in 5.1). D5 structures are clearly refolded and reoriented by the <sup>D7</sup> Ballard Antiform. Equal-area stereograms showing S5 and B5 lineations in the whole of the mapped area portray the refolding effect of this D7 fold (Figure 5.6a., 5.6b.). Map 5 (map box) shows the rotation of D5 structures around the hinge of this later fold, eg. North of Annagh bridge (H 040980), and also their reorientation south of Crocknahamid (G 990980), into the western limb of the D7 Ballard Antiform. Adjacent to the D3 Ballybofey slide and the D1-D2-D3 Central Donegal slide on the inverted limb of the Ballybofey Antiform (D3), D5 structures become asymmetric and extensional, suggestive of top to the north shear on the northward dipping S5 fabrics. This zone of intense D5 deformation may be associated with the pre-D5 orientation of S2-S3 surfaces in relation to the D5 stress field.

**Figure 5.6a.**

**S5 - whole of map area.**  $n = 854$ , maximum concentration of data points = 108/80N, mean = 106/80N. Slight bimodal distribution of data points corresponds to regional refolding by the D7 Ballard Antiform.

**Figure 5.6b.**

**B5 Lineations - whole of map area.**  $n = 363$ , maximum concentration of data points = 41/093, mean = 14/105. Bimodal distribution of data points corresponds to regional refolding by the approximate North - South trending F7 and F9 folds.

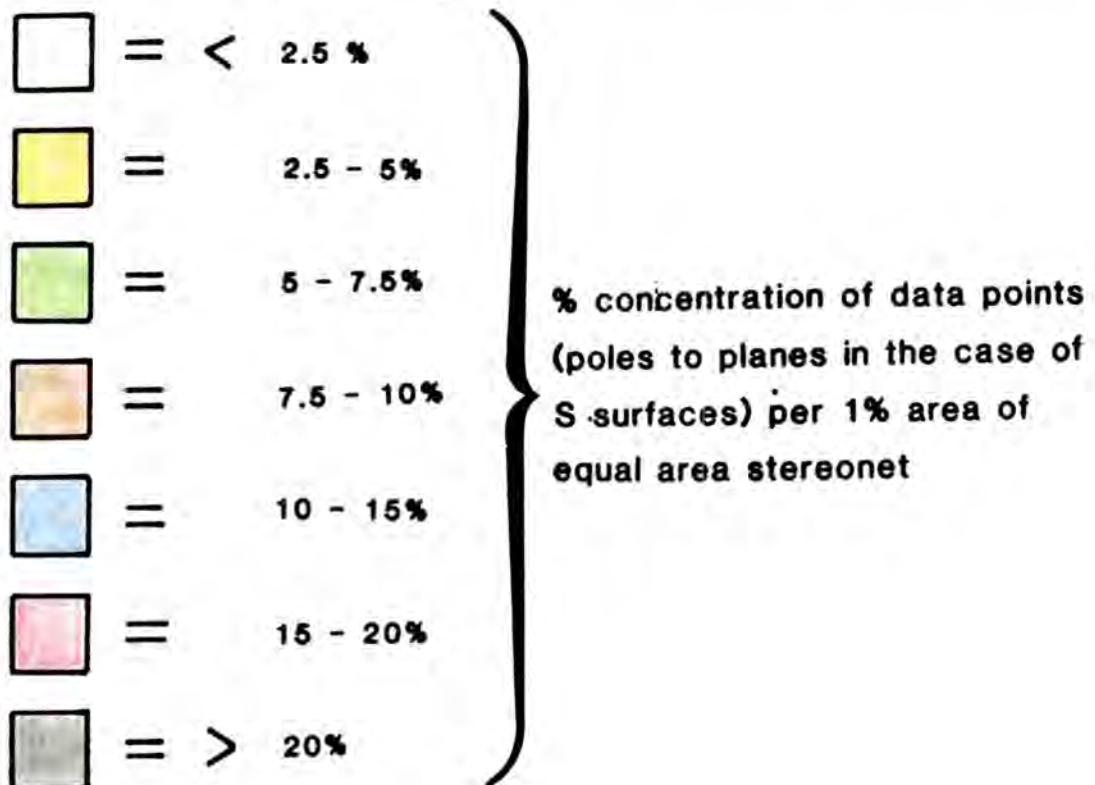
**Figure 5.6c.**

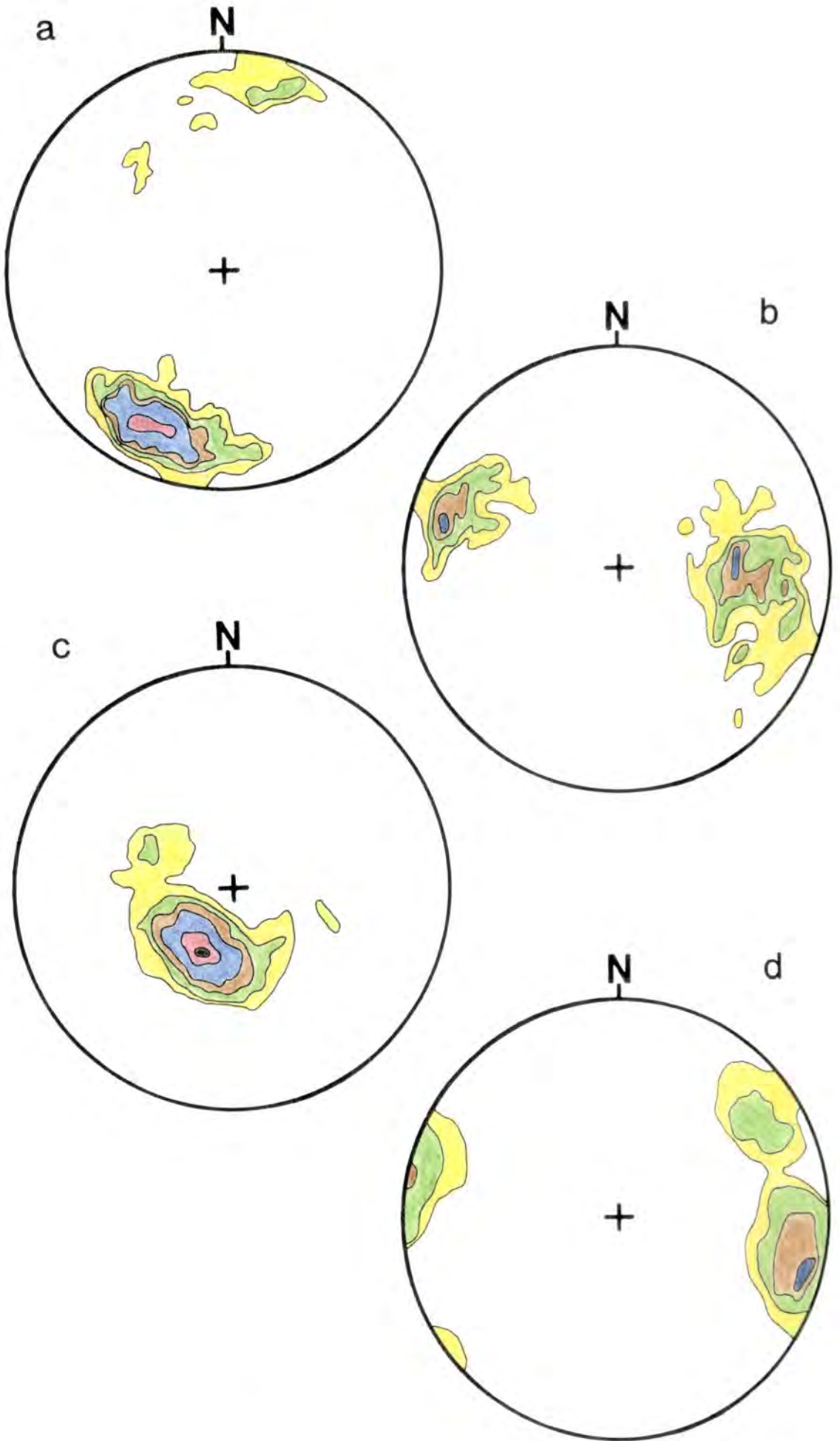
**S6 - whole of map area.**  $n = 47$ , maximum concentration of data points = 120/28NE, mean = 122/21NE. Slight bimodal distribution of data points corresponds to regional folding by the D7 Ballard Antiform.

**Figure 5.6d.**

**B6 Lineations - whole of map area.**  $n = 20$ , maximum concentration of data points = 6/106, mean = 13/096. Bimodal distribution of data points corresponds to regional refolding by the D7 Ballard Antiform.

**Contour intervals on equal area stereograms shown on facing page**





Throughout the mapped area, D5 compressional structures verge to the south.

### 5.3) The sixth deformation (D6) (Map 6 - map box)

D6 is regarded as being of limited significance within the mapped area with no major folds relating to this deformation being found. D6 structures appear to be folded around the D7 Ballard Antiform.

#### 5.3a) D6 - Area 1

Within area 1 on the western limb of the <sup>D7</sup> Ballard Antiform, S6 is a sporadically developed weak crenulation of the main S2 or S2-S3 fabric. Individual S6 surfaces may be spaced at up to 10 cm, and dip gently towards the north throughout area 1 (Map 6 map box). Mesoscopic F6 folds are rarely developed, those which have been located eg. Croveenananta (G 950940) are compressional open warps of neutral or poorly developed variable vergence with S6 axial planar and a half wavelength (trough to crest) of less than 0.25 m. F6 folds and B6 crenulation axes are parallel in general plunging gently towards the west in the western portion of area 1, and to the east on the eastern side of the F9 axial trace at Clogher South (G 960940) (Maps 6 and 10 map box). F6 folds clearly deform the S5 crenulation cleavage at Croveenananta (G 942941).

#### 5.3b) D6 - Area 2

Area 2 is relatively unaffected by the D7 Ballard Antiform, as such S6 surfaces where developed dip gently towards the north east and have a more North West - South East strike compared to area 1 (Map 6 map box). B6 lineations have also clearly been reoriented compared to area 1, typically plunging gently towards the East North East (Map 6 map box). As noted in 5.1) and 5.2), this refolding may be directly attributed to the D7 Ballard Antiform. Although sparsely developed in area 2, S6 fabrics clearly overprint S4 crenulations of S2 at Cloghan Beg (H 039997). The majority of measured B6 lineations relate to crenulation axes rather than F6 fold axes. F6 folds are poorly developed warps

of bedding (S0) and S2 and display no strong sense of vergence.

### 5.3c) D6 - Area 3

D6 structures are regarded as being of very limited occurrence in area 3. This once again may, as in the case of D5 structures (5.2c), be related to variations in the orientation of S2 surfaces across the D3 Ballybofey Antiform, as well as the predominance of gritty / psammitic lithologies. In general, S6 surfaces trend West North West - East South East and dip gently towards the north. B6 lineations plunge consistently to the east or south east at shallow angles (Map 6 map box). Thus, the orientation of D6 structures here compared to area 1 broadly corresponds to the refolding affect of D7. S6 fabrics clearly cross cut S4 crenulations of S2 at Kiltyfergal (H 054973), to give an approximate relative age. The majority of B6 lineations shown on Map 6 (map box), for area 3 are minor crenulation axes which are poorly developed and of neutral vergence.

### 5.3d) D6 synopsis

D6 is regarded as being of limited significance within the mapped area. Whilst S6 surfaces and B6 lineations overprint the major folds of the second and third deformations, and also clearly cross cut D4 and D5 structures, they are themselves refolded by the D7 Ballard Antiform. The refolding effects of this late antiform are evident on Map 6 (map box), especially in relation to the swing in strike of S6 surfaces south of Crocknahamid (G 995994) into the western limb of this antiform. Throughout the mapped area S6 dips gently towards the north or north east, depending on their position relative to the F7 axial trace (Figure 5.6c). B6 lineations for the whole area are shown on Figure 5.6d. The two concentrations of data on this stereogram represent B6 lineations plunging gently to the East North East, or sub-horizontal lineations trending West North West - East South East. This distribution is spatially controlled by the Ballard Antiform (Map 6 map box).

#### 5.4) The seventh deformation (Map 6 - map box)

The D7 Ballard Antiform is the last major refold to have developed within the mapped area. As such, it is the dominant influence on the present orientation of the structural elements which relate to the several deformational 'episodes' which preceded it. The Ballard Antiform plunges steeply towards the north and is therefore approximately orthogonal to the major earlier D2 and D3 structures which it clearly refolds (Map 10 map box). D7 is thought to be a compressional deformation of regional extent and significance, the orientation and nature of its associated minor structures to some degree being controlled by the attitude of the surfaces they deform.

##### 5.4a) D7 - Area 1

Area 1 represents the western limb of the D7 Ballard Antiform and within this area all earlier formed structures have undergone reorientation relative to the remaining portion of the mapped area (see 4. , 5.1, 5.2, 5.3). S7 is well developed throughout the area, especially within the Gaugin Quartzite. It is an approximate North - South striking compressional crenulation which typically dips steeply towards the east. S7 obviously deforms both minor F3 folds as well as S4 crenulations at Gaugin Mountain (G 982948), and also overprints S5 fabrics at Drumderrydonan (G 983956). S6 is not consistently well developed enough for outcrop evidence to be found of it being cross cut by D7 structures. S7 within the Gaugin Quartzite may be spaced at upto 25 cm intervals between adjacent S7 surfaces, and has the overall appearance of a 'late stage' fabric. S7 crenulations are commonly monoclinial in nature, the reoriented middle limb of the crenulation being upto 1cm wide. The cleavage is axial planar to F7 folds (which parallel B7 crenulation axes) with short middle limbs upto 1 m in length. These folds are close, have sharply defined 'angular' hinges and typically plunge steeply towards the north, sometimes passing through the vertical to plunge south (Map 6 map box). D7 folds in the eastern portion of area 1 commonly verge east and towards the Ballard Antiform hinge.

In the western portions of area 1, overall vergence is less definite, possibly being towards the west adjacent to the Carnaween Fault (G 920930). There is no increase in the intensity of the D7 deformation adjacent to the Caledonide (North East - South West) trending faults, D7 structures being best developed in psammitic and quartzitic lithologies throughout the area.

The Ballard Antiform has produced a major reorientation of the D1-D2-D3 Central Donegal slide to the west of Ballard at (H 020940), as well as clearly re-folding the D3 Ballybofey Antiform at Slievemullagh (H 010950) (Maps 3, 10, 15, map box). S3 crenulations developed within the Gaugin Quartzite at Slievemullagh have been steepened and reoriented by D7 folding, in some instances S3 now dips towards the south (Figure 4.9a.).

#### 5.4b) D7 - Area 2

As noted previously (5.1b, 5.2b, 5.3b), the Ballard Antiform does not seem to have significantly effected the earlier formed structures of area 2. It is therefore assumed that this D7 fold fades and dies out towards the north (see 5.4d). S7 is a well developed crenulation throughout area 2, especially in the more psammitic and gritty lithologies. It trends approximately north south, dips steeply towards the east and has the appearance of a 'late stage' compressional crenulation. As in area 1, S7 may be developed at a spacing of upto 25 cm between adjacent S7 surfaces and in many cases has a monoclinial geometry with the short reoriented limb of the crenulation being upto 1.5 cm long. S7 is axial planar to mesoscopic F7 folds with short middle limbs upto 0.75 m long, and which parallel B7 crenulation axes. F7 folds are typically close with 'angular' hinges that plunge moderately towards the north (Map 6 map box). The reduction in the angle of plunge of B7 lineations in comparison to area 1 can be related to the pre-D7 orientation of the surfaces being deformed. This is largely dependent on the geometry of the D3 Ballybofey Antiform, with the shallow dipping surfaces on the northern limb of this structure leading to the development of more moderately plunging B7 lineations.

Throughout area 2, D7 structures appear to have no strong, consistent sense of vergence related to the Ballard Antiform. The only large scale trace of this fold is the km scale warping of the Boultypatrick Grit outcrop in the vicinity of Brockagh (H 045955). Minor crenulations associated with D3, D4, and D5 are clearly reoriented about this D7 fold (Maps 3 and 4 map box). Thus, D7 is clearly of more limited intensity within area 2 compared to area 1.

#### 5.4c) D7 - Area 3

Area 3 lies entirely to the east of the Ballard Antiform axial trace. S7 is a moderately well developed compressional crenulation cleavage throughout area 3, striking north south and dipping steeply to the east (Map 6 map box). On a regional scale S7 obviously overprints the D3 Ballybofey Antiform, the slightly more North North West strikes to the north east of this D3 axial trace probably being related to the variation in the pre-D7 orientation of the S2 surfaces (Map 6 map box). On an outcrop scale, S7 fabrics clearly cross cut both S3 crenulations and F3 hinges on a number of occasions eg. Lettershambo (H 070995). D7 once again typically has a monoclinial geometry on both the S7 crenulation scale and the larger mesoscopic F7 fold scale. The rotation of the short middle limb on these structures suggests a vergence consistently towards the axial trace of the D7 Ballard Antiform to the east (Map 6 map box). B7 crenulation axes parallel larger F7 fold axes which are typically closed angular structures plunging moderately towards the north on the more gently dipping upper normal limb of the D3 Ballybofey Antiform. Variations in the amount of plunge of F7 folds may once again be related to the pre-D7 orientation of S2 surfaces. There are no major folds of D7 age developed within area 3, the entire area being on the eastern limb of the D7 Ballard Antiform.

#### 5.4d) D7 synopsis

Thus the D7 Ballard Antiform is the last major refold to have developed within Central Donegal. It trends North South and plunges towards the north

, the angle of plunge of B7 lineations relating to the pre-existing orientation of the S2 fabric. Stereograms showing the steeply plunging nature of B7 lineations (occasionally plunging to the south on the inverted limb of the D3 Ballybofey Antiform), and approximate North South strike of the steep easterly dipping S7 fabric are shown on Figures 5.7a., 5.7b. The moderate to steeply plunging nature of the D7 Ballard Antiform suggests that the two fold limbs have not undergone a significant amount of vertical movement during this deformation i.e. rotation about a sub-vertical axis. This is verified by the limited variation in the angle of plunge of pre-existing crenulation axes between areas 2 and 3 (eastern limb), and area 1 (western limb). There has however been a rotation of approximately 30° in the trend of these earlier formed structures. The steep plunge of the Ballard Antiform, together with its orthogonal attitude in relation to D2 and D3 structures enable its effects to be clearly portrayed on the horizontal map surface (Maps 6 and 10 map box).

The vergence of minor D7 structures is in general towards the Ballard Antiform, the axial trace of which is believed to die out to the north of Brockagh (C 050010) in area 2. To the east of the Belshade Fault in the Lough Doo area (H 042938), no trace can be found of this D7 fold. As such it must be assumed to swing into parallelism with, and not be dislocated by the Belshade Fault (Map 6 map box). Thus, the Ballard Antiform may pass through the poorly exposed ground to the south of the Owengarve River (H 002939), prior to being intersected by the Barnesmore pluton. Conversely, the antiformal trace may simply die out in the vicinity of Clogher Burn (H 020940) (Map 6 map box).

The siting of the D7 Ballard Antiform has probably been influenced by a number of factors, not least the presence of earlier structures. This D7 fold appears to superimpose directly on the proposed axial trace of a D2 return hinge between the D2 Commeen Fold and the D2 Altnapaste/ Gorey sheath fold (see 3.3e.) (Map 2 map box). As such, the D2 return hinge may have provided a zone in which the D7 Ballard Antiform found it preferential to nucleate and

**Figure 5.7a.**

**S7 - whole of map area.**  $n = 254$ , maximum concentration of data points = 010/78E, mean = 174/76E. Girdle distribution of data points relates to the pre-existing orientation of surfaces being deformed by D7, together with refolding by the East - West trending D8 structures.

**Figure 5.7b.**

**B7 Lineations - whole of map area.**  $n = 122$ , maximum concentration of data points = 56/008, mean = 71/015. Bimodal distribution of data points relates to the pre-existing orientation of surfaces being deformed, which can be directly attributed to the D3 Ballybofey Antiform.

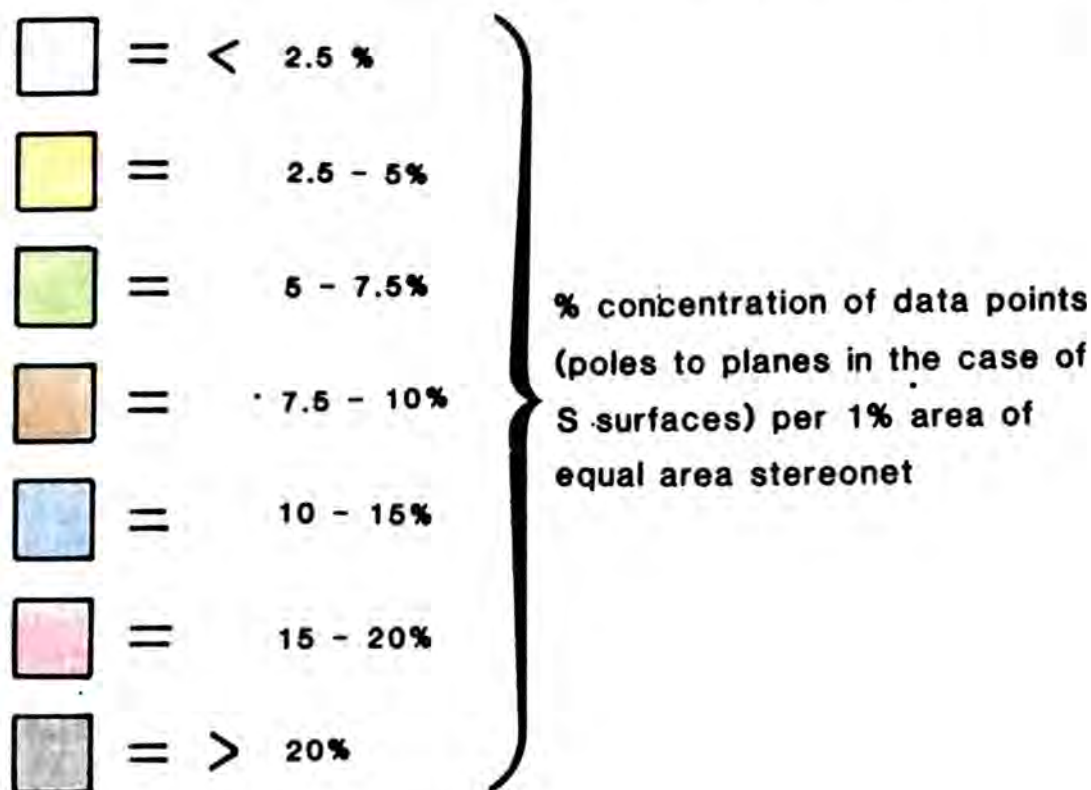
**Figure 5.7c.**

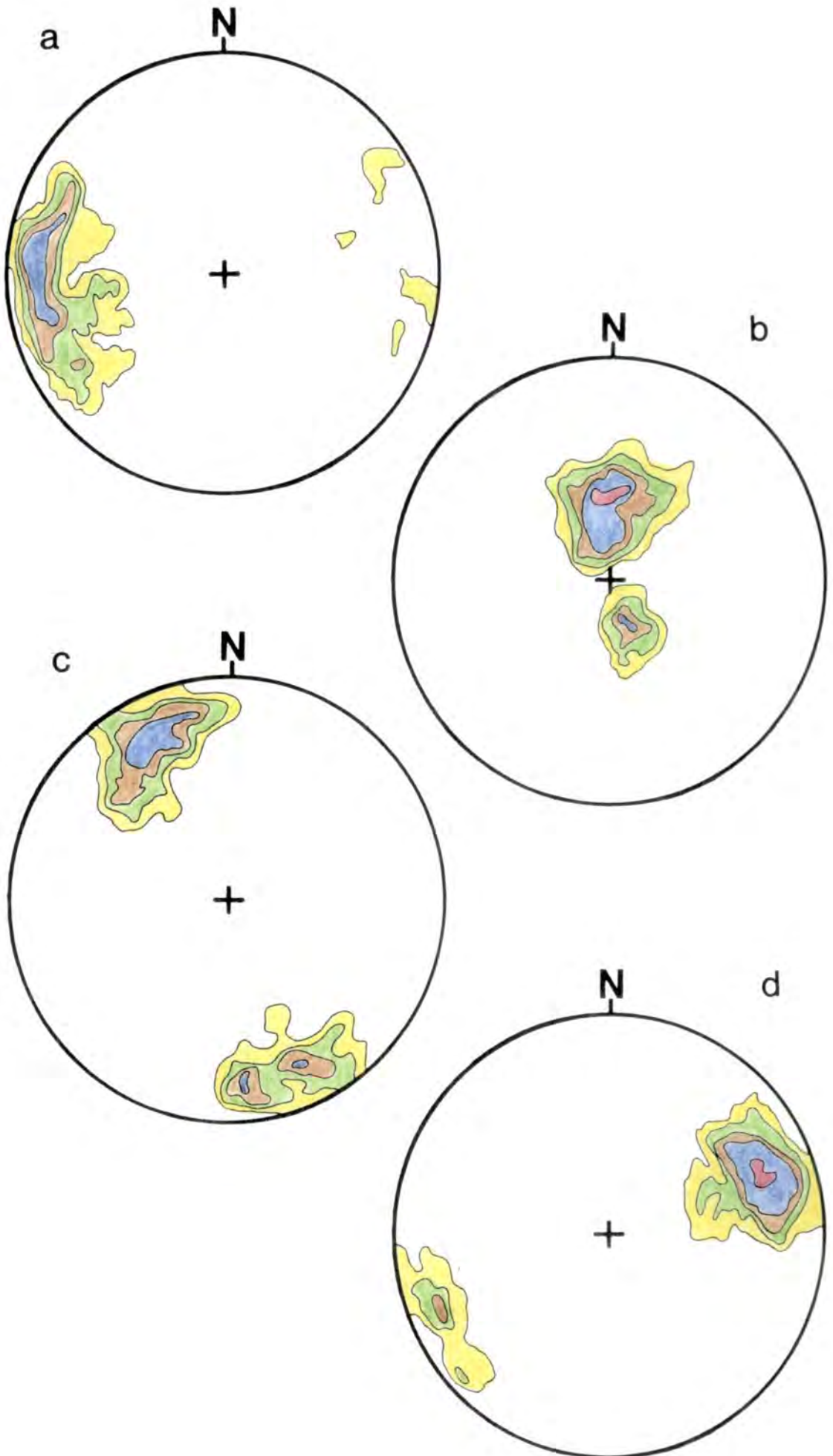
**S8 - whole of map area.**  $n = 201$ , maximum concentration of data points = 066/77SE, mean = 065/82SE. Bimodal distribution of data points corresponds to refolding by F9 folds, and is also related to the pre-existing orientation of surfaces being deformed.

**Figure 5.7d.**

**B8 Lineations - whole of map area.**  $n = 106$ , maximum concentration of data points = 20/072, mean = 17/069. Bimodal distribution of data points relates to the factors noted above (Figure 5.7c.).

**Contour intervals on equal area stereograms shown on facing page**





develop. The pre-existing structural controls noted above have led to a complex, orthogonal, triple refolding relationship to the north west of Altnapaste (H 045960) (Map 10 map box).

On the regional scale, Pitcher, Shackleton and Wood (1971) correlated the Ballard Antiform with the approximate North South trending fold of the Lough Derg slide at (H 080760). Structures of similar orientation and form to those developed during D7 in Central Donegal have been observed at (H 085764) adjacent to the Lough Derg slide. Approximately 25 km to the east in the vicinity of Convoy (H 220015), structures of similar type and trend have been located at (H 250010). These structures verge west as would be expected if no large D7 folds existed to the east of the Ballard fold. Regional folding will be discussed more fully in Chapter 6.

### 5.5) The eighth deformation (D8) (Map 7 - map box)

D8 structures are widespread throughout the mapped area, especially in the east where lithologies are more susceptible to developing late crenulations. The eighth deformation is responsible for a km scale warp of fabrics on the inverted limb of the D3 Ballybofey Antiform at Garranbane Hill (H 055 925). Apart from this warp, D8 structures appear to have no major effects on the overall structural geometry of the area.

#### 5.5a) D8 - Area 1

S8 is one of the most obvious overprinting crenulations in area 1, being largely confined to the north of the Ballybofey slide and the more pelitic lithologies. It strikes North East - South West and dips steeply towards the South East (Map 7 map box). Any apparent reversals in vergence direction based on bedding (S0) / cleavage (S8) intersection angles must be regarded as a product of the cross cutting crenulation geometry on original D2 and D3 fold morphologies. B8 crenulation axes within area 1 consistently trend North East - South West, commonly plunging gently towards the north east (Map 7 map box). The ma-

majority of B8 lineations shown on Map 7 relate to measurements of B8 crenulation axes. Where F8 folds have been observed, they are open, upright compressional structures, with middle limbs upto 20 cm long suggesting vergence towards the north (eg. Gaugin Mountain (G 982961). S8 crenulations cross cut S7 surfaces on Gaugin Mountain at (G 983949), as well as S6 crenulations at Ballynamon (G 991975), to give their relative age in the deformation chronology. On the gross scale, D8 structures are clearly seen to cross cut the D3 Gaugin Synform (Gaugin Mountain (G 980950) (Map 7 map box).

#### 5.5b) D8 - Area 2

D8 is a consistently well developed, sometimes moderately intense deformation episode throughout area 2. S8 strikes North East - South West and typically dips steeply towards the north west (Map 7 map box). The majority of B8 lineations shown on Map 7 relate to minor crenulation axes with half wavelengths less than 1 cm wide. These axes and associated larger F8 folds commonly plunge gently towards the north east. F8 folds are open, upright compressional structures with short middle limbs upto 1 m long indicating vergence towards the south east. Adjacent to the Leannan Fault, Termon Pelites in the Cummirk River area (B 995020) contain reoriented D8 structures (Map 7 map box). The more North North East - South South West trend of D8 structures compared to the rest of area 2 is presumably related to drag associated with sinistral movement on the Leannan Fault. S8 crenulations clearly deform S7 surfaces at Letterbrick (C 007015), as well as S4 and S5 fabrics on numerous occasions eg. Cloghan Beg (H 039997).

On the gross scale, D8 structures have not been reoriented across the axial trace of the D7 Ballard antiform in the Brockagh area (C 050010), nor have they been rotated by the western limb of this D7 fold. Thus, the orientation of D8 structures in area 1 is similar to those in areas 2 and 3 (Map 7 map box).

### 5.5c) D8 - Area 3

D8 is a consistently well developed and obviously overprinting deformation throughout this area. S8 strikes North East - South West across the axial trace of the D3 Ballybofey Antiform. However, on the northern side of this axial trace, S8 usually dips steeply towards the north west, whilst on the southern side it dips moderately steeply to the south east (Map 7 map box). The variation in dip direction of S8 surfaces is related to the pre-D8 orientation of S2 surfaces being deformed, which is directly attributable to the D3 Ballybofey Antiform. B8 lineations plunge gently towards the north east throughout area 3 (Map 7 map box). B8 crenulation axes parallel mesoscopic F8 folds which are close, have a 50 cm half wavelength (trough to crest) and are of neutral vergence. S8 contractional crenulations consistently overprint D4, D5 and D6 structures eg. Ballybotemple (C 057999) to give their relative age in the deformation chronology. Within the Garranbane Hill area (H 060930), D8 is responsible for a km scale open, upright synformal warp of the main S2 fabric. This structure plunges gently towards the north east and is the only significant large scale feature produced by the eighth deformation.

### 5.5d) D8 synopsis

Throughout the mapped area, S8 is a North East - South West trending steeply dipping crenulation which clearly overprints the D3 Ballybofey Antiformal complex as well as the D7 Ballard Antiform. The orientation of S8 surfaces within the mapped area is shown on Figure 5.7c. Although D8 structures are consistently well developed (especially in the pelitic lithologies), the North East - South West trending warp of S2 fabrics at Garranbane Hill (H 060930) appears to be the only large scale expression of the eighth deformation within the mapped area. Minor B8 lineations associated with D8 are relatively common, generally plunging gently towards the north east, although south west plunging B8 lineations in area 1 are recorded (Figure 5.7d.). The slight bi-modal distribution on this stereogram (Figure 5.7d.) may thus be related to the pre-existing

orientation of S2 surfaces.

### 5.6) The ninth deformation (D9) (Map 8 - map box)

D9 is a sporadically developed overprinting deformation best seen in the northern and central portions of the mapped area. It is responsible for km scale gently North North East plunging antiformal warp to the west of Gaugin Mountain (G 970940) (Map 8 map box). Apart from this warp, D9 produces no large scale structures and is purely a minor overprinting deformation with little or no large scale effect on the pre-existing structural geometry.

#### 5.6a) D9 - Area 1

D9 structures are sporadically preserved within area 1, being best seen at Gaugin Mountain (G 980950). S9 is a poorly developed crenulation cleavage striking North North East- South South West and typically dipping moderately steeply towards the east (Map 8 map box). The majority of B9 lineations shown on Map 8 refer to B9 crenulation axes which may plunge gently towards both the North North East and the South South West. These crenulation axes parallel mesoscopic F9 fold axes which are open structures (occasionally becoming close), compressional, with short limbs upto 1 m in length and which typically verge towards the west or are neutral (Plate 38b.).

Evidence of the relative age of D9 structures in area 1 is limited. They obviously cross cut the D3 Ballybofey Antiform and Gaugin Synform, as well as clearly refolding F3 folds at Drumderrydonan (H 009963) (Plate 38a.). To the west of the D7 Ballard antiform in the vicinity of the Owengarve River (H 020950), the North North West trending S9 fabrics dip moderately to the east and verge towards the west. This slightly different orientation, compared to those S9 fabrics developed west of Gaugin Mountain (G 980950), is regarded as being a product of variably oriented S2 surfaces prior to D9. The variable orientation is the result of D7 folding discussed in 5.4).

The D9 antiformal warp which is developed parallel to the Reelan River to the east of Clogher South (G 965940), plunges gently to the North North East and slightly deforms the D3 Ballybofey slide and D1-D2-D3 Central Donegal slide (Map 8 map box). It is also responsible for a warping of the D3 Ballybofey Antiform axial trace and D3 Gaugin Synform axial trace shown on Maps 3 and 14 (map box). This sub-horizontal D9 warp has also folded the B3 lineations at Clogher South (G 950948) and the L2 - L3 mineral elongation lineation (G 955950), sufficiently for them to plunge gently to the west to the north of the Central Donegal slide (Maps 3 and 9 map box). This is in the opposite direction to B3 lineations and L2 - L3 mineral elongation lineations towards the north and east in area 1. To the south of the Central Donegal slide and the Ballybofey slide, the westerly plunge of the sub-parallel B3 lineations and L2 - L3 mineral elongation lineations is attributed to a rotation along these slide planes (Chapter 4.)(Map 9 map box). The F9 warp may have enhanced the westerly plunge of these linear features in some instances, but however, was not the major cause of the change in plunge direction since westerly plunging mineral elongation lineations are developed to the east of the D9 warp (and to the south of the Ballybofey slide) at Cronakerny (H 002935). This is the only significant large scale feature produced by the ninth deformation in the whole of the mapped area.

#### 5.6b) D9 - Area 2

D9 structures are poorly developed throughout area 2. S9 crenulations are sporadically developed, strike North North East - South South West throughout the area, and typically dip moderately / steeply towards the east (Map 8 map box). In the western portion of area 2, B9 lineations (F9 fold axes and B9 crenulation axes) commonly plunge towards the south south west, whilst in the eastern parts of this area, B9 lineations plunge towards the north north east (Map 8 map box). This rotation in plunge direction (representing a rotation through the horizontal of 30°) may be a component within the overall original D9

geometry. Equally, the south south west plunging B9 lineations in the western part of area 2 are adjacent to the Leannan and Carnaween fault systems (Map 8 map box). Sinistral movement along these faults (Pitcher et al. 1964), together with downthrow to the south east may have reoriented the shallow plunging D9 lineations throughout the eastern portion of the map (areas 1 and 2).

Mesoscopic F9 folds are open, upright warps of S2, with a half wavelength (crest to trough) of 25 cm and of neutral vergence and variable plunge (noted above). Within area 2, critical evidence concerning the relative age of the D9 structures can be seen at a number of localities where S9 clearly overprints the S8 crenulation cleavage eg. Letterbrick (C 001021), Meenagolan (B 988015).

#### 5.6c) D9 - Area 3

D9 structures are very poorly developed in area 3, especially to the south of D3 Ballybofey Antiformal axial trace. This spatial distribution may be related to the predominance of gritty / psammitic lithologies in this portion of the area. S9 has trends North North East - South South West and dips moderately / steeply to the east (Map 8 map box). B9 lineations are rarely developed: those which have been measured plunge gently towards the north north east (Map 8 map box). Mesoscopic F9 folds are open warps of neutral vergence and a 20 cm half wavelength (trough to crest). Within area 3 critical evidence for the relative age of D9 structures can be seen at a number of localities where S9 crenulations cross cut the S8 fabric eg. Lettershambo (H 077991).

#### 5.6d) D9 synopsis

Throughout the mapped area, S9 is a weak, approximately North - South striking crenulation which dips steeply towards the east (Figure 5.8a.). To the immediate west of the D7 Ballard antiform it trends North North West - South South East and it dips moderately to the east. This change may be attributed to the pre-D9 orientation of S2, which in turn can be related to the D7 Ballard Antiform. B9 lineations dip gently to the south south east in the western portion

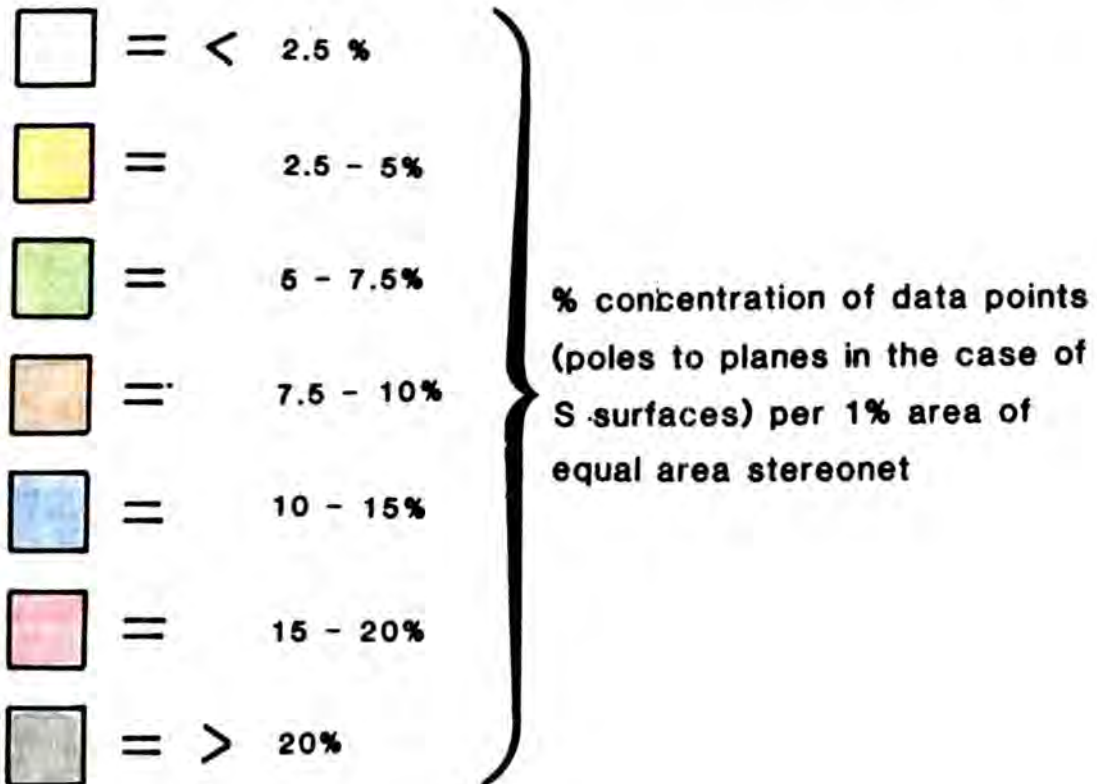
Figure 5.8a.

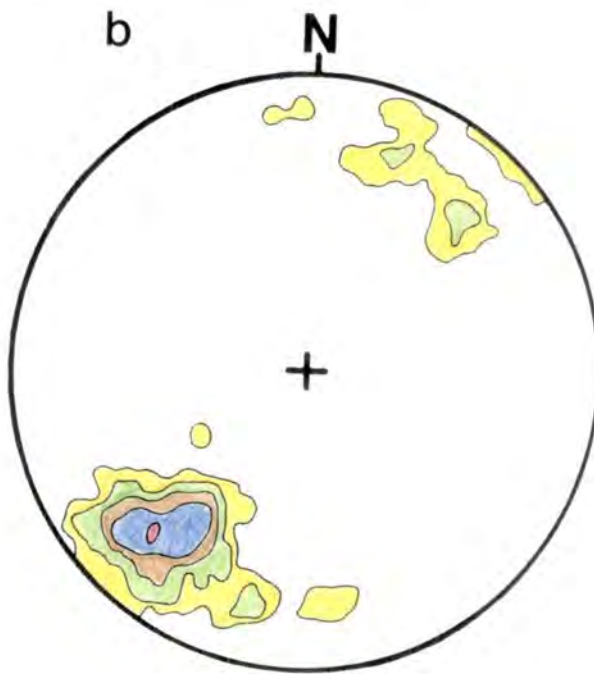
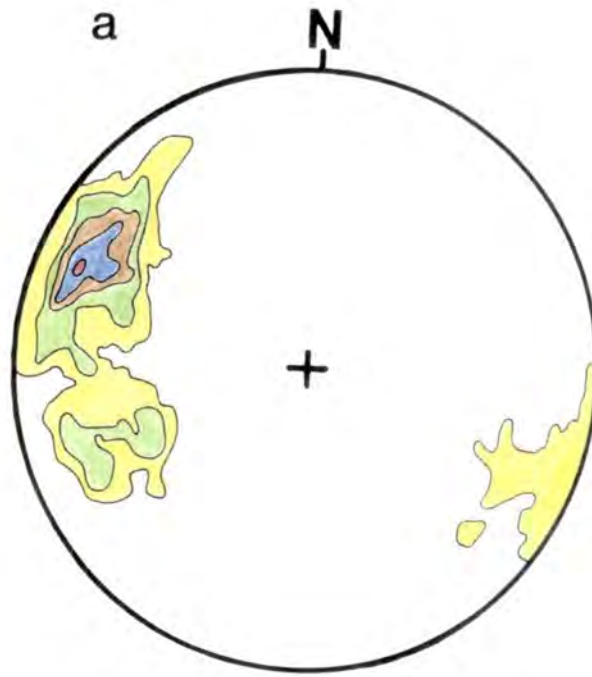
**S9 - whole of map area.**  $n = 155$ , maximum concentration of data points = 020/75SE, mean = 012/75SE. The distribution of data points forms a slight girdle that can be related to movements along the Leannan Fault system.

Figure 5.8b.

**B9 Lineations - whole of map area.**  $n = 119$ , maximum concentration of data points = 23/222, mean = 13/211. The bimodal distribution of data points may be related to the pre-existing orientation of surfaces being deformed, together with later movements along the Leannan Fault system.

Contour intervals on equal area stereograms shown on facing page





of the map, and shallowly towards the north north east in the east (map 8 map box). This bimodal distribution is shown on Figure 5.8b., and may be an original component of D9 fold geometry, or it equally could be related to displacements along the Leannan Fault system. If related to faulting, one would possibly expected to have seen a similar effect on earlier fold axes such as F7 which have a similar trend, although are more steeply plunging. The only major structure relating to D9 is the broad antiformal warp to the east of Clogher South (G 970940), which causes a limited rotation of F3 fold axes and L2 - L3 mineral elongation lineations.

### 5.7) Brittle Faulting

The North East - South West trending brittle faults which transect the mapped area belong to the Leannan Fault system described in detail by Pitcher et. al. (1964). These faults are regarded as sub-vertical structures (dipping very steeply to the north west) which have an overall sinistral displacement in the mapped area. They also appear to commonly downthrow towards the south east eg. Belshade Fault (see 3.3), Carnaween Fault (see 4.5).

Mapping has shown the Leannan and Carnaween faults to be linked in some instances by anastomosing faults which bound reoriented blocks eg. Clogher North (G 940965). This major linking fault is marked by brecciated grits and quartzite, together with gullies and tracts of marsh along its length. It appears to have developed where the Leannan and Carnaween faults are closest together (less than 1 km), and clearly indicates contemporaneous movement along these two faults (Map 1 map box). Approximately 1 km to the north west of the Belshade Fault in the north east corner of the map, a previously unmapped North East - South West trending fault which can be traced for several km to the limit of the present mapping is shown. The fault plane is nowhere exposed although its trace is marked by brecciated psammites, gullies and it has influenced the course of a tributary of the River Dee (C 120024). Movement along this fault is thought to be limited; it does however disrupt the sedimentary

transition between the Lough Eske Psammities and Termon Pelites.

North North West trending sub-vertical faults are developed towards the west of the area adjacent to the Leannan Fault. They appear to be of limited magnitude, cross cutting the Leannan and Carnaween faults in the Croaghubbrid and Silver Hill area (G 905920). This suggests that they post-date the major fault system. As they are confined to the south west portion of the map, they may be related to the increasing scissor motion and downthrow postulated in 4.5) along the Carnaween Fault.

**PLATE 36a.**

**Locality** - Stroangibbagh (G 008943)

Contractional S5 crenulation cleavage developed within semi-pelites of the Reelan Formation. Quartz segregations are folded by minor F3 folds (shown on the overlay), which are themselves later refolded by the crenulations relating to the fifth deformation.

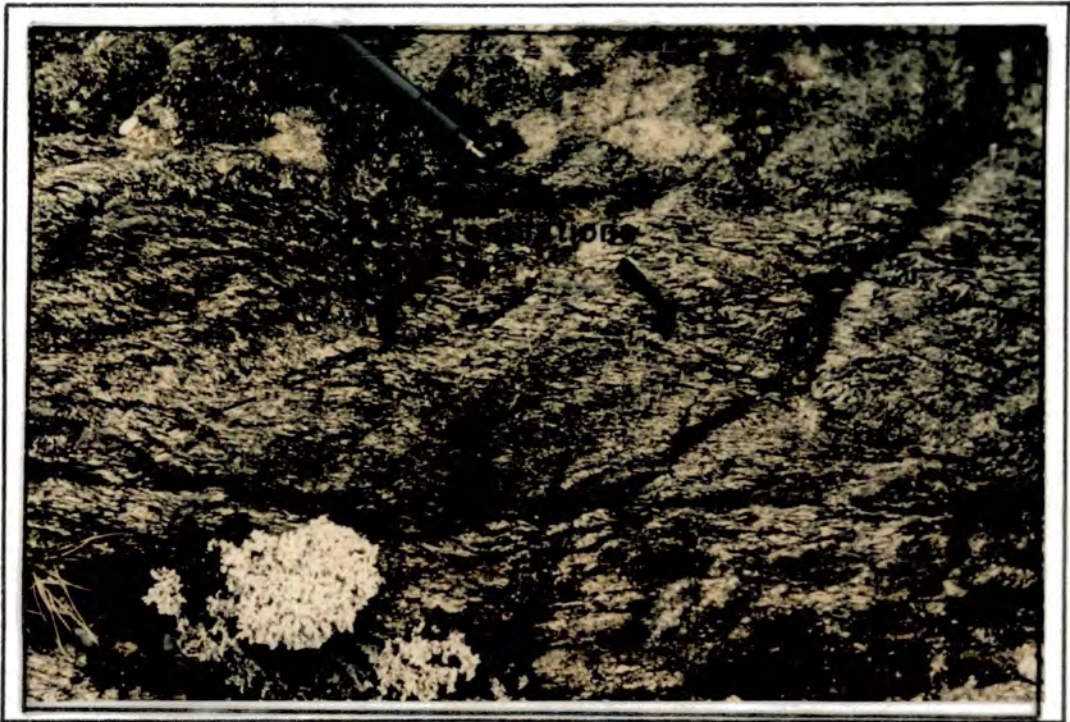
**PLATE 36b.**

**Locality** - Croveenananta (G 947936)

Conjugate S5 crenulation cleavages developed within the Lough Eske Psammites. This is the only recorded instance of a conjugate cleavage having formed in S5.



a.



b.

**PLATE 37a.**

**Locality** - Croveenananta (G 946941)

Photograph of an upright F5 fold pair , with the southern limb (on the left hand side of the photograph) of the close, mesoscopic F5 synform having sheared during D5. The suggested sense of shear is shown on the overlay. An intense axial planar S5 crenulation cleavage is clearly visible.

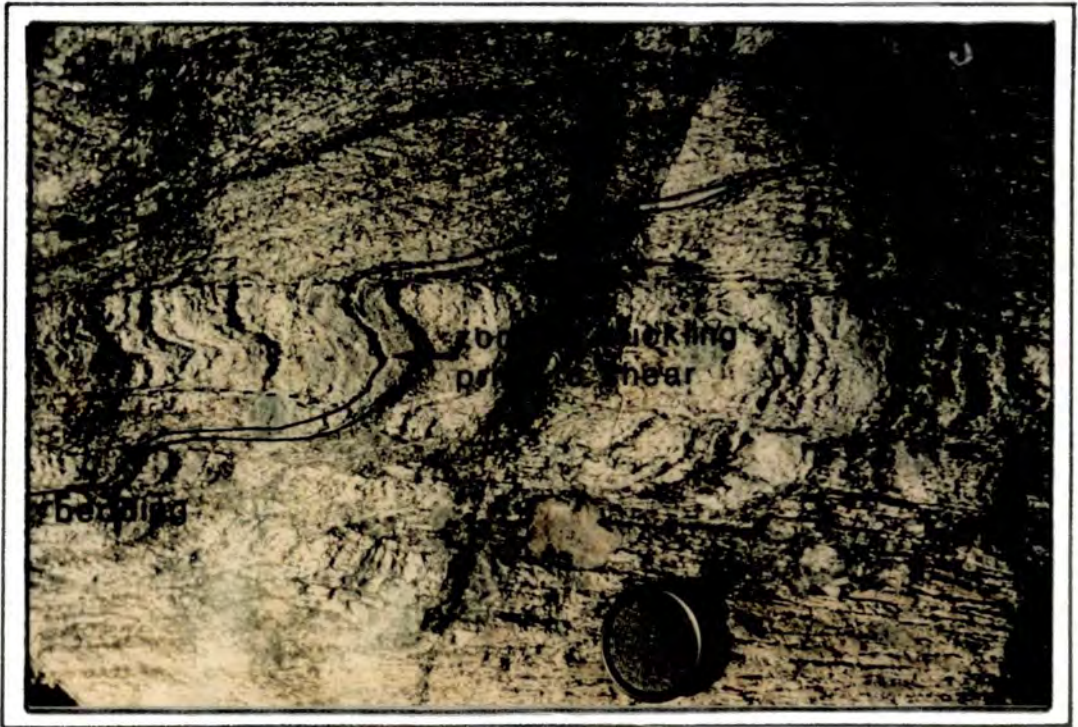
**PLATE 37b.**

**Locality** - Lacroagh (G 935939)

Intense D5 shearing in a dextral sense as viewed. Mesoscopic F5 folds of bedding and the S2 - S3 fabric (outlined on the overlay) possess sheared and excised limbs, witnessed by the reduction in the width of certain beds. A well developed S5 crenulation cleavage is axial planar to the F5 folds, its orientation being marked on the overlay.



a.



b.

**PLATE 38a.**

**Locality** - Drumderrydonan (H 009963)

Open, mesoscopic F9 refold of an earlier F3 fold hinge (right hand side of the photograph), developed within calcareous pelites of the Reelan Formation. The axis of the upright refolding approximately passes through the hammer head.

**PLATE 38b.**

**Locality** - Gaugin Mountain (G 985956)

Close, mesoscopic, upright F9 folds developed within the Gaugin Quartzite. The folds plunge moderately away from the observer (towards the south east) and have a half wavelength of approximately 1m (hammer at top left hand side of photograph for scale).



a.



b.

**CHAPTER 6**  
**REGIONAL CORRELATIONS.**

## CHAPTER 6

### REGIONAL CORRELATIONS

In this chapter the structural, stratigraphic and metamorphic framework established in Central Donegal will be extended to, and correlated with observations from elsewhere in the Dalradian inlier of North West Ireland. After discussing structural correlations in the region, stratigraphic differences will be considered and related to possible facies variations and sedimentary basin geometries. A summary of Dalradian metamorphism in Central Donegal will be related to the structural evolution of that area, followed by a broad regional correlation and synopsis.

#### 6.1) Correlation of Dalradian structures in North West Ireland

It is thought that early, major periods of deformation commonly associated with metamorphism are correlatable (even if not strictly synchronous) over an area such as North West Ireland. Structural correlations will thus focus on these critical early structures.

##### 6.1a) The structure of southern Donegal and western Tyrone.

Any correlations into this ground to the south of the present area of detailed study draws heavily upon the Ph.D. studies of Wood (1970), Pitcher, Shackleton and Wood (1971), Pitcher and Berger (1972) and the present authors brief traverses through the area. The nature of the tectonic contact of the Dalradian succession on the Lough Derg Psammities of possible Moinian affinities (Anderson 1948, Powell 1965), has been described by Borradaile (1974). See Figure 1.3 and Map 17 - map box.

In essence, Pitcher, Shackleton and Wood (1971) thought that the Ballybofey Antiform (Chapter 4) was the major control on the disposition of Dalradian stratigraphy in South and Central Donegal. The moderately northerly dipping southern limb of this overturned fold is inverted and in tectonic contact

with the underlying Lough Derg Psammities which act as basement to the Dalradian. (Plate 39a.). Wood (1970) observed southerly verging crenulations of the main fabric and related these structures to the inverted Dalradian succession having been thrust southwards over the Lough Derg Psammities. Although Wood thought that these 'minor' structures post-dated the 'D2' Ballybofey Antiform, he noted that they became more common towards the underlying tectonic slide. Borradaile (1974), in accordance with Pitcher, Shackleton and Wood (1971) and Pitcher and Berger (1972), believed the Lough Derg slide to be D2 in age. However, he noted that microscopic textures from within the Dalradian rocks adjacent to the Lough Derg slide indicated that the main fabric was S2 or later, and was folded by structures apparently relating to a "structurally inverted northward dipping fold limb" i.e. the Ballybofey Antiform. The present studies in Central Donegal (Chapter 4) which suggest a D3 age for oblique dextral overthrusting towards the south associated with the Ballybofey Antiform therefore correlate well with the observations of Wood (1970) and Borradaile (1974) i.e. the post-D2 age of the Ballybofey Antiform. Borradaile (1974) demonstrated increasing strains towards the Lough Derg slide, and also showed that the slide truncated the upper limb of a synform in the Moine - like footwall rocks (Lough Derg Psammities). Mineral elongation lineations observed by Wood (1970), Borradaile (1974) and the present author plunge gently towards the north west on the main S2-S3 fabric. Shear sense indicators (asymmetric pressure shadows, asymmetric boudins (Simpson and Schmidt 1983) in the Dalradian adjacent to the Lough Derg slide e.g. at Lough Derg (H 090760) and in the Finmore Hill region (H 022772), suggest southerly directed oblique dextral overthrusting of the Dalradian over the Lough Derg Psammities. In some instances however, the Dalradian appears to have moved parallel to the strike of the slide junction in a sinistral manner e.g. Ballykillowen Hill (H 013763), (Plate 39b.). These local reversals in shear sense suggest, as would be expected, a complex spatial and

temporal evolution of shear within this basement - cover interface. Complications along this tectonic junction have been invoked by Borradaile (1974), with rotations parallel to the plane of detachment of the two juxtaposed 'blocks'.

The Lough Derg slide and associated structures are refolded by the North - South trending Lough Derg Antiform (Lough Derg (G 085764)) which plunges moderately towards the north east. This fold has been correlated with the Ballard Antiform of Central Donegal which also folds structures related to the Ballybofey Antiform (Pitcher, Shackleton and Wood 1971). Minor structures associated with these late upright folds in southern Donegal eg. Lough Derg (G 085764) are very similar to D7 structures in Central Donegal, trending North North East - South South West, with axial planes dipping steeply towards the east and angular, close fold hinges plunging steeply towards the north (see 5.5).

Thus, southerly directed dextral overthrusting related to the D3 Ballybofey Antiform appears to be the dominant structural control throughout South and Central Donegal. The third deformation relates to intense shearing on the lower inverted limb of this fold, eventually carrying the entire Dalradian package over Moine - like basement. There is thus a broad 35 km wide D3 shear zone (Ramsay and Graham 1970), which is witnessed in Central Donegal by rotations of F3 fold axes towards the stretching (X) direction (Chapter 4), and in southern Donegal by rotation of folded quartz veins into the stretching direction resulting in limbless quartz rods (Borradaile 1974). Such a width of zonal D3 shear will obviously contain discrete movement zones, the positioning of which may be related to localised strain and displacement gradients partially controlled by lithological variations. Such a zone may also have a complex temporal and spatial evolution, as demonstrated by the folding of the D3 Ballybofey slide by folds of the same 'generation' (Chapter 4). The metamorphic effects of the Ballybofey Antiform are noted in section 6.3). The North - South trending

Ballard and Lough Derg antiforms are representatives of a 'late' deformation of regional extent. This deformation was orthogonal to the general Caledonide trend and may have produced the major strike swing of Central Donegal and western Tyrone. Basement configuration could also be an influence on such major strike swings.

#### 6.1b) The structure of North West and Western Donegal (Map 17, map box)

The structures of Central Donegal are separated from those in west and north west Donegal by the Leannan Fault system (Pitcher et. al. 1964). This sub-vertical North East - South West trending fault system has a net sinistral displacement in excess of 40 km, downthrows consistently to the South East and is believed to represent a splay of the Great Glen Fault in Scotland. The main displacement associated with the Great Glen Fault is believed to pass to the north of Donegal. On the gross scale, the Dalradian of north west Donegal trends North East - South West, dips gently towards the south east and is essentially the correct way - up. In Central Donegal to the north of the axial trace of the D3 Ballybofey Antiform, the Dalradian rocks are also basically the correct way - up, but dip gently towards the north or north east. The overall dip and younging directions within the two regions are therefore suggestive of an open, upright synform between the two areas. The proposed synform has since been sinistrally displaced and lost on the north western side of the Leannan Fault, although Pitcher et.al. (1964) believe it may be present on the southern side of the Slieve League peninsula. On the eastern side of the Leannan Fault however, such a structure exists in the Londonderry area (the Lough Foyle Synform / Inishowen Syncline) (Pitcher and Berger (1972), Roberts and Treagus (1977)). This point will be returned to later.

To the north west of the Leannan Fault, the earliest identified tectonic structure consists of a penetrative alignment of biotite, muscovite, chlorite, quartz

and opaques. This S1 cleavage is typically parallel to bedding, but has occasionally been shown to verge and face up towards the north west on bedding (Hutton 1977). A similar S1 alignment of phyllosilicates is present locally in Central Donegal, preserved in the hinges of later folds (see 3.2). No vergence relationships can be obtained directly from S1, although north west directed thrusting and hence NW facing would integrate well with proposed basin models (see 6.3). In north west Donegal there are no reported major structures of definite D1 age with which to equate the D1 origins of the Central Donegal slide (see 3.2). The Knockateen slide of north west Donegal (Pitcher and Berger (1972), White and Hutton (1985)) is developed at the same stratigraphic level as the Central Donegal slide, but is thought to be solely a D2 structure. However, it may have an earlier D1 history, demonstrated by a reversal in D2 facing across it North East of Glenties at (G 850970) (Dr. A. Bell pers. comm. 1987). This is the largest and most significant of D1 structures observed in north west Donegal, and it is interesting to note that it occurs towards the southern end of the Knockateen slide in a structural domain (East - West trending structures) which is more directly correlatable with Central Donegal. Correlation is enhanced when the approximate 40 km of sinistral movement are restored along the Leannan Fault system. Dr. A. Bell has also noted oblique S1 fabrics near the harbour slipway on the southern side of the Loughros Peninsula (G 650925) (pers. comm. 1987). Also observed in western Donegal are small scale facing reversals in S2, West of Portnoo on the Dawros Peninsula (G 680965) (Dr. D.H.W Hutton pers comm. 1987).

In north west Donegal, Anderson (1978) has recorded S1 fabrics on the Rossapenna Peninsula (C 109373) facing up towards the north west on bedding, as has C.S. Jones at an adjacent locality at The Scolts (C 108374) (pers. comm.). Hutton (1983) reports S1 fabrics from the Muckish area (B 990280), and has also noted upward facing North West verging S1 surfaces at Ards Priory (C 109373).

S. Jolley (pers.comm. 1987) has recorded S1 being crenulated by S2 at Marble Hill (C 060370). Thus, there is a wealth of data (much unpublished) relating to the first deformation in west and north west Donegal implying D1 is upward facing and verging towards the north west. The postulated larger D1 structures recorded by facing reversals on S2 appear to be confined to the southern portions of north west Donegal. The D1 situation in this region may thus be analogous to the structures observed in Central Donegal on the south east side of the Leannan Fault. The Knockateen slide may thus represent an analogous structure to the Central Donegal slide, although the aforesaid slide clearly does not possess such an intense D1 expression.

D2 structures in Central Donegal originally verged and faced (upwards ?) to the south east (chapter 3). To the west of the Leannan Fault, D2 structures typically verge and face (apart from the exceptions noted above) upwards towards the north west. Anderson (1978) records F2 folds verging and facing up towards the north west at Rossapenna on Rosguill (C 109373). D2 tectonic slides cut through F2 fold hinges, juxtaposing originally separate limbs and have an overall thrust sense towards the north west (Hutton 1983). In northern Donegal, White and Hutton (1985) record no reversal in D2 facing across the D2 Knockateen slide as originally proposed by Pitcher and Berger (1972) (Map 17 map box). K. McCaffrey (pers. comm. 1987) also finds no evidence for a reversal in D2 facing across this slide in West Fanad (eg. Ballyheerin (C 180390).

In the Gweebarra Bay area of western Donegal the pattern remains the same, Meneilly (1982) recording major inclined South East plunging F2 folds which face up to the north or north east. Axial planar to these F2 folds is a S2 crenulation cleavage which clearly transposes an earlier S1 fabric. Farther to the south west in the Slieve League peninsula, D2 structures appear to verge up towards the north east eg. Skelpoonagh Bay (G 520860), although the whole

area is complicated by D3 structures which commonly verge towards the south eg. Carrigan Head (G 560750) (Dr. D.H.W Hutton pers. comm. 1987 and authors own observations) (Howarth et. al. 1966).

There would appear therefore to be no major reversal in D2 facing or vergence throughout west or north west Donegal. The continuation of the previously mentioned Foyle Synform in Eastern Donegal must therefore lie to the south of Slieve League in the Donegal Bay area. An S2 cleavage fan about this synform, which separates D2 slides of divergent thrust sense would satisfy the gross D2 geometry outlined above (Roberts and Treagus, 1977). (see Fig 6.3)

D3 structures of north west Donegal are poorly developed in relation to those of Central Donegal (Chapter 4). There does however, appear to be an intensification southwards of the third deformation towards western Donegal and Slieve League. The correlation of D3 structures is aided by their relationship to the MP2 metamorphic peak which they post-date in both Central and north west Donegal.

In north west Donegal, Hutton (1983) believed D3 structures to be typically verging and facing up towards the south east on the right way up limbs of the major F2 folds. However S. Jolley (pers. comm. 1987), believes many of these S3 crenulations to be extensional structures related to northwards directed D2 thrusting, with relatively few contractional F3 folds observed. This being the case, D3 can be regarded as being absent or very weak in north west Donegal. In the Rosguill area of north west Donegal, Anderson (1978) records northward dipping F3 fold pairs which commonly verge towards the south eg. Crocknamurleoy (C 098390). In the Gweebarra Bay area of West Donegal, D3 structures once again post-date the peak of regional metamorphism, with F3 folds generally verging South (Meneilly (1982)), as is the case in Slieve League (noted previously). Thus, throughout west and north west Donegal, D3 structures commonly

verge and intensify towards the south. Due to this consistent southerly vergence, the continuation of the D3 Ballybofey Antiform to the west of the Leannan Fault must lie to the south of the Slieve League peninsula, once again suggesting a large sinistral displacement along the Leannan Fault system. Post-dating D3, the North East - South West Main Donegal Granite shear zone developed to the north west of the Leannan Fault (Pitcher and Berger 1972). This is a vertical shear zone with a sub-horizontal North East South West stretching lineation which was coeval with granite emplacement at approximately 400 ma. (Hutton 1982, Halliday et. al. 1980). No evidence for this intense post-D3 deformation has been found in Central Donegal, the shear zone dieing out before it reaches the Leannan Fault.

Thus, the overall structural correlation between Central Donegal and north west / west Donegal is well-founded, with the main regional metamorphism (MP2) occūring between the second and third deformations in both instances. There is abundant evidence for the first deformation verging and facing up towards the north west throughout north west Donegal, possibly becoming more intense towards the south, with the development of D2 facing reversals immediately beneath the Knockateen slide and across the Central Donegal slide. D2 structures generally verge and face towards the south in Central Donegal, and towards the north in north west Donegal. Therefore, the Lough Foyle Synform which appears to be a zone of D2 tectonic divergence in eastern Donegal and Londonderry (see below), must intersect the Leannan Fault (in the Glenswilly area (C 080100))and be displaced at least 50 km to lie to the south of the Slieve League Peninsula. To the north west of the Leannan Fault, D3 structures verge consistently South and also appear to intensify in this direction. When approximate displacements on the Leannan Fault are restored, this correlates well with the intense D3 southerly directed overthrusting seen in Central and south Donegal.

## 6.1c) Structure of Eastern Donegal and the Sperrin Mountains, Tyrone.

To the east of the Leannan Fault in north east Donegal, Roberts (1971, 1972) has recorded a number of 'D1' structures which are now believed to be of D2 age (Dr. D.H.W Hutton pers. comm. 1987). However, true D1 structures are preserved at a number of localities. S1 is clearly preserved at Fahan (C 335273), although no vergence or facing directions can be identified (K. McCaffrey pers. comm. 1987). Mesoscopic, upright, upward facing D1 folds of neutral vergence are recorded from the northern coast of Inishowen at Culdaff (C 550500) (Dr. D.H.W Hutton pers. comm. 1987). In eastern Inishowen, Roberts (1972) identified 'D1' (now classified as D2) upright, upward facing folds about North East - South West axes which suggested tectonic transport towards the north west. Associated with these folds was an axial planar slaty cleavage. Similar structures have been mapped by Roberts (1971) on the western coast of Inishowen adjacent Lough Swilly.

Thus, D2 structures in Inishowen (north east Donegal) verge and face upwards to the north west, with associated S2 surfaces dipping gently to the south east. In Central Donegal, F2 folds verge and face to the south east, with S2 surfaces dipping moderately to the north. The two regions therefore contain D2 structures that are symmetrical about a broad synformal complex ( the Lough Foyle Synform ) centered on Lough Foyle in north east Donegal and Londonderry (Sanderson et al.1980). This synform is believed to represent a later superimposed structure on the true D2 median lying approximately 10 km to the north, the Inishowen Syncline (Pitcher and Berger 1972, Roberts and Treagus 1977). However such an interpretation causes stratigraphic problems, with the Lough Foyle Succession not repeated to the north of the Inishowen Syncline. Opposing D2 vergence and facing is thus separated by an imprecise zone centred on Lough Foyle. Thin section studies from Derry City (New Bridge area) show that the

North West dipping S2 surfaces to the south of the Lough Foyle Synform are a spaced and intensely sheared fabric defined by chlorite, quartz, muscovite and opaques. Thus, contrary to the model of Pitcher and Berger (1972) and Roberts and Treagus (1977), the Lough Foyle Synform is believed to be a D2 structure rather than D1. Although the Loch Awe Synform of Scotland and the Lough Foyle structure apparently have the same geometry, they can clearly therefore not be directly equated with one another.

To the south east of the Lough Foyle Synform, the correlative of the Tay Nappe in the Sperrin Mountains of Counties Tyrone and Londonderry has been a matter of speculation. Pitcher and Berger (1972) proposed a major South East facing anticline, the Claudy Anticline tracing through County Londonderry (the axial trace of which is shown on Figure 4.8.). This structure was believed to repeat the Dungiven (Loch Tay) Limestone (Gower 1973) on each limb of the fold, with the Dalradian lithologies to the south of its axial trace being inverted. However, adjacent to the supposed Dungiven / Loch Tay limestone on the northern limb of this anticline, pelites and limestones of the Lough Foyle Succession occur, whilst adjacent to the equivalent limestone bands on the southern limb, coarse grits are observed. Stratigraphic difficulties thus exist within this structural interpretation. Hutton (pers. comm. 1987) has recorded a correct way up Dalradian succession as far south as Glenelly in County Tyrone (H 600920), to the south of Pitcher and Berger's proposed axial trace. To the south of the Glenelly Valley the Dalradian sequence is inverted with S1 consistently parallel to bedding (S0), and minor D2 structures verging north towards Glenelly and the proposed axial trace of a D2 antiform. Thus, the axial plane of this major isoclinal D2 Glenelly Anticline dips moderately to the north, with the fold axis plunging gently to the east and the overall structure being upward facing towards the south east.

The apparent repetition of the Dungiven / Loch Tay Limestone about Pitcher, Shackleton and Woods (1971) proposed axial trace of the correlative to the Tay Nappe (the Claudy Anticline) is deceptive. Arthurs (1976) has shown that the supposed Loch Tay Limestone on the northern limb of this structure is in fact only one limestone band out of a large number within the Newtonstewart Quartzitic Group, the unit which occupies the hinge of the supposed fold. Arthurs (opp. cit.) preferred to place the axial trace of the 'Sperrin Overfold' further south, trending North East - South West through the Newtonstewart area. Thus, both Arthurs (1976) and Hutton (pers. comm. 1987) have proposed axial traces of major upward facing anticlines to the south of Pitcher, Shackleton and Wood's Claudy Anticline. The major D2 structures developed within the Sperrin Mountains must correlate in some manner with the large scale F2 folds observed within Central Donegal.

Between the Sperrin Mountains and Central Donegal there are a number of major late structures which must be taken into consideration when correlating the earlier D2 structures. To the south east of Castleterg (H 260850), Arthurs (1976) records a "major open synform" which trends North - South and from map evidence plunges gently towards the south. This upright synform is regarded as passing to the west of Strabane and intersecting the Pettigoe Fault (Map 17 map box). This fold is believed to contain the rocks of eastern Donegal and western Tyrone in its hinge zone, folding the Dungiven limestone / Aghyaran Formation marker horizon. Thus, the Aghyaran Formation of western Tyrone and southern Donegal, correlated with the Loch Tay / Dungiven Limestone by Wood (1970), Pitcher, Shackleton and Wood (1971), Pitcher and Berger (1972) and Gower (1973) is on the western limb of this North - South trending synform, whilst the Dungiven / Loch Tay Limestone (Pitcher and Berger 1972, Gower 1973) East of Newtonstewart (H 400850) is on the eastern limb of this structure (Map 17 map box). This major downward warp of Dalradian stratigraphy

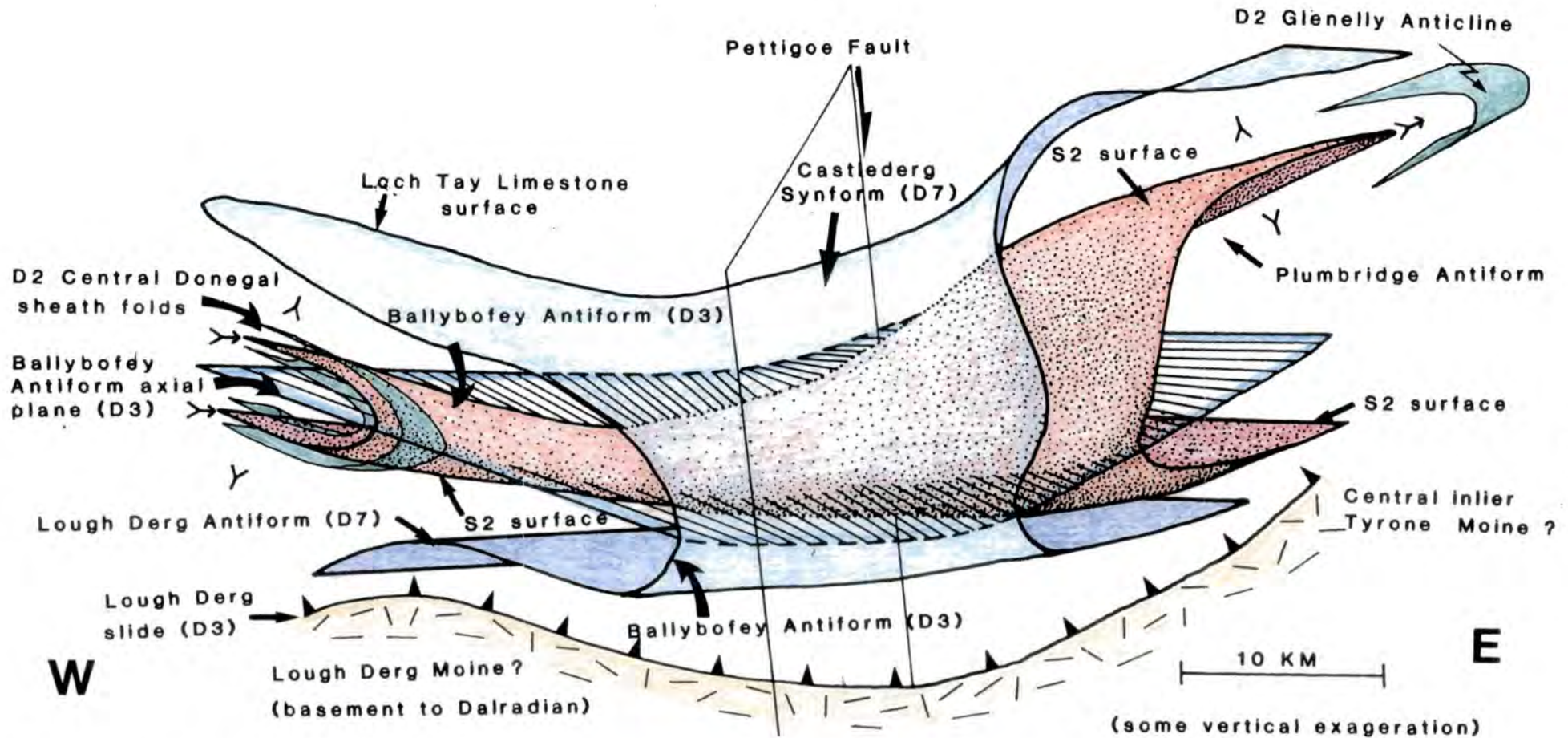
is regarded as possibly being of the same generation as the Ballard Antiform of Central Donegal and the Lough Derg Antiform of south Donegal.

Another major structure which cuts across east Donegal and west Tyrone / Londonderry is the North East - South West trending sub-vertical Pettigoe Fault. This late essentially brittle fault appears to have a major effect on the gently northwards dipping stratigraphy and structures of east Donegal and the Sperrin Mountains. The Pettigoe Fault has considerable downthrow to the south east, with Lough Derg Psammites (basement to the Dalradian) now in contact with Carboniferous sandstones and shales towards its south western end, and to the north east at Magilligan (C 680340) J<sup>u</sup>r<sup>a</sup>s<sup>s</sup>ic sediments and Dalradian metasediments are juxtaposed (see below). Riddihough and Young (1971), in a gravity survey of the area, suggest that the Pettigoe Fault is "a major dislocation with a probable vertical displacement of several thousand feet downthrowing to the SE.". This is verified by the preservation of approximately 800 m of Triassic sediments, plus Liassic and Carboniferous strata in the Magilligan borehole (C 680340) to the east of the Pettigoe / Lough Foyle Fault (IGS Malon sheet, 1:250,000 published in 1976). Thus a vertical downthrow to the south east in excess of 1.25 km is suggested along the Pettigoe / Lough Foyle Fault system. This downthrow to the south east, together with the regional easterly plunge of D2 and D3 structures therefore enables a much higher structural level with lower metamorphic grades (Hartley 1938) to be observed in the Sperrin Mountains, compared to Central Donegal. The structural and stratigraphic correlations shown on Figure 6.1. and Table 1. have taken the gross plunge and downthrow directions into account.

The Central Donegal D2 folds contain Lower and lower Middle Dalradian rocks within their hinge and at present face down to the south east on the regional scale. These D2 folds are regarded as being a deeper level equivalent to

the upward facing D2 Glenelly Anticline of the Sperrin Mountains which has Middle Dalradian rocks in its core (Map 17 map box). The downward facing Central Donegal D2 structures are refolded by the Castlberg Synform to become upward facing in the Sperrin Mountains (Figure 6.1.). Although mesoscopic and minor F3 folds of similar geometry to those of Central Donegal are common (Dr. D.H.W Hutton pers. comm. 1987), no major F3 folds which would equate with the Ballybofey Antiform have been located within the Sperrin Mountains. The North East dipping axial plane of the Ballybofey Antiform is therefore thought to be below the present level of erosion in the Sperrin Mountains. This axial plane may possibly intersect the wide D3 shear zone associated with oblique dextral overthrusting towards the south of the Dalradian cover over Lough Derg Psammites. (Anderson 1948, Powell 1965, Borradaile 1974) (Figure 6.1.). The steep North East plunging Plumbridge Antiform (Figure 6.1.) obviously folds the D2 Glenelly Anticline and is regarded as possibly being of the same generation as the Ballard, Lough Derg and Castleberg folds. Thus, with vertical displacements along fault systems and regional plunge directions taken into account, a broad correlation of Dalradian structure and stratigraphy (see 6.2) is possible between Central Donegal and the Sperrin Mountains.

Thus, D1 is associated with upward facing, North West verging structures in northern Donegal which appear to intensify towards the south, producing younging reversals across the southern portions of the Knockateen slide and the Central Donegal slide. Related to the second deformation, the Lough Foyle Synform represents a zone of D2 tectonic divergence, with shallow southerly dipping thrusts in the north, and northerly dipping thrusts in the south. The third deformation verges and intensifies towards the south, eventually carrying the Dalradian cover sequence over Moine - like basement in southern Donegal.



Schematic three dimensional diagram showing the gross Dalradian structure of Central Donegal and the Sperrin Mountains

- ↗ D2 Facing direction
- ↘ gross younging direction

CORRELATION OF DALRADIAN STRATIGRAPHY IN N.W. IRELAND

	NW Donegal	Inishowen	Glencolumbe - kille	Central and South Donegal	Sperrin Mountains
UPPER DALRADIAN		Inishowen Grits  Cloghan Green Beds  Fahan Slates and Grits		Croaghgarrow Formation  Shanaghy Green Beds  Mullyfa Grits	Newtonstewart Quartzitic Fm. (= Convoy Gp)
MIDDLE DALRADIAN	Kilmacrenan Grit  Boheolan Quartzite  Termon Pelite  Cranford Lst.  UNCONFORMITY  SlieveToocey Quartzite  Tillite	Culdaff Lst.  Upper Crana Quartzite  Lower Crana Quartzite  Linsfort Black Schist  Glengad Schist  Lag Limestone  UNCONFORMITY  Malin Head Quartzite	Slieve League Formation  TRANSITION  SlieveToocey Quartzite  Tillite	Aghyaran Fm.  Killeter Quartzite Termon Pelite = Lough Eske Psammite / Boultypatrick Grit / Croaghbrid Pelite Reelan Fm. TRANSITION Gaugin Quartzite Tillite	Dungiven Lst. and volcanics  Mullaghcarn / Dart grits and psammites Glenelly Schist
LOWER DALRADIAN	KNOCKATEEN SLIDE  Lough Finn Dark Schists Loughros Fm. Falcarragh Lst. and Pelites Sessiagh - Clonmass Fm. Ards Quartzite Ards Pelite Altan Lst. Creelough Fm.		Glencolumb - kille Dolomite Glencolumb - kille Schists	CENTRAL DONEGAL SLIDE  Croveenananta Formation	

## 6.2) Correlation of Dalradian stratigraphy in North West Ireland.

The similarity of Dalradian metasediments in North West Ireland and South West Scotland has long been recognised (Geikie 1891). Within North West Ireland and to the west of the Leannan Fault, there is a sequence of Lower Dalradian (Appin Group) metasediments named the Creeslough Succésion, which correlates with the Ballachulish Succésion of Scotland (Pitcher and Berger 1972) (Table 1.). These rocks are separated from the overlying Kilmacrenan Succésion (Argyll Group) by the Knockateen slide (see 6.1b) (Map 17 map box). To the south east of the Leannan Fault there are two facies within the Kilmacrenan Succesion, a north west Donegal facies and a Central Donegal facies (Pitcher, Shackleton and Wood 1971, see Figure 4.8.). Apart from the Newtonstewart Quartzitic Group and the Dungiven Limestone, the Dalradian rocks of the Sperrin Mountains have previously been regarded as belonging entirely to the Upper (Southern Highland) Dalradian. Whilst some notable units within the Middle Dalradian are almost continuous throughout the Dalradian outcrop of the British Isles eg. Port Askaig Tillite and associated quartzite, and the Loch Tay Limestone (Harris and Pitcher 1975), it is apparent that Dalradian stratigraphy between these marker horizons may undergo rapid facies variations as seen in Central Donegal (Pitcher, Shackleton and Wood 1971).

### 6.2a) Stratigraphic correlation between Central Donegal and North West Donegal

As noted in Chapter 2, the Dalradian Succesion of Central Donegal has been separated into two tectonic packages by the Central Donegal slide, both packages ubiquitously younging away from the slide zone. Tectonic package A comprises the Croveenananta Formation, Port Askaig Tillite Formation, Gaugin Quartzite and Reelan Formations (Table 1.). This basic association of a tillite overlain by a quartzite, and bounded above and below by calcareous pelites and limestones

is a sequence that can basically be correlated to north west and west Donegal as well as Fanad, although there are some minor variations (Harris and Pitcher 1975) (Table 1.). The Slieve Tooley Quartzite overlies the tillite, and is itself superseded by a thick limestone, the Cranford Limestone (Table 1.). This unit is present intermittently above the Slieve Tooley Quartzite and could represent a basin margin platform facies (that may have occasionally become emergent producing local unconformities (Pitcher and Berger 1972). At Glencolombkille on the Slieve League peninsula of West Donegal, Howarth et al. (1966) have made a detailed study of the Dalradian succession adjacent to the tillite. They have found that graphitic pelites (Glencolombkille Schist) and dolomites (Glencolombkille Dolomite) underlie tillite and the Slieve Tooley Quartzite, as has recently been identified at Fanad in northern Donegal (White and Hutton 1985). However, above the Slieve Tooley Quartzite there appears to have been some form of facies change with no limestones or dolomites being present. In their place is a thick sequence of pelites, graphitic pelites and gritty psammites with occasional limestones becoming more common towards the stratigraphic top. The formation has a transitional contact with the underlying quartzite (Kemp 1966, Pitcher and Berger 1972) and is thought to be a lateral equivalent to the Reelan Formation of Central Donegal. Thus, an overall facies change above the Slieve Tooley Quartzite develops through Donegal towards the south. Following deposition of the Port Askaig Tillite and overlying quartzite unit there would appear to have been deposition of limestones in north west Donegal and Fanad. The limestones were contemporaneous with the accumulation of clastic material in Central and southern Donegal. Carbonate clasts within calcareous pelites overlying the tillite - quartzite sequence in Central Donegal could possibly be derived from the limestones (Cranford Limestone see Table 1.) of north west Donegal. However, no palaeochannels containing terrigenous / clastic carbonate material have been identified in the Cranford / Lag Limestones of north west Donegal.

gal / Fanad. It would therefore seem probable that the clastic input noted in Central and south west Donegal (Glencolombkille) was derived laterally (North East - South West), or from the south east margin of the developing Dalradian sub-basin centred on this southern area. At the stratigraphic base of tectonic package B in Central Donegal, there is a relatively thick sequence of graphitic pelites (with thin limestone lenses upto 10 m long) which pass via an extended sedimentary transition into the overlying Boultypatrick Grits (see 2.3b.). The grits gradually fine upwards towards the Lough Eske Psammites as described in section 2.3b. The lateral equivalent to the Lough Eske Psammite, and probably in part the underlying Croaghbrid Pelite and Boultypatrick Grits, are the Termon Pelites. For details of this lateral facies transition see section 2.3d.. The Boultypatrick Grits and overlying Lough Eske Psammites thicken and coarsen towards the south around the hinge of the D3 Ballybofey Antiform. Thin (less than 10 m ) quartzite and limestone units within the Lough Eske Psammites also become more frequent towards the south. The Termon Pelites are thinly bedded and rather calcareous, coarsening towards the Lough Eske Psammites. In north west Donegal, the Termon Pelites are upto 2.4 km thick (Harris and Pitcher 1975) with a more graphitic lower portion which is interbedded with occasional thin dolomites and psammites (Pitcher and Berger 1972). Upwards, the graphitic pelite content diminishes and is replaced by a calcareous chloritic pelite which is intercalated with a fine grained pale green psammite, as seen in the transition with the Lough Eske Psammite. In the central parts of the Termon succession, lenses of calcareous psammite are developed, especially in the Cranford area (C 190330) (Pitcher and Berger 1972). However, farther to the south west in the Glenties area (G 818945), Cambray (1964) records a series of pebbly grits (the Knockletteragh Grits) occupying this central portion of Termon Pelite stratigraphy. The coarsening towards the south of psammites to grits within this central part of the Termon Pelites is in accordance with the overall fa-

cies transition into the Lough Eske Psammities. The Termon Pelites are possible representatives of a shallow water succession with ripple marks being preserved (Pitcher and Berger 1972), and cross lamination in more quartzitic beds to the north of Rathmullan (C 295280) (M. J. Deasy, unpublished B.Sc. thesis, Trinity College Dublin 1984). The Craignish Phyllites of the Islay region of Scotland are a similar rock type to the Termon Pelites and occupy an analogous stratigraphic position (Harris and Pitcher 1975). Within these phyllites have been found gypsum pseudomorphs, possibly suggesting a tidal - shelf deposit (Anderton 1975). The graphitic pelites of Central Donegal (the Croaghbruid Pelite) are probably equivalent to the lower Termon Pelites which are also slightly graphitic, while the Lough Eske Psammities and Boulypatrick Grits are related to the coarsening (towards the south) psammite and grit sequence of the middle Termon Pelite Formation of north west Donegal.

The summary stratigraphic log through tectonic package B of the Central Donegal succession (Figure 2.3.) is very similar to the hypothetical sedimentary log for submarine fan progradation produced by Walker (1979). However, as the Dalradian stratigraphy represents a trough several hundred km long, with palaeoflow directions often paralleling the North East - South West trending margins (Barraclough 1981, Anderton 1985), then turbidity currents may have flowed downslope towards the trough axis, prior to turning and flowing parallel the axis of the trough. Any consistent proximal - distal relationships developing from any one source may be obscured by adjacent sources farther 'up' the trough (Walker 1979).

The thickening and coarsening of the Lough Eske Psammities and Boulypatrick Grits towards the south, together with the lack of coarse palaeochannel fill deposits within the Termon Pelite (in the north), would suggest that the coarse clastic detritus represented by the grits and psammities was derived ei-

ther laterally or from the south. Thin limestone and quartzite lenses within these psammitic rocks (especially towards the south) may represent local control on sedimentation by marginal faults to the developing sub-basin.

The fine grained, pure Killeter Quartzite passes via a brief sedimentary transition from the underlying Lough Eske Psammite and Termon Pelite (see 2.3e.) (Table 1.). This unit can be traced right around the hinge of the Ballybofey Antiform and forms a useful marker horizon when defining this structure (Pitcher, Shackleton and Wood 1971). The Killeter Quartzite occasionally contains pebbly horizons which form graded units upto 1 m thick as described in 2.3e, no cross bedding having been found within the quartzite. Wood (1970) notes that the Killeter Quartzite thins towards the south and eventually becomes entirely absent on the southern inverted limb of the Ballybofey Antiform. The equivalent horizon above the Termon Pelite of north west Donegal, Inishowen and Fanad is the Crana Quartzite (Table 1.). This unit has a number of internal subdivisions but is essentially a thick (1.5 km, Pitcher and Berger 1972) coarsening up sequence of coarse grained graded quartzites and psammities which may contain lenses of graphitic pelite and limestone. Palaeocurrent observations within the Crana Quartzite of Inishowen (Barraclough 1981) suggest North East - South West axial flow along the Dalradian trough, possibly towards the south west (Phillips 1981). However, there also appears to be a general thinning and fining sequence towards the south and the Killeter Quartzite, as noted above, which becomes entirely absent in south Donegal (Wood 1970). Proximal (Crana Quartzite) to distal (Killeter Quartzite) relationships, although complicated by the elongate nature of the Dalradian trough noted above, would appear to suggest a source for the detrital material either axially, or to the north west. This is apparently the reverse situation to the underlying Termon Pelite / Lough Eske Psammite geometry.

In Inishowen, there is a rapid transition upwards from the Crana Quartzite into a thick limestone interbedded with graphitic pelites, the Culdaff Limestone, an equivalent of the Loch Tay Limestone and representative of the Middle / Upper Dalradian boundary (McCallien 1935, Pitcher and Berger 1972, Roberts 1972, Gower 1972) (Table 1.). Gower (1973) believed that the deposition of limestone and the onset of basic volcanism were contemporaneous. However, Pulvertaft (1961) and the present author (section 2.3d.) have recorded highly chloritic green beds developed within the Termon Pelites stratigraphically beneath the Loch Tay Limestone equivalents. These earlier developed volcanic deposits (together with the volcanogenic clasts developed within the Boulypatrick Grits described in 2.3b.) may be representatives of a previous episode of basic volcanism associated with the development of the Dalradian sub basin in south Donegal. The Aghyaran Formation of southern Donegal and western Tyrone is a transitional sequence from the underlying Killeter Quartzite of limestones and graphitic pelites, and has been correlated with the Culdaff, Dungiven, Loch Tay Limestone horizon by Wood (1970), Pitcher, Shackleton and Wood (1971), Pitcher and Berger (1972), Gower (1973) and Phillips (1975). Wood (1970) states that the overall amount of limestone within the Aghyaran Formation increases northeastwards i.e. towards the more typical representatives of the Loch Tay Limestone horizon in Donegal. On the northern limb of the Ballybofey Antiform, the calcareous rocks of the Convoy Formation pass via a brief sedimentary transition from the underlying Killeter Quartzite (Ghobrial 1954, Wood 1970, Pitcher, Shackleton and Wood 1971, Pitcher and Berger 1972, Gower 1973). The Convoy Formation has a greater proportion of limestones towards its stratigraphic base (Gower 1973), and must to some degree be equivalent to the Aghyaran Formation of south Donegal (Wood 1970) (Table 1.). On the gross scale, the pelitic content (including graphitic pelite) within the Culdaff Limestone, Convoy Formation and the Aghyaran Formation is in-

creasing towards the south. As no palaeochannels with terrigenous fill have been observed in the Culdaff Limestone of northern Donegal, the increasingly clastic input towards southern Donegal must have been derived axially, or from the south.

Developed stratigraphically above the Aghyaran Formation of southern Donegal are a thick sequence of grits (Mullyfa Grits), green beds (Shanaghy Green Beds see Plate 14b.) (Max and Long 1979) and psammities with graded pebble horizons (Croagharrow Formation see Plate 40) (Table 1.). As these rocks are positioned stratigraphically above the Aghyaran Formation, they are thought to belong to the Southern Highland Group or Upper Dalradian, and in part equivalent to the upper portions of the Convoy Formation which has been noted to become increasingly psammitic and gritty (Gower 1973) (Table 1.). There thus appears to have been a coarsening and thickening of the rocks stratigraphically above the Culdaff Limestone / Aghyaran Formation horizon, towards the south around the closure of the Ballybofey Antiform. This trend mirrors facies changes observed in the Middle Dalradian around the hinge of this fold. On Inishowen in northern Donegal, the Culdaff Limestone is overlain by a series of slates, grits and volcanics (McCallien 1935, 1937, Pitcher and Berger 1972, J.C. Roberts 1973) (Table 1.). These rocks have a typical Southern Highland Group (Upper Dalradian) aspect, and are obviously of a similar nature to the lithologies of southern Donegal previously described.

In summary, the tillite / quartzite association is consistent throughout Donegal (and much of the Dalradian basin). However above these horizons there appears to have been rapid facies changes, with a greater clastic input in the south of Donegal compared to farther north where limestones are deposited on the underlying quartzite. The overall thickening and coarsening of the Termon Pelite / Lough Eske Psammite towards the south is suggestive of the Dalradian

trough either being fed axially or from the south. Sub-angular clasts of blue quartz and perthitic feldspar upto 1 cm in diameter within the Boultypatrick Grits and Lough Eske Psammites of Central and South Donegal are indicative of the increasing proximity of high grade basement in this region. The overlying Crana Quartzite / Killeter Quartzite sequences however clearly fine and thin towards the south , eventually becoming absent in southern Donegal (Wood 1970). This appears to suggest a clastic input from the north, as well as axially, as recorded by Barraclough (1981) on Inishowen (north Donegal). The limestone units of the Middle / Upper Dalradian boundary in Donegal show a gross trend of increasing terrigenous clastic input towards the south (base of the Convoy and Aghyaran Formations). No palaeochannels with terrigenous clastic fill have been recorded from the increasingly pure limestones towards the north, and it must therefore be assumed that there was a reversal in palaeocurrents, with terrigenous clastic input being sourced either axially or from the south.

The Middle (Argyll Group) Dalradian of Donegal therefore shows a complex spatial and temporal basin evolution, with a number of apparent reversals in the direction of sediment input. As noted previously however, the Dalradian basin appears to have extended for several hundred km along an approximate North East South West trend, (Harris et al 1978) and as such one may expect axial currents to develop parallel to the basin margins (Walker 1977, Barraclough 1981, Anderton 1985). Therefore, the true source areas and palaeogeographies should be considered in relation to this third dimension. Basin closure and orogenesis within ancient terrains frequently inhibits these observations, with only the gross basin geometries and facies variations remaining. On the overall scale however, it is interesting to note that the thickening and coarsening Middle Dalradian sequences of southern and Central Donegal are towards the south and the present exposures of Pre- Caledonian high grade basement (Lough Derg / North East Ox inliers, Long and Yardley 1979). These granulite facies rocks dated at

895 ma. ( $\pm 60$  my. , Max, O'Connar and Long 1984) may indeed be related to the source area of the Eo-Cambrian Middle Dalradian sub-basin of Central and South Donegal. The question then arises (Phillips 1981) as to whether the tectonic junction between basement rocks of Moinian affinity (Anderson 1948, Powell 1965, Borradaile 1974) and Dalradian cover rocks of south and Central Donegal (Wood 1970, Pitcher, Shackleton and Wood 1971, Pitcher and Berger 1972) hides an original unconformity. If so, then the Dalradian Succession of North West Ireland would appear to have been deposited entirely within an ensialic trough founded on Grenvillian (approximately 1000ma.) basement. The North East Ox / Lough Derg basement may in fact represent an upstanding horst related to extension associated with Central / South Donegal basin development to the north, as well as the proposed failed rifting event which led to the intrusion of basic sheets and expulsion of volcanics at the Middle / Upper Dalradian boundary (Anderton 1985). The final successful phase of rifting obviously took place to the south of this basement block, and also to the south of the Dalradian rocks of County Mayo (Long and Yardley 1979). The basement horst may extend as far east as the Central inlier of Tyrone.

#### **6.2b) Stratigraphic correlations with the Sperrin Mountains, Tyrone and Londonderry.**

The stratigraphy of the Dalradian succession in the Sperrin Mountains (Hartley 1938), has recently been re-examined by Hutton (pers. comm 1987). As noted in 6.1, the Dalradian rocks to the north of the upward facing D2 Glenelly Anticline are regarded as essentially dipping towards the north and being the right way - up, whilst to the south of the axial trace the succession is inverted (see 6.1). Hutton's revised stratigraphy for the Sperrin Mountains is shown on Table 1, basically the sequence is :

Newtonstewart 'Quartzitic' Group (TOP)

Dungiven Limestone with associated volcanics

Mullaghcarn / Dart Schists

Glenelly Schists (BASE)

As regards regional correlation, the only reliable marker horizon is the Dungiven Limestone, equated with the Loch Tay Limestone by Hartley (1938), Pitcher, Shackleton and Wood (1971), Pitcher and Berger (1972), Gower (1973) and Phillips (1975). Arthurs (1976) recognised the stratigraphic complexity of this horizon, with a number of limestones also occurring in the adjacent Newtonstewart 'Quartzitic' Group. Associated with the Dungiven Limestones are volcanics, with intrusive epidiorites and pillow lavas being developed near Strabane (McCallien 1936, Srivastava 1955), and at Craig in the main Sperrin Mountains range (Arthurs 1976), enhancing correlations with the Loch Tay Limestones and Tayvallich Volcanics in Scotland (Harris and Pitcher 1975). Arthurs (1976) describes graphitic pelites as being ubiquitous within the Dungiven Limestone, whilst Gower (1973) also records an interbanding with slate and grit. Phillips (1976) notes that the pelitic element within the Dungiven Limestone becomes more abundant towards the west and southern Donegal. A correlation can therefore be drawn between the Aghyaran Formation / Dungiven Limestone and the Loch Tay Limestone (Harris and Pitcher 1975) (Table 1.).

Arthurs (1976) also notes intrusive epidiorites (metadolerites) and chloritic schists (greenbeds) within the Dart and Mullaghcarn Formations, both now thought to be equivalent to each other (Hutton pers. comm. 1987). These rocks are believed to be representatives of the Middle (Argyll Group) Dalradian in the Sperrin Mountains, the volcanic input being equivalent to that observed in the Termon Pelite / Lough Eske Psammities of Central and south Donegal. The

coarse grits and psammities of the Mullaghcarn / Dart Formations and indeed the Glenelly Formation (inter bedded pelites and gritty psammities containing blue quartz) are considered to be the lateral equivalents to the extremely thick sequence of Croaghubbrid Pelites, Boulypatrick Grits, and Lough Eske Psammities of Central and south Donegal (Table 1.). According to the revised stratigraphy, the Newtonstewart 'Quartzitic' Group which Arthurs (1976) describes as a quartz - feldspar - muscovite schist is equivalent to the Convoy Formation of eastern Donegal (Ghobrial 1955, Srivastava 1955, Pitcher, Shackleton and Wood 1971, Pitcher and Berger 1972, Gower 1973), (Table 1.). The Newtonstewart 'Quartzitic' Group contains slivers of graphitic pelite and interbeds of limestone (Arthurs 1976), and may be a transitional member between the Convoy and Mullyfa Formations.

Thus, the overall stratigraphic / structural relationships between Central / South Donegal and the Sperrin Mountains appear to correlate reasonably well on the gross scale (Figure 6.1.). The upward facing D2 Glenelly Anticline representing a D2 fold at a higher structural level than the D2 Central Donegal folds. As these folds are regarded as originally being upward facing, it would be expected that the tight to isoclinal Glenelly Anticline would be folding Middle Dalradian metasediments, rather than the Lower and Middle Dalradian as observed in the D2 Central Donegal folds. The Dalradian Succession below the Dungiven Limestone of the Sperrin Mountains therefore appears to be a lateral equivalent to, and situated within the Middle Dalradian sub-Basin of South and Central Donegal as described in 6.2a. The model of diverging nappes from a central synformal zone as proposed by Pitcher and Berger (1972) and Roberts and Treagus (1977) therefore broadly corresponds. However, the major structures are of the second generation (D2), with the South East facing Tay Nappe equivalent being located farther south than thought by Pitcher and Berger (1972). This relocation of the major fold axis obviously affects the stratigraphic correla-

tions as has been noted, although the Dungiven / Loch Tay Limestone horizon still forms the best marker horizon (Figure 6.1.), (Table 1.).

### 6.3) Metamorphism within Central and South Donegal.

Central and South Donegal displays a polymetamorphic history, with temporal and spatial evolution in metamorphic grade clearly related to the evolution of major structures within the area. It is difficult to ascertain at what metamorphic grade the first deformation initiated, the alignment of quartz, muscovite, biotite and opaques defining S1 (suggesting a lower greenschist facies of metamorphism - Turner 1981), may simply represent a mimetic mineral growth at a later stage. However a low greenschist facies of metamorphism during D1 would correspond to similar grades developed elsewhere in Donegal at this 'time' eg. chlorite, quartz and feldspar developed in north west Donegal (Hutton 1977), thin section observations, Derry City. A governing factor in the grade of metamorphism is the thickness of the sedimentary pile. It is probable that as south and Central Donegal contain a large thickness of Middle Dalradian psammities and grits relating to the sub-basin development noted in 6.2), and as the first deformation in both north west and Central Donegal involves the SlieveTooey / Gaugin Quartzite horizon, then the D1 structures preserved in Central Donegal are representative of greater burial depths and therefore higher grades of metamorphism. It is not clear however, how much cover relating to the Upper (Southern Highland Group) Dalradian has since been eroded throughout Donegal.

D1 structures throughout north west and west Donegal verge and face towards the north west (see 6.1), whilst in Central Donegal, although major D1 structures have been identified, no vergence or facing information for this deformation is available. However, in order for right way - up younger rocks to be emplaced over inverted older rocks (the post - D1 situation along the Central

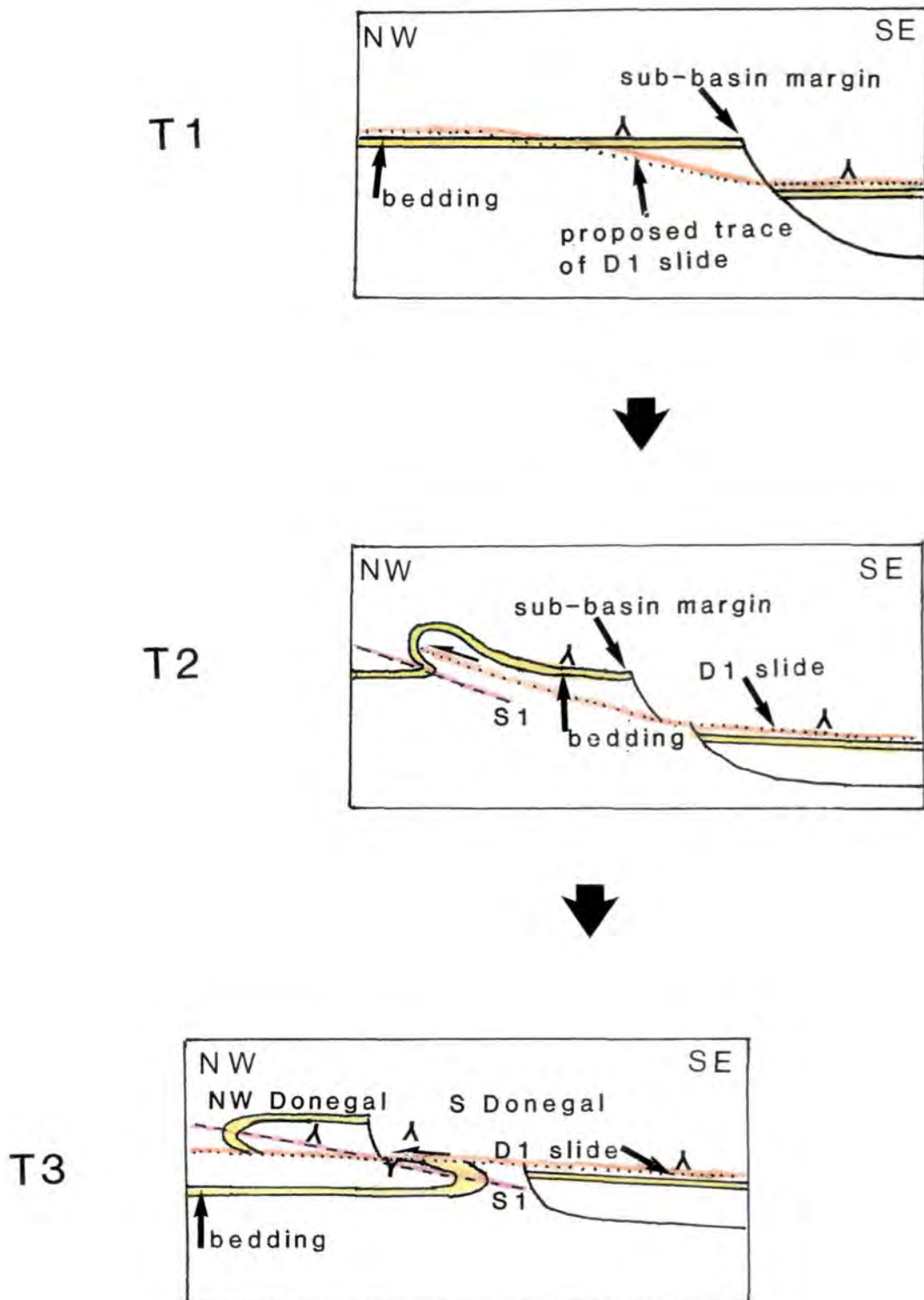
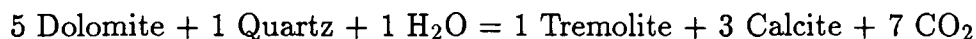


FIGURE 6.2.  
 POSSIBLE MODEL  
 FOR D<sub>1</sub> THRUSTING  
 IN NW IRELAND.

Donegal slide), a D1 fold hinge must presumably have been cut by D1 sliding. If the Central Donegal sub-basin thickened towards the south (witnessed by the increasing thickness of Boultypatrick Grits and Lough Eske Psammities towards south Donegal), then northwesterly directed D1 thrusting would cut up section through the younger Middle Dalradian basinal rocks of Central and south Donegal. The D1 Central Donegal slide can not be a simple reactivation of a listric extensional basin margin fault as the footwall is inverted. This tectonic slide has had the effect of emplacing younger basinal sediments originating from the south, on top of older shelf sediments in the north, and therefore implies North West directed thrusting as suggested by D1 structures in northern Donegal. Evidence for the southern Donegal sub-basin margin is based entirely on rapid across strike facies variations as observed at the Termon Pelite / Lough Eske Psammite transition, and as are presumed to occur in the Upper (Southern Highland Group) Dalradian between the Convoy and Mullyfa Formations. This simple model explains the gross geometry of upward facing and North West vergence, together with a younging reversal across the Central Donegal slide farther south (Figure 6.2.). Crustal thickening generated by the first deformation may have contributed to an increased metamorphic grade during the second deformation. It must be remembered however that the presently exposed ductile deformation may have a brittle expression higher in the nappe pile which has since obviously been eroded.

The metamorphic peak in Central Donegal was post-D2 (MP2). In the mapped area MP2 staurolite has been recorded on Gaugin Mountain (G 979955), whilst Cambray (1964) recorded kyanite from a similar location. MP2 garnets are present throughout the mapped area, containing inclusion trails of S2 and being wrapped by S3 fabrics (Plate 41a.). MP2 biotite and muscovite are also ubiquitous in the mapped area. Limestones in the Reelan Formation South of Slievemullagh (Stroangibbagh (H 010943)), and also within the Croaghubbrid

Pelite North of Gaugin Mountain (G 985960) contain diopside, tremolite and calcite with no quartz present. This assemblage corresponds to Winkler's (1974 p. 124) reaction of



At 5 kb fluid pressure this equates to a temperature of approximately 650° c. (Turner 1981 p. 167). The presence of staurolite and almandine is suggestive of temperatures between 550°c and 600°c, and kyanite (recorded by Cambray (1964) indicates pressures of approximately 5 kb at these temperatures (Turner 1981 p 157), (Winkler 1974 p. 89). Thus, the rocks of Central Donegal were probably buried to a depth of 15 - 18 km and heated to approximately 600°c during and after the second deformation ie. lower amphibolite facies. In southern Donegal, the MS2 / MP2 metamorphism produced a muscovite, biotite and garnet assemblage (Wood 1970), with similar index minerals also being recorded by Howarth et al. (1966) in the MP2 almandine / amphibolite facies metamorphism of the Glencolumbkille area (south west Donegal). Throughout north west Donegal there was a static MP2 metamorphism producing an assemblage of muscovite and biotite with porphyroblasts of garnet (Pitcher and Berger 1972, Hutton 1977). The MP2 relative age of metamorphism throughout Donegal aids in the correlation of the major D2 structures (Yardley 1980, Phillips 1981). The grade of metamorphism associated with the second deformation appears to diminish in the Lough Foyle and Inishowen area, only reaching lower greenschist facies with an assemblage of chlorite, biotite, muscovite and local garnet (Arthurs 1976). Within the Dalradian metasediments of the Sperrin Mountains, the metamorphic grade associated with the second deformation appears to be middle greenschist with biotite, muscovite and garnet porphyroblasts being common (Hartley 1938, Arthurs 1976, Hutton pers. comm. 1987). There thus appears to have been an MP2 metamorphic peak throughout the Dalradian

outcrop of North West Ireland. This aids in the correlation of major structures in the region and was probably tectonically induced via the stacking of nappes within a nappe pile. Thus, higher grade metamorphism took place to the south east of northern Donegal and the Lough Foyle Synform, where the lowest grade Dalradian rocks of North West Ireland are found, and following the third deformation there was retrograde metamorphism throughout most of Donegal, with some localised prograde metamorphism relating to granite intrusion in north west Donegal (Pitcher and Berger 1972). However, in Glencolombkille, south and Central Donegal there appears to have been a second phase of prograde 'regional' metamorphism, which post-dates the regional retrogressive metamorphism noted above.

In the Glencolombkille area of south west Donegal (G 540850), Howarth et al. (1966) record two episodes of prograde metamorphism. The earlier MP2 event records an almandine - amphibolite facies of metamorphism, whilst the later 'event' is of upper greenschist facies with porphyroblasts of biotite and garnet developing. This later metamorphism produced large (upto 5 mm in length) biotite and chlorite porphyroblasts in the Port Askaig Tillite Formation, and appears to have largely post-dated ductile deformation (Howarth et al. 1966).

In Central Donegal this late prograde metamorphism (MP5 in Central Donegal deformation chronology, see 5.2.) resulted in the growth of inclusion-free garnet porphyroblasts which cross cut S5 crenulation cleavages. Also developed are ubiquitous biotite porphyroblasts upto 4 mm long that are especially common in the tectonic schist horizon as well as the Port Askaig Tillite Formation. These biotite porphyroblasts commonly parallel the S5 fabric, although are occasionally seen to cross cut the hinges of B5 crenulations. Garnets of MS2 / MP2 age and MP5 generation may be recognised by their different relationships

to S2 and S3 fabrics, and also by the tendency of MS2 / MP2 garnet porphyroblasts to contain numerous quartz inclusion trails (internal S2 fabric), while MP5 garnets are commonly euhedral and inclusion free (Plate 41b.). Within the mapped area of Central Donegal, there is a slightly greater tendency for for MP5 biotite and garnet porphyroblasts to be developed towards the south, especially in pelitic and semipelitic rocks. This may be a product of increasing metamorphic grade towards the south of the area, or could be related to lithological variations. However Wood (1970), Pitcher, Shackleton and Wood (1971), Pitcher and Berger (1972) and Yardley (1980) have noted increasing metamorphic grade within the Dalradian sequence towards the Lough Derg Psammites which act as basement to the Dalradian cover (see 6.2a). Wood (1970) recognised a period of retrogression between the MP2 metamorphism and a second progressive event which clearly post-dated the Ballybofey Antiform. This second metamorphism steadily increases in grade towards the south, from biotite grade in the Lough Eske Psammites and Mullyfa Formation, to kyanite grade in the Croagharrow Formation immediately adjacent to the Lough Derg slide (the basement / cover contact) (H 070760). Although Wood's isograd surfaces may have been strongly influenced by lithological variations across strike, it is apparent that the grade of the second metamorphism increases towards the south. Wood goes on to state that "Rocks on either side of the thrust (Lough Derg slide) have been subjected to post-thrusting amphibolite facies metamorphism". Thus, the second progressive metamorphism post-dates the juxtaposition of Lough Derg Psammites (basement) and the Dalradian cover. Church (1962) notes that the original granulite facies Lough Derg Psammite has been overprinted and retrogressed by a later amphibolite facies event. Both the Lough Derg slide and the sub-parallel isograd surfaces are folded by the North - South trending Lough Derg Antiform.

Thus on the inverted limb of the D3 Ballybofey Antiform, an increasing

metamorphic grade is preserved towards the south which post-dates the development of the Lough Derg slide and thrusting of the Dalradian cover over basement (Lough Derg Psammities). This second metamorphic climax within the Dalradian also clearly overprints an original granulite facies metamorphism within the Lough Derg Psammities. The absolute time difference by which the second progressive metamorphism in the Dalradian post-dates thrusting associated with the D3 Ballybofey Antiform is not certain. As isograd surfaces approximately parallel the Lough Derg slide however, a generic relationship can be assumed. Wood (1970) believed that the Moine rocks (Lough Derg Psammities) acted as a "heat source" for this second metamorphism. However the present author believes that a more plausible explanation relates to the generation of a nappe pile associated with the third deformation. Throughout Donegal, the southerly vergence of D3 structures is suggestive of a tectonically thickened sequence and related crustal loading towards the south. The lower portions of the D3 nappe pile i.e. the inverted southern limb of the Ballybofey Antiform, would therefore be expected to represent not only a zone of intense shearing associated with nappe translation, but also a region of increasing metamorphic grade. The development of increasing metamorphic grade towards the base of the D3 nappe pile is also indicative that the rate of thrusting, shearing and folding towards the south was relatively slow, giving time for the overthrusting rocks to cool sufficiently not to create inverted isograds (see Graham and England 1976, England and Thompson 1984, Thompson and England 1984). In any future study, the temporal and spatial evolution of the 25 km wide D3 shear zone on the inverted limb of the Ballybofey Antiform, should be related in detail to the progressive metamorphic processes it induces. Yardley, Long and Max (1979), Yardley (1980) and Fettes et. al. (1985) all record increasing grades of metamorphism in the Dalradian adjacent to the Slieve Gamp (Ox Mountains) basement of County Mayo, which is regarded as being equivalent to the

Lough Derg Psammities. The increasing grade of metamorphism post-dates the MP2 metamorphic event in the Dalradian cover, and may thus have a similar relationship to ductile thrusting.

Following this second prograde metamorphism in south and Central Donegal together with Glencolombkille, there was a period of retrogressive metamorphism and chloritisation, which can presumably be related to uplift and cooling of the Dalradian block and associated pre-Caledonian basement to the south. Thus, although this project has been primarily structural / stratigraphic in outlook, it has been possible on the gross scale to relate major metamorphisms to structural controls which vary temporally and spatially ie. polymetamorphism as a product of the southerly overthrusting of the D3 nappe pile.

In summary, the first deformation is regarded as having developed at lower greenschist facies of metamorphism, and is believed to represent thrusting towards the north west along relatively discrete displacements such as the Central Donegal slide and the Knockateen slide. North West vergence and upward facing D1 relationships in north west Donegal, coupled with younging reversals across the D1 slide planes in southern Donegal indicate that this deformation was not simply related to reactivation of original extensional basin margin faults within the Dalradian Succession. The second deformation is post - dated by lower greenschist facies metamorphism in the north, increasing to amphibolite facies in the south, possibly reflecting the development of larger South East facing nappes in this direction. A zone of D2 tectonic divergence is centred on the Lough Foyle area, with shallow southerly dipping S2 surfaces in the north west, and northerly dipping S2 fabrics in the south. No trace of the Lough Foyle Synform is found to the west of the Leannan Fault, the whole of north west and west Donegal apparently lying to the north of this axis. Large scale South East facing F2 folds in Central Donegal and the Sperrin Mountains (the Glenelly Anticline)

may be equivalent to the Tay Nappe structure of the Grampian Highlands of Scotland. The third deformation intensifies towards the south, being absent or very weak in north west Donegal. D3 consistently verges towards the south east and produces a nappe like fold in south and Central Donegal, the Ballybofey Antiformal complex with a 25 km wide sheared inverted limb which eventually carries the entire Dalradian cover rocks over Lough Derg Psammities (basement of Moinian affinity) to the south. Associated with this oblique dextral overthrusting towards the south is an increase in metamorphic grade (which slightly post - dates the thrusting) towards the deeper levels of the nappe and associated shear zone which are exposed in southern Donegal. Late North - South trending folds refold the major D2 and D3 structures, and also complicate correlations of Dalradian structure and stratigraphy into the Sperrin Mountains, as does the Pettigoe Fault which has a large downthrow to the south east. However, stratigraphic correlations are simplified by the ability to trace the Dungiven / Aghyaran Limestones (equivalent to the Loch Tay Limestone) through this area, together with the recognition of a Middle (Argyll Group) Dalradian sub - basin centred on south and Central Donegal and the facies changes thereby invoked.

NW Donegal

S Donegal

Lough Foyle Synform (D2)

NW

SE

NW facing and verging  
D2 structures

SE facing and verging  
D2 structures

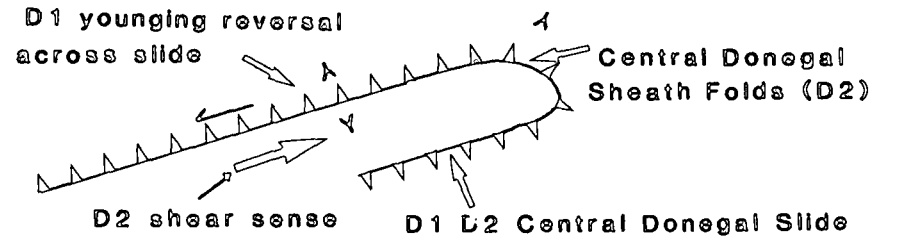
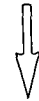
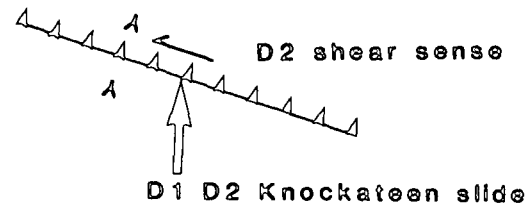


Figure 6.3

D3 structures verge  
consistently towards the SE

D3 structures verge towards the SE  
and the Ballybofey Antiform (D3)

Schematic diagram of D1, D2 and D3 vergence and facing relationships in Donegal.

**PLATE 39a.**

**Locality** - Finmore Hill, County Tyrone (H 013763)

Highly strained psammities of the Oughtadreen Formation (Dalradian cover) adjacent to the tectonic interface (the Lough Derg slide) with the Lough Derg Psammities (basement of Moinian affinity). Numerous quartz segregations are present within this platy high strain zone.

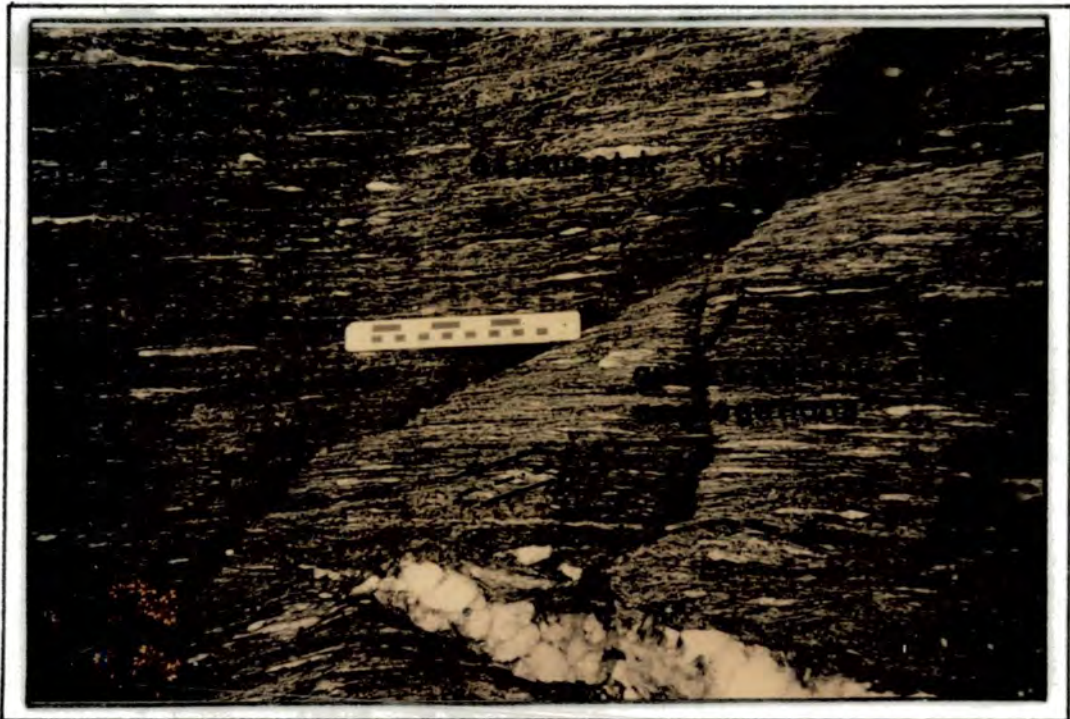
**PLATE 39b.**

**Locality** - Finmore Hill, County Tyrone (H 013763)

Highly strained psammities and semi-pelites of the Oughtadreen Formation within the Lough Derg slide zone (D3). Numerous quartz segregations aid in the definition of the shear direction, which may undergo local reversals. Large (upto 5 mm in diameter), euhedral red garnets which stand proud on weathered surfaces are visible towards the bottom of the photograph.



a.



b.



a.

#### PLATE 40

**Locality** - Lough Chill, County Tyrone (H 160750)

Coarse graded pebble bed within the Croagharrow Formation, Upper (Southern Highland Group) Dalradian. Pebbles of sub-rounded quartz are up to 4 cm in diameter, and exhibit a reduction in grain size over a distance of 50 cm through the deposit. Grading suggests that the Croagharrow Formation is inverted, younger than the Mullyfa Formation and Shanaghy Green beds, and youngs towards the Lough Derg Psammites adjacent to the Lough Derg slide. Inversion of the unit is related to the Ballybofey Antiform.

**PLATE 41a.**

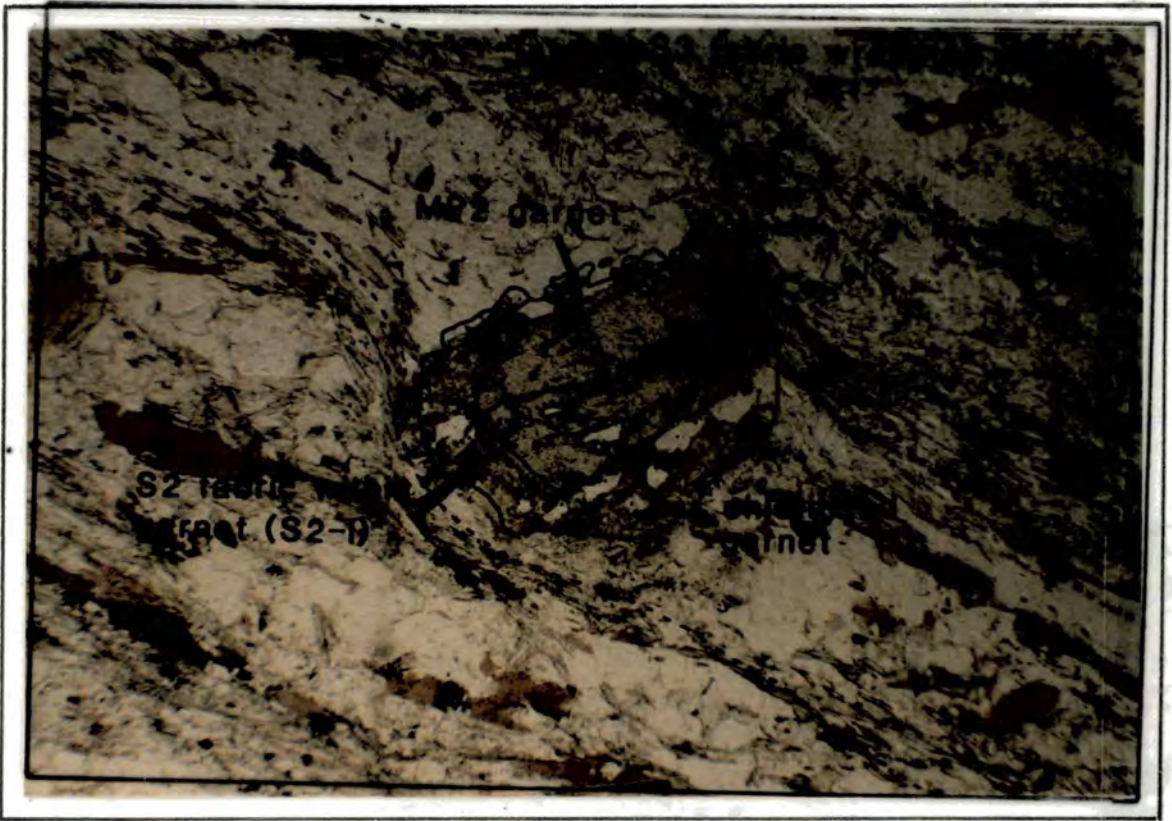
**Locality** - Gaugin Mountain (G 984957)

An Mp2 garnet porphyroblast with a chloritised outer rim (and containing an internal S2 fabric defined by quartz trails), is clearly wrapped by the external S3 fabric. The length of field of view of this photomicrograph (taken under crossed polars) is 4mm.

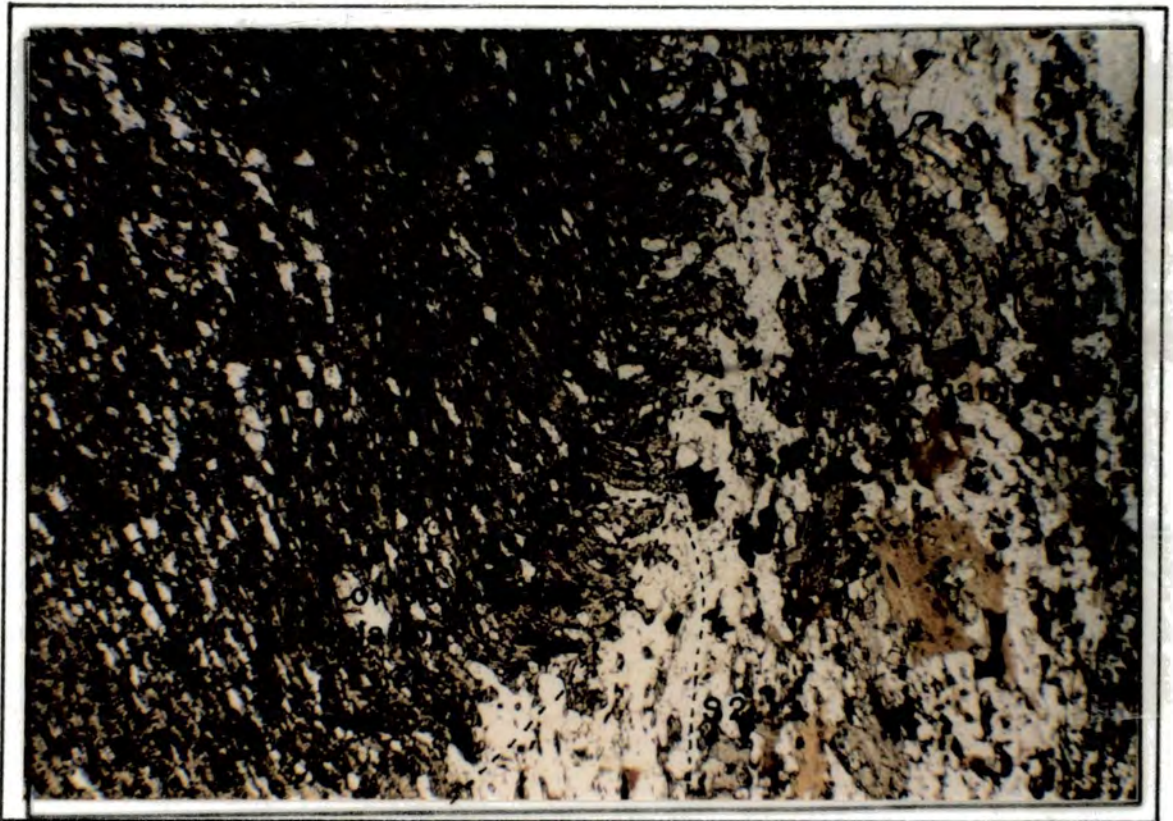
**PLATE 41b.**

**Locality** - Gaugin Mountain (G 984961)

On the left hand side of this photomicrograph (taken under crossed polars with a length of field of view of 4mm), a large MP2 garnet porphyroblast with an internal S2 fabric (defined by quartz inclusion trails) is developed. The S2 fabric within the garnet can be traced via a small zonal crenulation into the adjacent metasediment, suggesting there has been little rotation about this garnet (shown on the overlay). An inclusion - free garnet porphyroblast on the right hand side of the photomicrograph is representative of the later MP5 metamorphism.



a.



b.

## CHAPTER 7

# CONCLUSIONS

## CHAPTER 7.

## 7.1) Major conclusions to Chapter 2

(1)

The Dalradian Succession of Central Donegal is in fact a tectonic stratigraphy, with juxtaposed sequences occurring along the Central Donegal slide. The Dalradian rocks ubiquitously young away from this slide zone.

(2)

Dalradian rocks which were formerly thought to represent one stratigraphic unit (the Owengarve Formation) are now regarded as representing two stratigraphic sequences, the Croveenananta and Reelan Formations. Thus, a portion of the original Owengarve Formation which was thought to be Lower (Appin Group) Dalradian, is in fact a member of the Middle (Argyll Group) Dalradian.

(3)

Volcanogenic clasts and greenbeds have been identified from within the lower Middle Dalradian Succession. This is the lowest stratigraphic position in the Dalradian of North West Ireland from which such rocks have been identified, and represents an early stage of volcanism and crustal stretching possibly related to the formation of the southern Donegal sub-basin.

## 7.2) Major conclusions to Chapter 3

(1)

The D1 Central Donegal slide is a major structure marked by a zone of tectonic schist which, after the unfolding of later deformations, appears to have emplaced right way up younger rocks on top of older inverted lithologies, ie. an overall lag geometry but with a probable thrust shear sense.

(2)

Within Central Donegal, the gross structure relating to the second deformation is a sequence of kilometric scale sheath folds, at present suggesting shear downwards towards the south east, although originally they were associated with oblique shear upwards towards the south east.

(3)

Reworking related to the second deformation led to reactivation of the Central Donegal slide, and further development of tectonic schists.

### 7.3) Major conclusions from Chapter 4

(1)

The D3 Ballybofey Antiformal complex is associated with oblique dextral overthrusting in a major shear zone towards the south east, in which the entire Dalradian stratigraphy is eventually carried over Lough Derg Psammities (basement).

(2)

Associated with the third deformation is the reactivation and utilisation of the Central Donegal slide and related tectonic schists, where these are favourably oriented with respect to the D3 stress system. In areas where these earlier structures are unsuitably oriented for reactivation, they may be cut out by D3 sliding, as with any other part of the deformed stratigraphy.

(3)

F3 fold and crenulation axes rotate towards the mineral elongation (stretching) lineation in areas of increasing D3 strain i.e. the inverted limb of the Ballybofey Antiform. Such rotations initiate at up to 10 km away from major discrete D3 displacement planes in the zones of highest strain.

(4)

To the south of the Ballybofey Antiform, a large synformal return hinge, the Silver Hill Synformal complex is developed which appears to fold tectonic slides of the same generation. This suggests a prolonged, progressive third deformation with the possibility of shear directions evolving temporally as well as spatially.

#### 7.4) Major conclusions to Chapter 5

(1)

The attitude and form of later crenulation cleavages is greatly influenced by the nature and orientation of the earlier surfaces which they deform.

(2)

Different generations of crenulation cleavages and associated crenulation axes of variable orientations will define separate refolding patterns, when refolded by the same later fold.

(3)

As the Ballard Antiform is the last major refold to develop in Central Donegal, and is orthogonal to the major early folds, it is the dominant influence on the present orientation of all earlier tectonic elements.

(4)

The presence of anastomosing faults within the Leannan Fault system is indicative of penecontemporaneous movement along adjacent faults eg. Leannan Fault and Carnaween Fault

## 7.5) Major conclusions to Chapter 6

(1)

The D2 structures within the Dalradian of North West Ireland pre-date the peak of regional metamorphism (MP2), and are centred about an imprecise zone of divergent D2 ductile thrusting, the median line of which lies in the Lough Foyle area, the Lough Foyle Synform.

(2)

The gross structure of the Sperrin Mountains and Donegal can be correlated, with the D2 Central Donegal sheath folds representing a deeper expression of the South East verging, upward facing D2 Glenelly Anticline of the Sperrin Mountains. This structure may be equated with the Tay Nappe of Scotland.

(3)

The southerly verging third deformation associated with the development of the Ballybofey Antiform intensifies through Donegal towards the south, eventually thrusting Dalradian cover over Moine - like basement in southern Donegal. Associated with the formation of these major folds and ductile thrusts is a greenschist / amphibolite facies metamorphism which increases in grade towards the base of the D3 nappe pile exposed in southern Donegal.

(4)

In South and Central Donegal, a Middle Dalradian sub-basin developed, producing a succession that can be broadly correlated with the Dalradian stratigraphy of the Sperrin Mountains. The provenance of the basin fill is believed to be largely along the Dalradian trough and / or from the south east.

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There are many people in Donegal whom I would like to thank, especially Thomas and Annie Doherty for making Donegal a home from home during long field seasons, and Paddy and Bernie O Donnel for cheerfully accepting me into their home. Finally, I would like to finish with a big thankyou to Kathleen my fiancée for putting up with me, and close with a quote in Irish,

**“ Nuair a Rinne Dia  
Am Rinne Se neart de”**

**“When God made time,  
He made plenty of it ”**

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