THE GEOLOGY OF THE LOWER PALAEOZOIC ROCKS IN THE SOUTHERN RHINNS OF GALLOWAY, S.W. SCOTLAND : STUDIES IN AN IMBRICATE THRUST TERRANE

John A. McCurry

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Dedicated

to

Mum and Dad

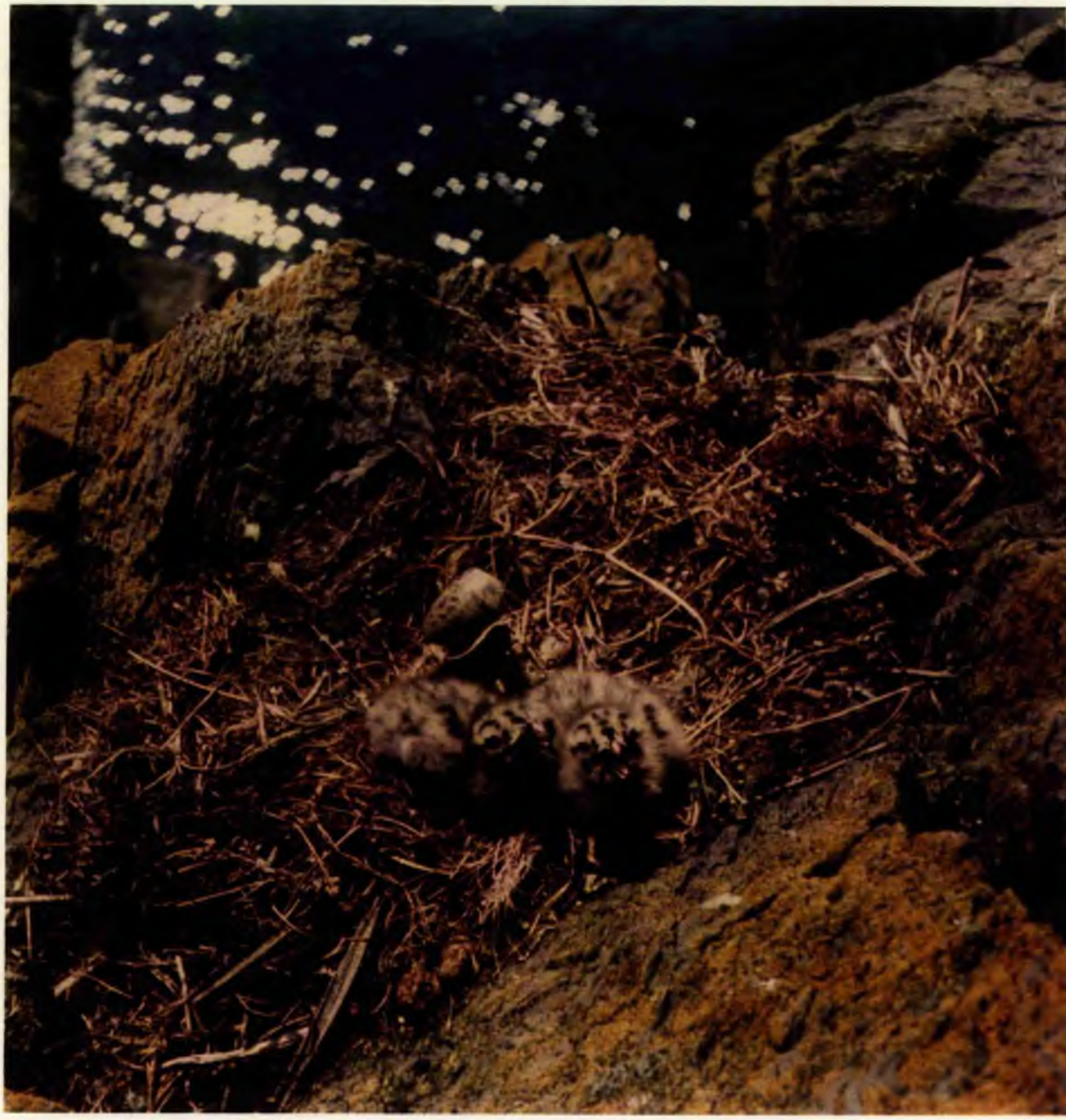
"What is essential is invisible to the eye"

Antoine de Saint-Exupéry

- *The Little Prince*

"then I saw all that God has done. ...
Despite all his efforts to search it out
man cannot discover its meaning.
Even if a wise man claims he knows
he cannot really comprehend it."

Ecclesiastes 8, v 17



Frontispiece: Common gull chicks nestle on a mudstone interbed deformed by slaty cleavage at Cairnywellan Head (NX09143989)

ABSTRACT

This thesis is the first detailed, modern account of the geology of the southern Rhinns of Galloway, SW Scotland subsequent to work by the Geological Survey last century. It integrates the geology described with the rest of the Southern Uplands-Down-Longford terrane and offers a plate-tectonic synthesis for its development.

The southern Rhinns consists of eleven NE-SW trending, sub-vertical tectonic blocks resulting from the thrust imbrication of a *c.* 35 million year Caradoc to Llandovery age sequence of chert, bentonite, shale, mudstone, greywacke and conglomerate. The pelagic/hemipelagic Moffat Shale Group acted as a locus for thrust development.

The greywackes have a siliceous petrography with sporadic input of volcaniclastic material and a major influx of detrital carbonate in the youngest formation. A recycled orogen provenance is indicated. Facies analysis indicates the catastrophic progradation of clastic, inboard deposits southeastwards over contemporaneous pelagic/hemipelagic, outboard deposits. Most of the formations were deposited in a highly confined basin, whereas the Port Logan Formation and Mull of Galloway Formation were deposited in large, unconfined submarine fans. Palaeocurrent flow was dominantly from the NE or NW, though the two youngest formations provide the first unequivocal evidence of major southeasterly derivation in the Southern Uplands.

The style and vergence of D_1 deformation changes across the Port Logan Bay Fault, the area to the SE constituting a 12 km zone of opposing fold and thrust geometry to that dominant in the terrane. A model of sequential Silurian simple shear and pure shear deformation in a steady-state trench environment above a NW-dipping subduction zone is proposed. A set of post-D_2 NW-vergent recumbent folds and thrusts related to end-Caledonian terminal collision of Cadomia and Laurentia provide evidence of major sinistral strike-slip along the Cairngarroch Fault prior to collision.

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CHAPTER ONE : INTRODUCTION

1.1 LOCATION OF THE STUDY AREA

The Rhinns of Galloway are situated in the Wigtown District of the Dumfries and Galloway Region in southern Scotland. They form the long and relatively narrow peninsula distinctively attached to the mainland of SW Scotland by an isthmus of low-lying land in which the major town of the area, Stranraer (NX06006050), is located (Fig. 1.1). This study examines the geology of the 'Rhinns' S of northing NX503 extending from Portayew (NX03805030) on the W coast to Sandhead (NX09705030) on the E coast. This southern section of the Rhinns is 28 km long and varies from 2.5-6.5 km in width, with a total area of about 87 km^2.

The peninsula has two strongly contrasting coastlines consisting predominantly of high, rocky cliffs with excellent exposure along its W coast, and low-lying raised beach terraces of poor exposure along its E coast (excepting the southernmost 2.5 km). Inland there is a thick covering of drift with resulting poor exposure. A well developed 'drumlin' landscape in the N is replaced southwards by a more hilly and in places rough terrain which is correspondingly better exposed. The maximum elevation of the area is 165 m at Cairn Fell (NX10303620), with coastal cliffs reaching a maximum height of 140 m at Dunman (NX09703350).

The area studied lies predominantly within the Central Belt of the Southern Uplands (Peach and Horne 1899), though it incorporates also the southern edge of the Northern Belt (Fig. 1.1). The thick Ordovician-Llandovery sedimentary succession consists of greywacke sandstone, conglomerate, siltstone and shale. Major deformation has affected the area and has given the bedding a sub-vertical attitude and a NE-SW trending strike. This southern portion of the Rhinns thus provides a well exposed dip section through the 'Central Belt' and its 'Northern Belt' boundary. A small 'granitic' pluton of late-Caledonian age is intrusive into the succession and is described by Holgate (1943).

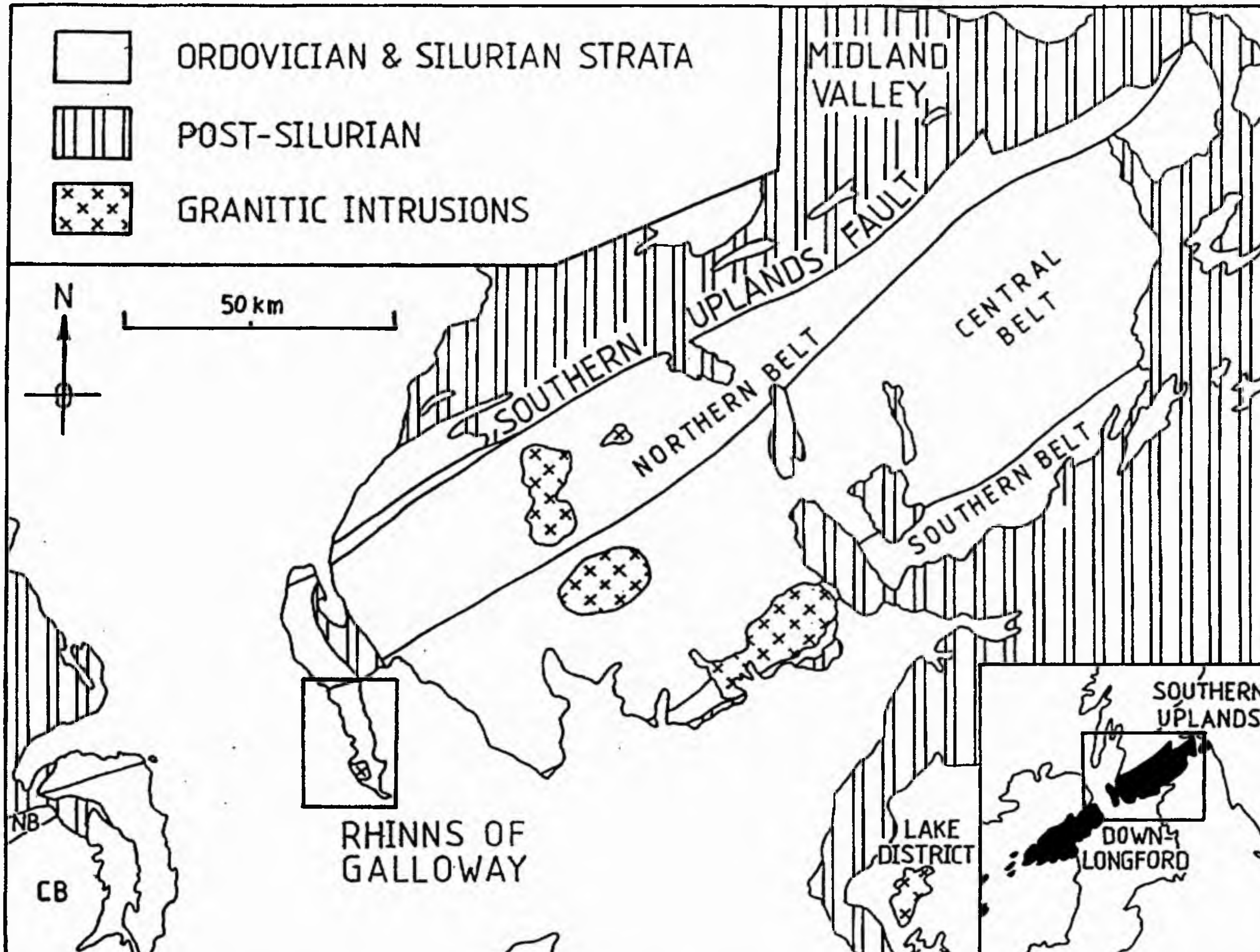


Fig 1.1: Location map of the southern Rhinns of Galloway.
NB - Northern Belt; CB - Central Belt.

Despite the excellent coastal sections, this work is the first on the sedimentary succession of the area since it was originally mapped by the Geological Survey last century (Irvine 1872, Geikie and Irvine 1873, Peach and Horne 1899). The study has involved remapping the area at a scale of 1:10,000 (approximately 6" to 1 mile) with selected areas mapped at a scale of 1:2,500 (approximately 25" to 1 mile). Research has been carried out into the stratigraphy, petrography, sedimentation and structure of the rocks of the area.

1.2 HISTORY OF RESEARCH INTO THE SOUTHERN UPLANDS-DOWN-LONGFORD TERRANE

Charting the history of research in the Southern Uplands-Down-Longford Lower Palaeozoic inliers provides a fascinating insight into the episodic progression of geological thinking over a two century period. Southern Upland-Down-Longford research has undergone three main phases in its development and at present controversy has once again arisen over the interpretation of the complex.

Pre-1955 - research in the Southern Uplands began in the late 18th century with observations by two of the founders of modern geology, James Hutton and Sir James Hall, that led the former to develop some of the fundamental principles of geology (1795), and the latter to produce the first deformation experiments on folding (1815). The first comprehensive geological interpretation of the region appeared about the mid-19th century after work by a number of researchers, the most prominent being Nicol (1848), Sedgwick (1850), Harkness (1850) and Murchison (1851). They envisaged a thick greywacke succession with two major black shale units intercalated, the basal member of this succession, the 'Hawick Rocks', being exposed in the axis of a 'great anticline' stretching from Berwick to Dumfries.

This concensus view was overturned in the 1870's and '80's by Charles Lapworth who undertook detailed stratigraphical work on the graptolite faunas of the Moffat Shales (1878). He placed the black Moffat Shales at the base of the greywacke succession (1876) and interpreted extensive linear outcrops of the shales as the axes of major folds. Lapworth (1889) went on to suggest the presence of a major anticlinorium and corresponding synclinorium, the respective axes of which being defined by the 'Leadhills Line' in the NW and the 'Hawick Line' in the SE.

In the light of Lapworth's research, Peach and Horne commenced a re-examination of all the Moffat Shale localities. This culminated in 1899 with the publication of their classic memoir 'The Silurian Rocks of Britain' Volume 1. The publication of this detailed, accurate and comprehensive work marked the end of a long period of active research in the southern Uplands with little new work carried out until the 1950's.

1955 - mid-1970's - major advances in sedimentological understanding helped elucidate the stratigraphy and structure of the thick greywacke succession in the 1950's. Petrological variation enabled subdivision of the greywackes (Walton 1955) and use of 'way-up' criteria in interpreting structure led to the rejection of Lapworths long-standing anticlinorium-synclinorium structural model (Craig and Walton 1959). Instead a system of major N-facing monoclines in which steep sub-vertical limbs alternate with intensely folded 'flat-lying' limbs possessing a sub-horizontal fold envelope was proposed (Craig and Walton 1959). This N-facing structure is in contrast to an overall stratigraphic younging southwards. The paradox is explained by the presence of major 'strike' faults cutting the succession and throwing down to the S. Subsequent detailed mapping of selected areas throughout the Southern Uplands (Kelling 1961, Gordon 1962, Rust 1965a,b, Weir 1968, Floyd 1975) led to the development of a petrographically defined lithostratigraphy locally within the greywacke succession and a regional pattern emerged generally lending support to the structural framework of Craig and Walton (1959). Attempts to unravel the history of deformation gave rise to two differing sequences. A dominant F_1 phase of folding and faulting with a minor F_2 phase and late kink band development was identified in the Ards Peninsula of Co Down (Anderson 1962). This was in contrast to the more complex polyphase deformation involving five distinct episodes described by Rust (1965a) and later Weir (1968) working in Galloway.

Mid-1970s - Present - plate tectonic theory was first applied to Southern Uplands interpretation after the landmark suggestion that the Caledonides had formed as the result of the opening and closure of a proto-Atlantic ocean (Wilson 1966). Dewey's far-sighted model (1969, 1971) proposed that NW-directed subduction beneath the Midland Valley had deformed a flysch sequence overlying the trench and adjacent ocean crust to produce the Southern Uplands. This was further defined as representing an underthrust pile of sedimentary wedges above a subduction zone similar to those described from modern arc systems (Mitchell 1974, Mitchell and McKerrow 1975). The Moffat Shales were recognised as the major decollement horizon within the thrust stack (Fyfe and Weir 1976, Weir 1977). Plate tectonic interpretation culminated with the proposal that the Southern Uplands represent a 'relict' accretionary prism (McKerrow *et al* 1977, Leggett *et al* 1979). This comprehensive and well argued model incorporated detailed stratigraphic and structural evidence from throughout the region as well as making analogies with modern accretionary fore-arcs.

Further work on the deformation history in Co Down supported the two phase sequence of Anderson (1962) and in addition identified a minor F_3 fold phase (Cameron 1981, Craig 1982). This interpretation received additional support from work by Stringer and Treagus (1981) in Galloway who resolved the polyphase deformation of Rust (1965a) and Weir (1968) into two fold phases equivalent to the F_1 and F_2 of Co Down. F_1 hinges were commonly observed to be transected by the S_1 cleavage (Phillips *et al* 1979, Stringer and Treagus 1980, Cameron 1981). Investigations by Oliver (1978, 1980-with Leggett, 1984-*et al*) established the presence of regional prehnite-pumpellyite facies metamorphism (locally zeolite facies) throughout the Southern Uplands-Down-Longford terrane.

The anomalous geology of the western end of the Down-Longford inlier always made it rest uneasy within the accretionary-prism model. Provenance studies in the Ordovician rocks of this area, backed up by the structural and stratigraphic evidence, led Morris (1979) to conclude their origin was more compatible with deposition and deformation in a marginal basin. Bluck (1983) used evidence from Silurian conglomerates in the Midland Valley to argue that the Southern Uplands represents an allochthonous accretionary prism thrust N over an arc terrane in the Midland Valley. Controversy - the Orlock Bridge Fault, defining the Northern Belt-Central Belt boundary, was examined along its entire length and was postulated as having a major sinistral strike-slip movement of at least 400 km resulting in the juxtaposition of two accretionary terranes of differing ages (Anderson and Oliver 1986). Murphy and Hutton (1986, Hutton and Murphy 1987) suggested a volcanic arc had once been present along the line of this fault, but had subsequently been removed by strike-slip motion. Iapetus, they proposed, closed at the end of the Ordovician, the Northern Belt representing either an accretionary prism or a deformed marginal basin, with the Central and Southern Belts resulting from end-Silurian imbricate thrust stacking of a succession basin. An alternative thrust-duplex model proposed by Stone *et al* (1987) envisages a two stage development to the Southern Uplands. Imbricate thrust-stacking of a marginal basin towards the end of the *Coronograptus cyphus* Zone caused uplift and the resultant formation of a foreland basin which underwent similar deformation at the end of the Silurian.

1.3 HISTORY OF RESEARCH IN THE SOUTHERN RHINNS

The first recorded observations made on the peninsula note the intense folding of the beds and their opposing sense of dip N and S of the Port Logan Bay area (NX09604080) (Carrick Moore 1848, 1856). Systematic mapping by Survey workers (Irvine 1872, Geike and Irvine 1873) attributed this change of dip to a major 'synclinal trough' with a corresponding anticline present 5 km to the N. This folding affected a succession consisting of:

(4) Dalveen Group

(3) Queensberry Grit Group

(2) Moffat Black Shale Group

(1) Ardwell Group

In a later re-survey (Peach and Horne 1899) the Moffat Shales were placed at the base of the succession and taken to be overlain diachronously by Caradoc Rocks in the N and the Queensberry Group succeeded by Hawick Rocks in the S. Each Moffat Shale was interpreted as an anticlinal inlier and detailed descriptions were given of the four sections along which they outcrop.

No major investigation of the geology has been undertaken since this work by Peach and Horne, although a number of minor localised studies have been carried out. Holgate (1943) examined the plutonic rocks of the 5 km^2 Portencorkrie Igneous Complex which he defines as consisting of an outer rim of pyroxene and hornblende diorite intruded by a central core of adamellite. Read (1926) noted that no mica lamprophyres were present N of a strike-parallel line lying immediately NW of the Mull of Galloway (NX15003050). A re-examination of the Ordovician rocks of the Rhinns led to a re-interpretation of the Ordovician-Silurian boundary as a faulted rather than stratigraphic contact (Kelling 1961). This contact was envisaged as a fault zone extending from Portayew to the northern end of Caringarroch Bay (NX04504950) and was named the Portayew Thrust. A detailed geochemical investigation of the Moffat Shales in the Southern Uplands included an inlier at the northern end of Clanyard Bay (NX10003820) as one of the sample localities (Watson 1976). Clockwise transecting S_1 cleavage was recorded in four folds exposed immediately S of a 0.5 km section of S-younging beds extending N from Ardwell Bay (NX07104530) (Stringer and Treagus 1980). Illite crystallinity and graptolite reflectance studies by Oliver *et al* (1984) established the presence of prehnite-pumpellyite facies metamorphism in the area. The Cairngarroch Fault at the southern end of Cairngarroch Bay was identified as the along-strike equivalent of the Orlock Bridge Fault in Ireland (Anderson and Oliver 1986) marking the position of the Northern Belt-Central Belt boundary.

1.4 AIMS OF THIS STUDY

In light of the present state of research in the Southern Uplands and in the part of the Rhinns studied, and with regard to the location and topography of the latter, a number of aims have been clearly envisaged for this study:-

(1) Mapping - to re-examine the geology of the area as described by the Geological Survey (Irvine 1872, Geike and Irvine 1873, Peach and Horne 1899) and to produce detailed up-to-date maps and an account of the geology in terms of stratigraphy, petrography, sedimentology and structure.

(2) Structural account - the excellent unbroken coastal exposure affords a rare opportunity to produce a very detailed and accurate structural section along a 23 km dip traverse of the Southern Uplands, and to produce a comprehensive account of the structure in that section.

(3) Correlation - the Rhinns are strategically placed between the main outcrop of the Southern Uplands to the NE and the Down-Longford inlier to the SW allowing accurate correlation between the two.

(4) Interpretation - in view of the differing tectonic interpretations now proposed for the Southern Uplands (McKerrow *et al* 1977, Murphy and Hutton 1986, Stone *et al* 1987), an examination of the geology of this well exposed and previously uninterpreted (in tectonic terms) area and its setting within a regional context will allow the detail of all three models to be tested without previous bias.

CHAPTER TWO : STRATIGRAPHY

2.1 INTRODUCTION

Stratigraphic studies in the Southern Uplands have previously concentrated primarily on the description and definition of locally based lithostratigraphies supplemented by biostratigraphic data where available (e.g. Kelling 1961, Anderson 1962, Hepworth 1981, Craig 1984). The structural complexity of the thrust terrane has exerted a strong influence on the stratigraphies described with most of the units defined having observable faulted rather than conformable boundaries. Many studies (e.g. Walton 1955, Kelling 1961, Floyd 1982) have placed heavy emphasis on the petrographic aspects of lithology with the advantage that the composition can be easily and accurately determined and comparisons made over large areas making regional correlation possible. This has borne fruit in providing the basis for a regional lithostratigraphy of the Northern Belt (see Stone *et al* 1987, Morris 1987), however has proved of little practical value in regional terms in the more uniformly silicic greywackes of the Central and Southern Belts. Biostratigraphy has been used to spectacular and lasting effect in the pelagic and hemipelagic sequences of Moffat Shale throughout the Southern Uplands since work by Lapworth in 1878. However it has only been used to limited effect within the sparcely fossiliferous greywacke successions (Warren 1964, Lumsden *et al* 1967) where its exclusive use can lead to confusion and contradiction with existing lithostratigraphies (see Walton 1983, p 121).

Strict application of stratigraphic principles (Hedberg 1976, Holland *et al* 1978) in a region like the Southern Uplands which has undergone complex deformation is not practicable. The tectonic disruption of the succession means boundary stratatypes can rarely be identified and the different lithologies tend instead to be separated by faults. Apart from this major failing, most conditions of formal stratigraphy are met in that units can be lithostratigraphically defined, are mappable, and have type sections. This form of stratigraphy with its important structural controls is referred to as a tectonostratigraphy (Kemp 1986).

In this study a remarkably high degree of lithological variation within the Rhinns has enabled complex subdivision of the rocks into tectonostratigraphic groups, formations and members (Maps A-D), with subdivision based equally on all aspects of lithology (Table 2.1). These tectonostratigraphic units are in most cases equivalent to the tectonic (fault-bounded) blocks into which the area is subdivided (Fig. 2.1), however emphasis has been placed on defining units as independent of structural controls as is possible with the intention of integrating them into a truly regional stratigraphy. This has been to achieved to a degree, particularly with regard to the younger formations which can be traced great distances both across-strike and along-strike despite the presence of major fault systems cutting through them.

Bedding within the NW-SE trending tectonic blocks has a sub-vertical dip and is intensely folded and faulted. Northwesterly younging predominates in the blocks to the NW of the Port Logan Bay Fault with the blocks to the SE typically southeasterly younging (Fig. 2.1). Despite this there is an overall progressive decrease in the age of successive blocks to the SE (Fig. 2.2). The stratigraphic base of a number of the blocks is marked by an imbricate zone of Moffat Shale.

This chapter begins with an examination of the position of the Ordovician-Silurian (Northern Belt-Central Belt) boundary. This is followed by a chronological (oldest to youngest) definition and description of the stratigraphic divisions. The Leadhills, Gala and Hawick Groups are each defined first followed by their formations and members. The Moffat Shale Group lithologies of each imbricate zone are described prior to the formation they stratigraphically underline. Finally this local tectonostratigraphy is placed in its regional context and the implications examined.

All graptolite information in the text is the result of either new collections made by the author (with identifications by Dr. I. Strachan) or recent collections made by

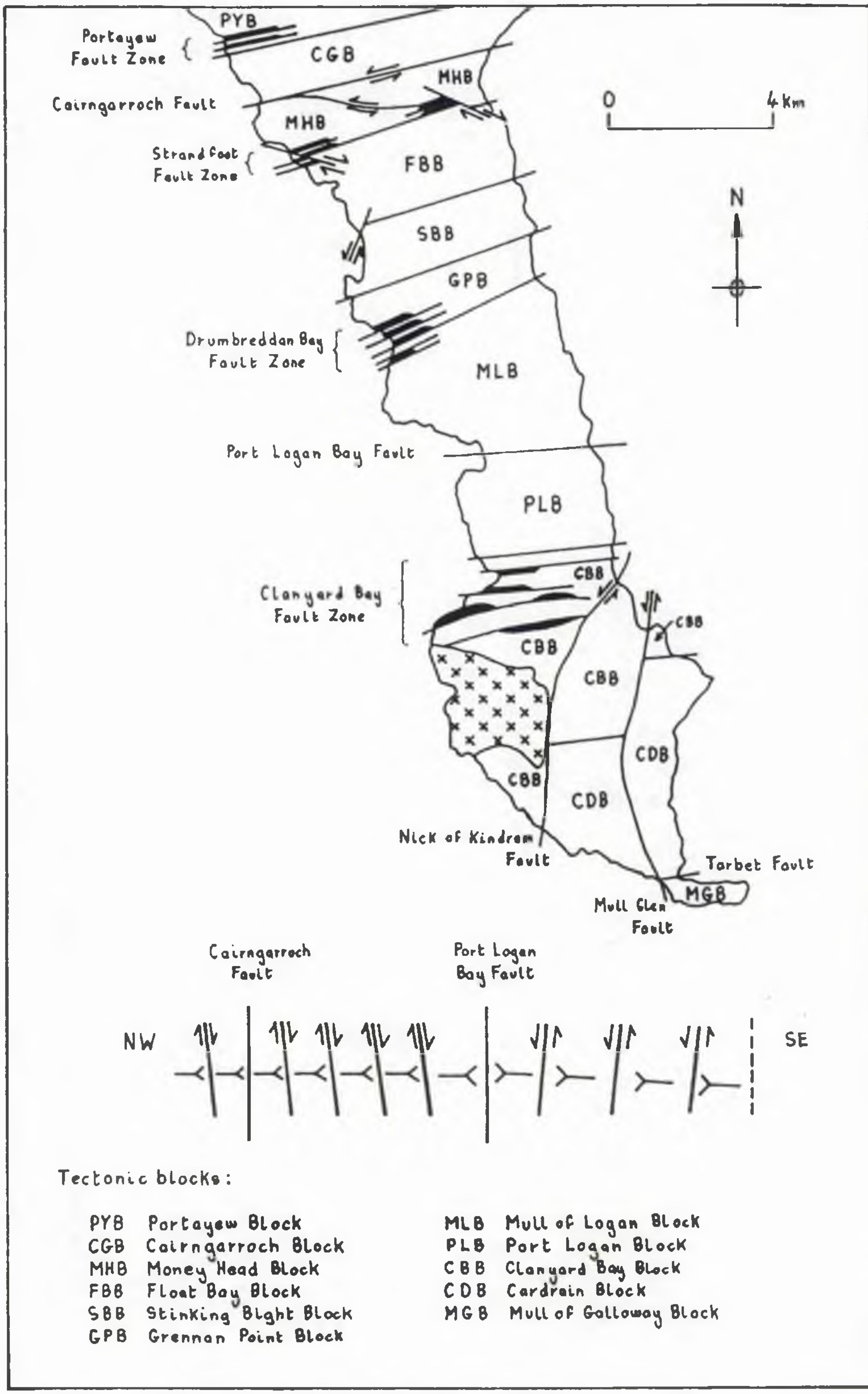


Fig 2.1: Tectonic structure of the southern Rhinns of Galloway Solid black - Moffat Shale Group; across pattern - granite-diorite intrusion.

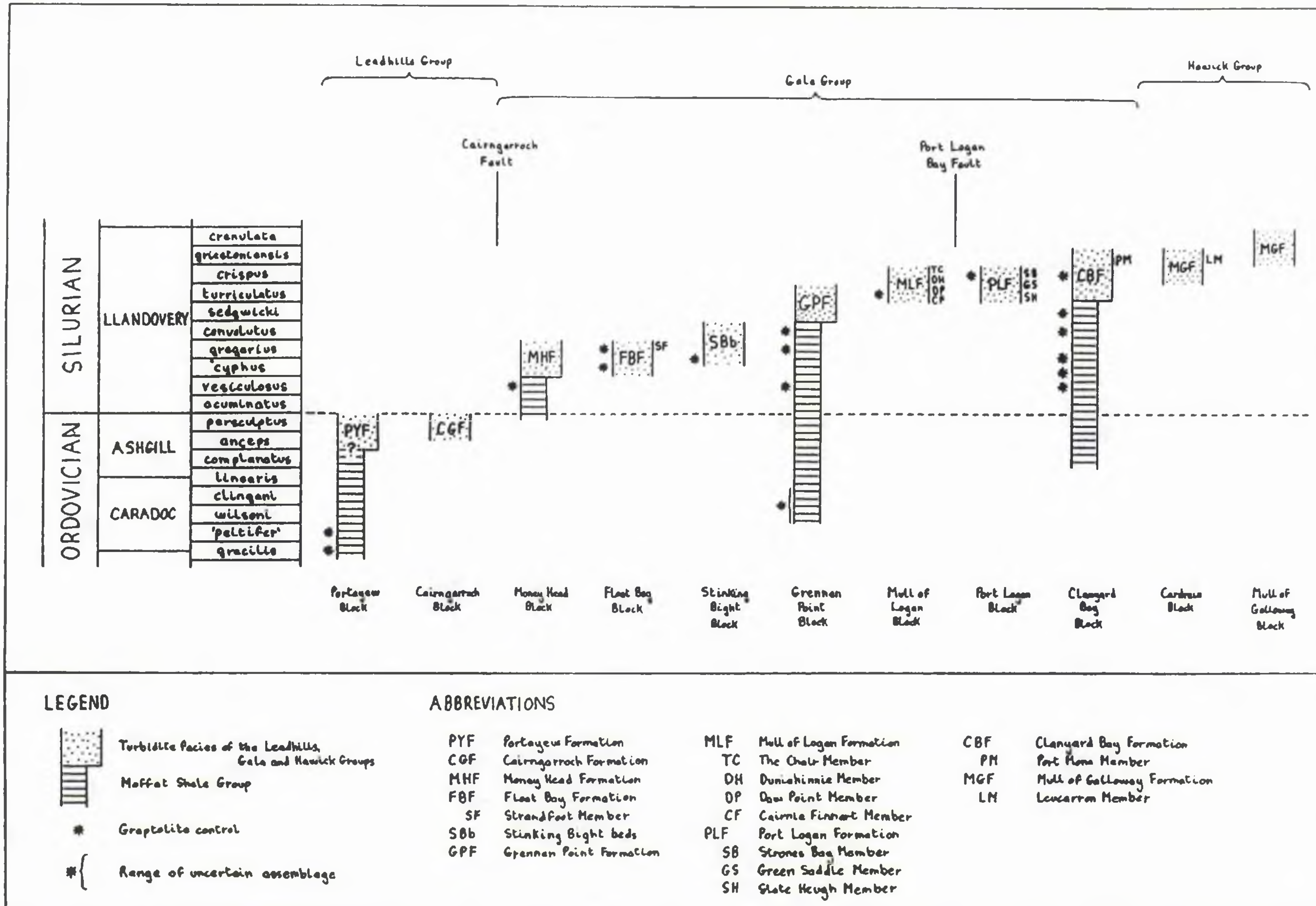


Fig 2.2: Tectonostratigraphy of the southern Rhinns of Galloway.

Formation	Member	Petrographic Character	Turbidite Facies	Dominant Grain Size	Bed Thickness	Packet Thickness	Dominant Bouma Sequence	Sand/Shale Ratio	Bed
Portayew Formation (base of)		Siliceous/lithic; high carbonate content in matrix	(1) C_1 (E)	Medium-coarse sands, silts and muds	<140 cm	D/F	T_{ae}	High	Coarse
			(2) G D_3	Muds and silts	<30 cm	40 m	NA, T_{de}	- -	-
Cairngarroch Formation		Hornfelsed; siliceous	D_2(D_1C_2G)	Medium-fine sands and silts	Typ. <60 cm, max 100 cm	D/F	T_{bd}, T_{bde}	V. high, amalgamation (metamorphic effect)	Rare d
Money Head Formation		Siliceous/lithic; sporadic enrichment in ferromagnesian minerals; low matrix content	(1) A_4 C_1 B_2 (A_3A_2)	Coarse-granular sands, rare pebbly sands	1-10 m +	D/F	T_{ae}, T_{abe}	V. high, frequent amalgamation	Coarse inverse
			(2) E B_2 (D_1)	Fine-v. coarse sands, silts and muds	2-100 cm	2-150 m	N/A, T_{ae}, T_{ce}, T_{be}	Low-v. high, sporadic amalgamation	Rare c
			(3) G (D_3)	Silts and muds	<20 cm	10-20 m	N/A, T_{de}	- -	-
Float Bay Formation		Siliceous/lithic	(1) C_1 (G B_2)	Medium-v. coarse sands, muds and silts	50-120 cm	D/F	T_{ae}, T_{abe}	Low-high	Coarse
			(2) G (D_1)	Muds, silts and rare fine -medium sands	<20 cm	2-30 m	N/A, T_{ae}	V. low	Rare c
	Standfoot Member	Siliceous/lithic	G D_3 (E)	Muds, silts and rare fine-coarse sands	<30 cm	D/F	N/A, T_{ae}	V. low	-
'Stinking Bight Beds'		Siliceous/lithic	(1) C_1 A_4 (B_2)	Medium-v. coarse sands	0.4-4 m +	D/F	T_{ae}, T_{abe}	V. high	Coarse
			(2) G C_1 D_3 (D_1 E)	Silts, muds and fine-coarse sands	Typ. <25 cm, max 100 cm	2-50 m	N/A, T_{abe}, T_{bce}, T_{bcde}	Low	Rare di and co
Grennan Point Formation		Siliceous/lithic	(1) C_2 C_1	Coarse-fine sand	Typ. 30-120 cm	D/F	T_{abe}, T_{abce}	Medium-high	Distrib coarse-
			(2) G D_3 D_1 (C_2E)	Silts, muds and fine-medium sands	<40 cm	2-25 m	T_{be}, T_{de}, T_{ae}	Low	Rare di
Mull of Logan Formation	Cairnie Finnart Member	Siliceous/lithic	(1) C_2 C_1	Fine - coarse sands	<100 cm	D/F	T_{ace}, T_{abce}, T_{ae}, T_{abe}	Low-medium (locally high)	Distrib coarse-
			(2) GE (D_1)	Muds, silts and fine sands	2-30 cm	1-30 m	N/A, T_{ae}, T_{ce}	V. low	Rare di
	Daw Point Member	Siliceous/lithic ferromagnesian mineral enrichment	(1) A_3 (A_4)	Coarse-granular sands	1-10 m +	D/F	N/A	V. high, typically amalgamated	Rare co and inv
			(2) EG	Silts, muds and coarse sands	<20 cm	<3 m	N/A, T_{ae}	Low	Rare co
	Dunishinnie Member	Siliceous/lithic; sporadic enrichment in minerals	(1) A_1 A_2 (F)	Conglomerate: matrix - ferromagnesian coarse sand, clasts - pebbles/boulders and slumped blocks (max (15 m x 25 m)	1 m + and unbedded	D/F	N/A	V. high	-
			(2) D_1 D_2 G A_2 A_4 (C_1 C_2)	Muds, silts and fine - pebbly sands	D and G facies <40 cm A and C facies 0.5-10 m +	90 m	T_{be}, T_{de}, T_{abe}, N/A	Low-high	Distribu coarse-
	The Chair Member	Siliceous/lithic; ferromagnesian mineral enrichment; low matrix content	(1) C_1 A_4 (A_2 A_3)	Medium-pebbly sands	1-10 m+	D/F	T_{ae}	High	Coarse- rare inv
			(2) G D_3 D_1 (E)	Muds, silts and fine-medium sands	<25 cm	Typ. 2-20 m, max 50 m	N/A, T_{ae}, T_{ce}	Low	Rare co
Port Logan Formation		Siliceous	(1) C_1 C_2	Fine-coarse sands	Typ. <1 m, max 3 m	D/F	T_{abce}, T_{abe}, T_{ace}	Medium-high	Coarse distrib
			(2) G (D_1)	Muds, silts and fine sands	<15 cm	<10 m	N/A, T_{ce}, T_{de}	V. low	-
	Slate Heugh Member	Siliceous	D_3 G D_1	Muds, silts and fine sands	Typ. <5 cm, max 15 cm	120 m	N/A, T_{de}, T_{ce}, T_{cde}	V. low	Rare d
	Green Saddle Member	Siliceous	D_3 G D_1	Muds, silts and fine sands	<10 cm	135 m	N/A, T_{de}, T_{ce}	V. low	-
	Strones Bay Member	Siliceous	D_3 G D_1 (D_2 C_2)	Muds, silts and fine sands	Typ. <30 cm, max 80 cm	150 m	N/A, T_{ce}, T_{de}, T_{ace}, T_{abe}, T_{cde}	Low	Rare d
Clanyard Bay Formation		Siliceous/lithic	(1) C_2 (C_1 D_1 G E)	Medium-fine sands muds and silts	<100 cm	D/F	T_{abe}, T_{ace}, T_{ae}, T_{ce}	Medium-high	Distrib
			(2) G D_3 (E)	Muds and fine-medium sands	<12 cm	15-40 m	N/A, T_{ae}, T_{ce}	Low	Rare d
	Port Mona Member	Siliceous	(1) C_1 B_2 C_2	Medium-fine sands	Typ. <150 cm, max 6 m	D/F	T_{abe}, T_{abce}, T_{ace}, N/A	Medium-v. high, rare amalgamation	Coarse
			(2) G E	Muds, silts and fine sands	<15 cm	10-40 m	N/A, T_{ce}	Low	-
Mull of Galloway Formation		Siliceous/lithic; high carbonate and matrix content	C_2 C_1 E (D_1 D_3 G)	Fine sands, silts and muds	Typ <60 cm, max 200 cm	D/F	T_{ace}, T_{abe}, T_{abce}, T_{ce}, N/A	Low-medium	Distrib coarse
	Leucarron Member	Siliceous/lithic; high carbonate and matrix content	(1) (as above)	"	"	"	"	"	"
			(2) B_2 C_1 (C_2 E)	Fine -medium sands, silts and muds	Typ. 30-120 cm, max 200 cm	3-12 m	T_{ace}, T_{ae}, T_{ade}, T_{ad}, N/A	V. high-sporadic amalgamation	Coarse distrib

D/F: dominant facies. N/A: not applicable. V: very. Typ: typically. Max: maximum. For: Turbidite Facies - see Walker and Mutti (1973) and Mutti and Ricci-Lucchi (1975). For: Sand/Shale Ratio - see Ricci-Lucchi (1975). For: Bed Grading - see Middleton (1967).

TABLE 2.1 - LITHOLOGICAL CHARACTERISTICS OF THE FORMATIONS

Dr. A.W.A. Rushton and Dr. D.E. White and contained in BGS reports PD86/160, PD87/46 and PD87/47. A recent re-examination of the Survey collections of last century (Irvine 1872, Geike and Irvine 1873, Peach and Horne 1899) has been made by Dr. I. Strachan and Dr. A.W.A. Rushton and is contained in BGS reports PD87/49 and PD87/50. Graptolites at one locality S of Float Bay (NX06404696) were collected by Mr. P. Davies and identified by Dr. B. Rickards. All graptolite identifications along with their locality and age are given in Appendix 1. The Walker and Mutti turbidite facies scheme (Facies A-G, 1973) is utilised throughout this chapter excepting Facies C for which the Mutti and Ricci-Lucchi subdivision into C_1 and C_2 (1975) is substituted. Subordinate facies are shown in brackets. Sand/shale ratios are described as high (>1), medium (*c.*1) or low (<1) as defined by Ricci-Lucchi (1975).

2.2. ORDOVICIAN-SILURIAN BOUNDARY

Within the Southern Uplands the Ordovician-Silurian boundary is well exposed at a number of localities within the Moffat Shales, e.g. see Barnes, Anderson and McCurry (1987) - (Appendix 2). Indeed the sequence described by Lapworth at Dobbs Linn (1878) has recently been designated the boundary stratatype between the two systems (Bassett 1985). This is in stark contrast to the greywacke succession in which the boundary is nowhere precisely located and its position(s) has (have) been a matter of speculation (see Anderson and Oliver, 1986).

The Rhinns affords the best exposure in Scotland across the boundary rocks though opinions as to its position and nature have been varied. The earliest survey workers regarded all the L. Palaeozoic rocks on the Rhinns as Llandeilo in age and mapped only one lithological boundary at Scarty Head (NX04494850) (Greike and Irvine 1873).

Peach and Horne (1899) were the first to recognise that a distinct belt of Ordovician rocks (Northern Belt) was succeeded to the S by a belt of mostly Llandovery rocks (Central Belt) though they 'occasioned considerable difficulty in drawing a base line for the northern limit of the Llandovery'. They considered the boundary to be a tightly folded bedding plane and their 10 miles to 1 inch map accompanying the 1899 Memoir positions it striking NE from a point just S of Cairngarroch Bay (NX04504870). By contrast when Sheet 3 (1 mile to 1 inch) was eventually published in 1923 the boundary had been moved 1200 m NW to just N of Cove Hip (NX04044990).

Kelling (1961) presented evidence that the boundary was faulted forming a thrust zone extending from just S of Portayew (NX04005000) to the northern end of Cairngarroch Bay (NX04304960). He named the fault zone the Portayew Thrust and envisaged it had a throw of at least 1.5 miles to the S. He further raised the possibility that the boundary might also occur conformably in the northerly younging greywackes N of the fault (1961, p 43), although no graptolite evidence for Silurian has yet been found in the Northern Belt to support this.

The boundary was redefined by Anderson and Oliver (1986) as a major fault zone exposed in the Rhinns at Calves Hole (NX04644905) at the southern end of Cairngarroch Bay, 1 km S of the position indicated on the 1982 edition of 1:50,000 Sheet 3. The fault can be topographically traced striking NE from Calves Hole for 800 m along a prominent valley. The Orlock Bridge Fault (as named by Anderson and Oliver 1986) has a unique mylonitic fault fabric unlike any of the other prominent faults in the Southern Uplands and is interpreted as a major sinistral strike-slip terrane boundary with at least 400 km movement along it. Calves Hole is the better exposed of the two Scottish localities where the fault fabric is found, with best exposure reserved for the more ductilely deformed Irish continuation of the fault.

The northernmost occurrence of Silurian graptolites along the coast is in the Moffat Shale inliers of the 250 m wide Strandfoot Fault Zone (NX05204815) which are *Cystograptus vesiculosus* Zone age (Map A, Fig. 2.2). No graptolites are found for 2.2 km N from here after which the Moffat Shales of the 420 m wide Portayew Fault Zone (NX03905020) yield Glenkiln and Hartfell faunas and Barren Mudstone lithologies suggesting a youngest age of at least *Dicellograptus complanatus* Zone (Fig. 2.2). As the greywackes, siltstones and shales between the two fault zones young exclusively to the NW (*cf.* F_1 folding described by Anderson and Oliver 1986, p 215) the boundary must lie within them and must also be a fault.

The boundary as depicted by the Survey in the 1923 and 1982 editions of Sheet 3 (the latter influenced by Kellings work, 1961) equates with an intense zone of brecciation containing sheared Moffat Shales, and formed the southern limit of the Portayew Fault Zone (NX03974995). Stratigraphically this is an unlikely position for the boundary as it would necessitate a massive jump of four graptolite zones in the base of greywacke sedimentation between two adjacent structural blocks, something atypical of both the Rhinns and Southern Uplands generally. Detailed examination of the coastline supports Anderson and Oliver's assertion (1986) that a major fault, the Cairngarroch Fault, is present at Calves Hole at the southern end of Cairngarroch Bay (NX04644905). The intensity of deformation displayed by the fault make it unique, with a strong foliation and quartz veining developed along its partially exposed trace at Calves Hole producing a mylonitic texture. A wide zone of brecciation associated with the fault is intruded by large granitic and dioritic masses, one of which extends inland along the fault trace for over 1 km. The lithologies differ markedly across the fault (see Table 2.1). To the N are thin to moderately bedded, medium to fine grained, siliceous greywackes (C_2D_1) contact metamorphosed by the intrusions to a black, glassy, biotite-rich hornfels. S of the fault are thick, massive, coarse greywackes (B_2C_1) and conglomerates (A_4) intercalated with thin bands of siltstones and coarse greywackes (E). These rocks are relatively rich in pyroxenous and basic clasts and have not undergone contact metamorphism. The evidence supports interpretation of the Cairngarroch Fault as a major shear zone and the most probably Ordovician-Silurian boundary.

Tracing the fault inland is difficult due to the thick covering of drift and resultant lack of exposure. Only at Thorters Reservoir (NT61006940) 200 km to the NE did Anderson and Oliver (1986) once again manage to accurately locate the distinctive Orlock Bridge Fault fabric. In the Rhinns the fault is topographically evident for over 1 km striking NE from Calves Hole along a steep-sided valley before being submerged beneath a drumlin filled landscape. In this study an attempt has been made to trace the fault as accurately inland as the poor exposure will allow. The lithology is rarely discernible from the meagre field outcrops and as a result thin sections were made from samples collected from them. Immediately noticeable is that much of the outcrop consists of a dark, glassy hornfels that in thin section is rich in biotite though never totally reconstituted. The disused quarries 200 m S of Cairngarroch (NX05924964) and immediately W of Ballochalee Glen (NX09005060) contains the most highly metamorphosed rocks with a gradual decrease in grade evident to the N and S of the latter quarry. The exposure indicates a broad belt of hornfels about 1 km wide stretching ENE along-strike for at least 5 km from Cairngarroch Bay (see Map A). No intrusive mass is exposed inland to account for the metamorphism though the roof zone of a granitoid complex is exposed on the coast and it seems likely the hornfels overlies a linear extension of this. The linear nature of the hornfels belt strongly suggests the intrusion has entered a zone of brecciation seen associated with the fault along the coast and thus the belt provides a vital indicator as to the position of the fault inland.

Further petrological analysis of the samples has revealed differences in composition that provide more accurate information as to the trace of the fault. A sample taken from an outcrop in a field 250 m NE of Balgreggan (NX08825047) is markedly rich in pyroxenous and basic clasts as are most of the samples taken from outcrops to the S of it. Samples taken from the disused quarry 200 m to the NE of this outcrop (NX09005060) and from the Eldrig Burn at Grid References (NX08805065) and (NX07955075) are rich in siliceous clasts and contain no pyroxenous material or basic clasts. These petrological differences match those encountered N and S of the fault along the coast and suggest its inland trace lies in the unexposed 80 m wide (across-strike) tract between the outcrop in the field above and the disused quarry NE of it (NX09005060) (see Map A). Interestingly this is the most intensely metamorphosed part of the hornfels belt.

An examination of the rocks exposed in the overgrown gorge gouged out by the Cairnwell Burn 900 m S of Balgreggan (NX08654935) (Fig.2.3) revealed a succession of imbricately repeated Moffat Shales (G) sandwiched between well bedded massive greywackes (C_1). This when traced SW along-strike is seen to be a continuation of the Strandfoot Fault Zone. 200 m downstream at Gruzy Glen (NX08844942) a tributary valley enters the main valley and is the topographic expression of a NW-SE trending wrench that slices through the imbricate zone dextrally displacing it by at least 250 m. Working northwestwards up this valley a thick sequence of Moffat Shales is sporadically exposed along its southwestern side while across the fault to the NE is a sequence of massive greywackes. Fault drag has given the bedding exposed along the glen an anomalous WNW-ENE strike. At the head of the glen where the burn bifurcates (NX08714957) (see Fig. 2.3), a sequence of Moffat Shales at least 50 m thick has been intensely sheared by anastomosing shear surfaces into microlithons with a rare phyllonitic fabric developed. The intensity and uniformity of the deformation within the wide shear zone emphasise its distinctiveness and shows marked similarities with the fabric of the Cairngarroch Fault. The shear

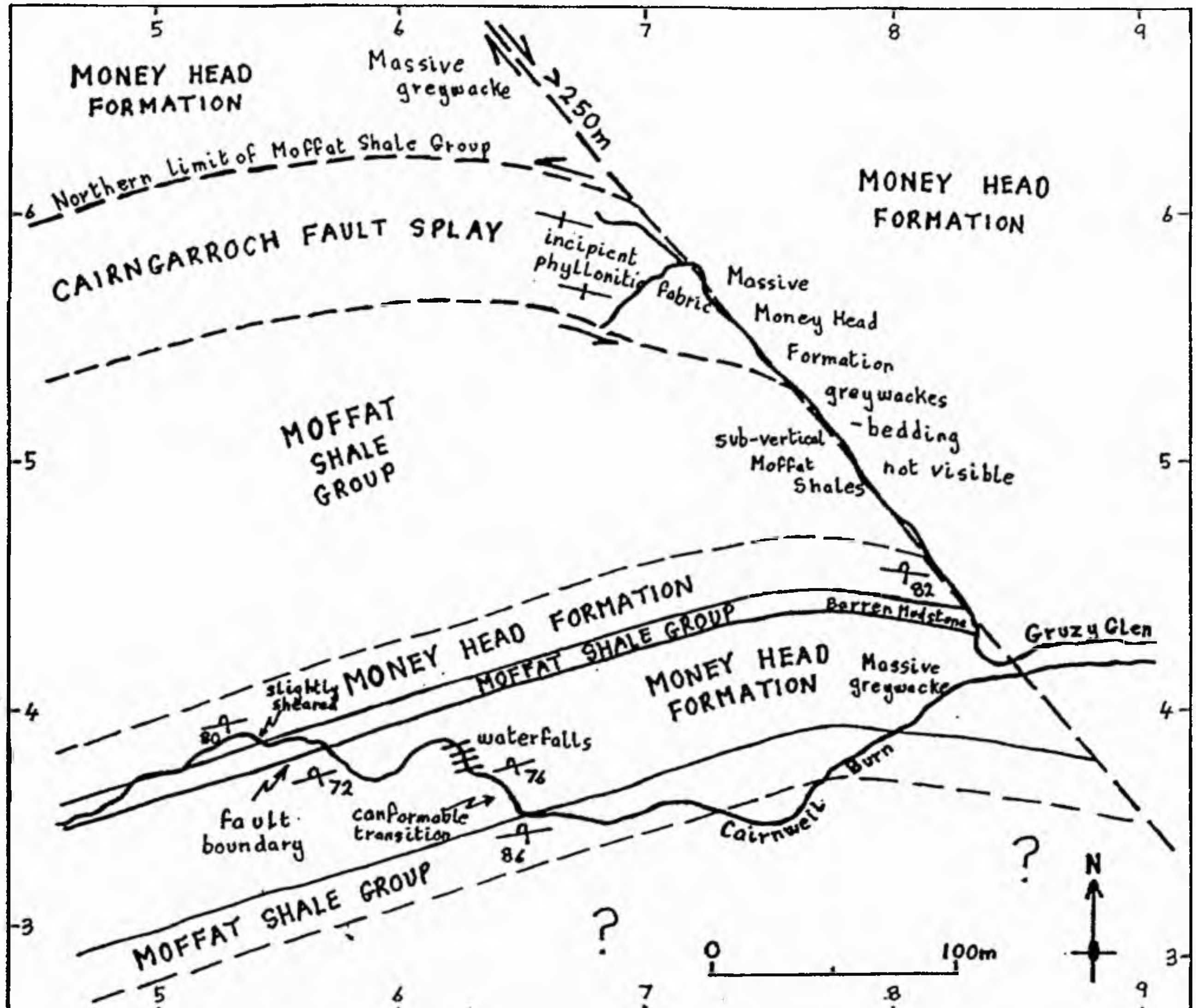


Fig 2.3: Map of the Moffat Shale Group imbricate zone in the Cairnweil Burn - Gruzy Glen area (NX0849).

surfaces possess the same anomalous trend as the bedding elsewhere in the glen, though a lack of exposure precludes further detailed description of the shear zone.

The petrological evidence suggests the boundary located 300 m NE of Balgreggan (NX08955055) is the Cairngarroch Fault and Ordovician-Silurian boundary. It is directly along-strike from the fault at Calves Hole and the presence of the pyroxenous greywackes immediately S of it is a distinctive feature seen regionally throughout the Southern Uplands (Walton 1955, Morris 1987). The 1.2 km long steep-sided valley extending inland from Calves Hole and NE of Balgreggan are the only places where the boundary has been accurately located and on Map A the fault trace has been positioned by extrapolating between these localities with the dextral wrench deemed to cut it at Grid Reference (NX08095040).

The shear zone affecting the Moffat Shales 700 m due S of Balgreggan (NX08714957) is remarkable in that no equivalent structure crops out along-strike on the coast. Indeed only the Cairngarroch Fault 1 km to the NE at Calves Hole shows the same intensity of deformation. These facts indicate that the shear zone is in fact a splay of the Cairngarroch Fault. The possibility that splay faulting might be associated with the Scottish continuation of the Orlock Bridge Fault was postulated by Anderson and Oliver (1986) who thought it might explain the general decrease in width and impressiveness of the fault moving northwestwards along its trace. In view of the major displacements and importance now attributed to the fault (Anderson and Oliver 1986, Murphy and Hutton 1986) it is not unlikely that a splay would migrate the 1 km S out of massive, brittle, strain resistant greywackes into a belt of relatively ductile, easily strained siltstones and shales already weakened by faulting. For most of its length it is likely the splay is positioned along the thick northernmost Moffat Shale sequence of the Strandfoot Fault Zone (see Map A), before arbitrarily branching westwards to join the main fault along a small valley that approaches it 100 m SE of Cairngarroch Croft (NX05724938). The angular relationship between the splay fault and main fault indicate it has undergone a sinistral strike-slip movement. Most of the movement is believed to have taken place prior to dyke intrusion dated at *c* . 425-395 Ma (Rock *et al* 1986) however as the fault cuts the intrusions and displaces the metamorphic aureole at Calves Hole some of the movement is clearly later.

Establishing the relative stratigraphic importance of the boundary fault has proved contentious (see Floyd *et al* 1987 and Anderson and Oliver 1987). Floyd *et al* (*op. cit* . p 219) erroneously challenge the *C. vesiculosus* Zone age attributed to the Moffat Shales of the Strandfoot Fault Zone by McCurry (in Barnes *et al* 1987 - (Appendix 2)) using information gained from Peach and Horne's Memoir of 1899, however the information used refers to a locality well to the S of where they intend and is from a different tectonic block. Floyd *et al* (*op. cit.*) state 'the only unequivocal evidence concerning the age of the black shale to greywacke transition across the Ordovician-Silurian boundary is of a jump from *Pleurograptus linearis* Zone along the Fardingmullach Fault (Floyd 1982) to *Coronograptus gregarius* Zone at the southern margin of the Hartfell tract (Leggett *et al* 1979), a step of seven zones to be taken up within at least three tracts, across a present-day distance of 10 km'. This statement and others like it in the paper serve to highlight the importance of the Rhinns section in advancing our understanding of the fault, its environs and stratigraphic significance. As the Moffat Shale/turbidite transition in the Standfoot Fault Zone has been determined as *C. vesiculosus* Zone, for the first time the age of a tectonic block immediately adjacent and to the S of the fault is known (Fig. 2.2). The age of the Cairngarroch Block immediately N of the fault is not known, but in the block N of this the Moffat Shales of the Portayew Fault Zone young at least to *D. complanatus* Zone. This means that a jump of at most four graptolite zones is taken up within the three tracts across the 2.1 km between the Strandfoot and Portayew Fault Zones (Fig. 2.2).

If as present evidence suggests there are no Silurian greywackes within the Northern Belt, then there must be a jump of at least three zones across the Cairngarroch Fault (Fig. 2.2). However even if we allow for the possibility of there being unrecorded Silurian greywackes within the Northern Belt, it still requires two steps of two zones each between the three adjacent blocks, which represent anomalously though not uniquely large steps between blocks. There is therefore a significant stratigraphic jump across the Cairngarroch/Orlock Bridge Fault, though it is not as great as previous workers have suggested (Leggett *et al* 1979, Fig. 2; Anderson and Oliver 1986, p 204-205). Even so the fault is clearly a uniquely different structure and of much greater stratigraphic importance than the other tract-defining faults defined by Leggett *et al* (1979) in the Southern Uplands.

2.3 TECTONOSTRATIGRAPHY OF THE RHINNS

2.3.1 Moffat Shale Group

This 100 m thick sequence of pelagic and hemipelagic sediments (first described by Lapworth in 1878 from type localities at Dobbs Linn and Craigmichan Scaurs NE of Moffat) was divided into what are three separate formations. The oldest of these, the Glenkiln Shales, consists of 6 m of black, pyritous, graptolitic shales, grey cherts, pale mudstones and tuffs of *Nemograptus gracilis* and *Climacograptus peltifer* Zone age. Above this the Hartfell Shales consist of a lower sequence at least 20 m thick of siliceous black shales, grey cherts and intercalated metabentonite bands overlain by a 28 m sequence of unfossiliferous pale grey mudstones (Barren Mudstones) containing rare, thin, graptolitic black shale horizons. The Hartfell Shales range in age from *Climacograptus wilsoni* to *Glyptograptus persculptus* Zone with the boundary between Upper and Lower within *P. linearis* Zone. The Birkhill Shales form the top 43 m of the sequence and consist of graptolitic black shales and mudstones with numerous pale, thin metabentonite bands. These are replaced towards the top of the succession by unfossiliferous grey mudstones. The Birkhill Shales range in age from *G. persculptus* Zone to within *Monograptus turriculatus* Zone with the boundary between Upper and Lower within *C. gregarius* Zone.

2.3.1.1 Moffat Shale Group of the Portayew Fault Zone

A reconnaissance survey of the Moffat Shales in this 420 m wide fault zone has revealed a 250 m wide tract containing Glenkiln and Hartfell Shales in association with some greywackes from the overlying Portayew Formation (Map A). The northern boundary of this tract is in faulted contact with the N-younging mudstones (G) and laminated siltstones (E) of the Portayew Formation at the northern end of Portayew Bay (NX03855038). Black shales are sporadically exposed to the S for 90 m across the shingle beach and in the cliffs ending at a fault zone containing brecciated grey cherts and siltstones and intruded by a thick felsite dyke. Peach and Horne (1899, p 409) identified Glenkiln age graptolites from the shales just N of the fault zone. For 130 m S from the dyke the bedding becomes brecciated and disorganised and is tectonically complicated but the lithologies are consistent with the Hartfell Shales and in particular the Barren Mudstones of the Upper Hartfell Shales. Graptolites collected from this area are mostly indeterminate, but one *Orthograptus* sp. (*quadrimucranatus* type), suggests a Hartfell age. Thin, poorly graded greywackes (C_1 (E)) become interspersed with the shales southwards, but the exact relationship between these units is not known. A further 30 m of black shales and grey mudstones are present S of the greywackes before ending abruptly at a faulted contact with sheared, N-younging, laminated siltstones E of the Portayew Formation 200 m S of Portayew (NX03935015). Graptolites collected by Peach and Horne from within this 250 m tract are stated to have indicated Glenkiln and Hartfell ages (Peach and Horne 1899, p 409). A re-examination of what remains of their collection (Appendix 1) confirms an *N. gracilis* or C. *peltifer* Zone (Glenkiln) age and indicate a possible

Hartfell age. The lithological identification of Barren Mudstones suggests the shales young at least to *D. complanatus* Zone. Thin slivers of pyritous black shales are present in the fault breccia at the southern limit of the Portayew Fault Zone 400 m SE of Portayew (NX04004998) and possibly represent the sheared remnants of black Moffat Shales.

2.3.2 Leadhills Group

This group consists of all the greywackes and associated turbidite facies (excluding Moffat Shales) cropping out between the Leadhills Line/Fault and the Orlock Bridge Fault (Fig. 2.4). Medium to coarse grained greywackes up to 1.5 m thick are separated by well developed shale partings producing relatively low sand/shale ratios with occasional more massive sandy units present. As the succession youngs thinly bedded sequences of well graded, fine grained greywackes and shales and thick sequences of blue-grey laminated siltstones become important. Petrographically the group divides into an older volcaniclastic sequence and a younger siliceous sequence. The Leadhills Group has a Caradoc-Ashgill age extending from *C. wilsoni* Zone to uppermost Ordovician.

2.3.2.1 Portayew Formation

This formation extends from the fault defining the southern limit of the Portayew Fault Zone 400 m SE of Portayew (NX04004998) for 3 km northeastwards to Port of Spittal Bay (NX02005215). A brief description is given here of the southern edge of the formation as exposed in the immediate vicinity of the Portayew Fault Zone (Map A). The succession extending N for 175 m from the southern boundary fault is composed of extensively sheared, pale, medium to coarse grained greywackes (C_1) and laminated siltstones (E) that are also seen cropping out within the 250 m wide tract of Moffat Shales to the N, as described previously. N of the Moffat Shales pale-grey/blue colour banded silts and mudstones (G) and laminated siltstones (D_3) dominate the sequence. Well graded, fine to medium grained sandy units less

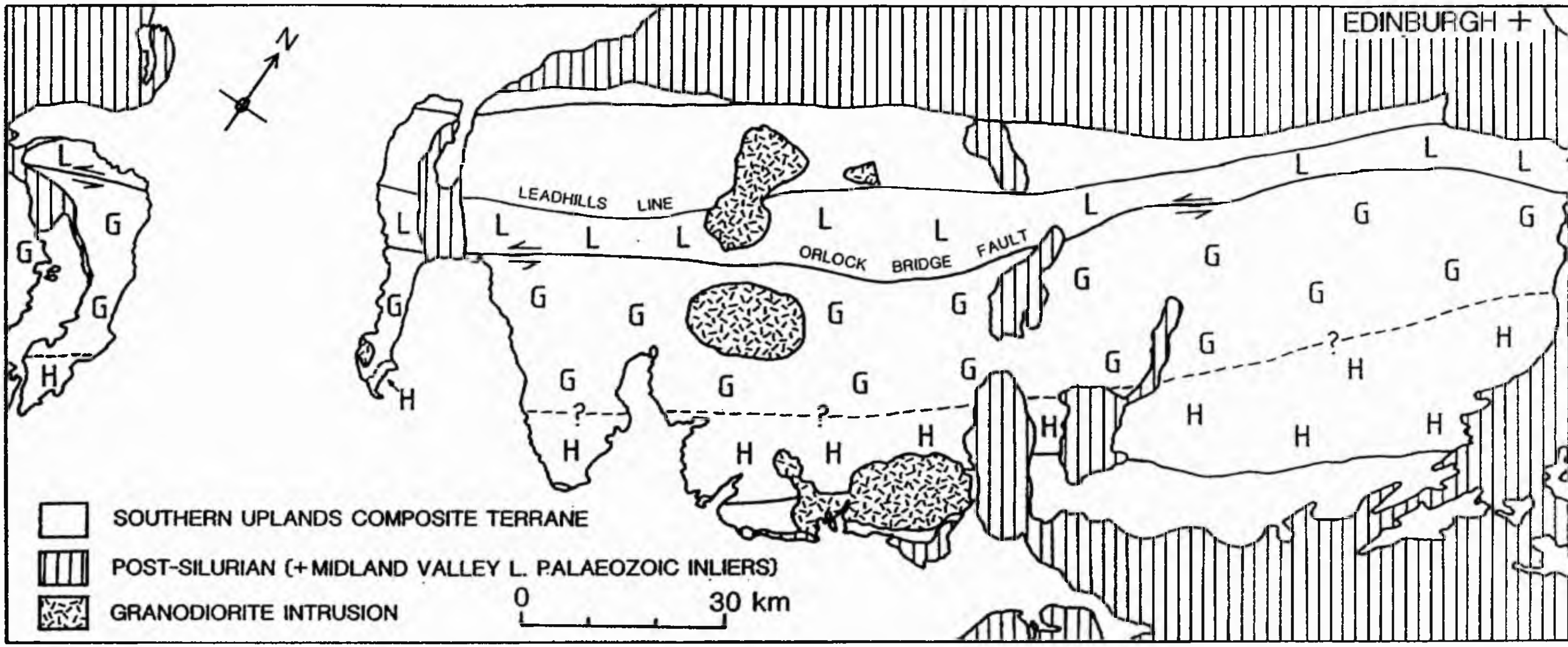


Fig 2.4: Map showing the distribution of the Leadhills Group (L), Gala Group (G) and Hawick Group (H) in the Southern Uplands and Co Down. Moffat Shale Group not shown.

than 1 m thick (C_1) appear upwards in the succession although the overall sand/shale ratio remains low at less than 1. Petrographically the formation is characterised by siliceous clasts with important acid volcanic and metamorphic components, and a carbonate matrix which imparts a pale colour to the greywackes. Although the formation has proved unfossiliferous it is believed to be younger than the *D. complanatus* Zone youngest age attributed to the Moffat Shales it overlies, but is not thought to range as high as the Llandovery (Fig. 2.2).

2.3.2.2 Cairngarroch Formation

Boundaries, thickness and type locality - the southeastern (lower) boundary of this formation is the Cairngarroch Fault and the northwestern (upper) boundary is the fault marking the southern edge of the Portayew Fault Zone. The formation has a thickness of at least 650 m and the type locality is the coastal outcrop between the cave 400 m S of Portayew (NX04004998) and Calves Hole (NX04644905) (Map A).

Lithology - over practically the whole of its outcrop this formation consists of a uniform, hardened, black, glassy biotite-rich hornfels, the result of thermal metamorphism by the intrusions associated with the Cairngarroch Fault. Sedimentary structures are only rarely obliterated and the succession is seen to consist of well bedded, medium to very fine grained base-missing turbidites (D_2 (D_1 C_2)) with beds typically less than 60 cm thick though reaching a maximum of 1 m (Table 2.1, Fig. 2.5). Bouma T_{bd} and T_{bde} sequences dominate the monotonous though distinctive succession with T_c divisions of cross-lamination and convolute bedding infrequently present and sometimes occurring together within the same bed. The degree of metamorphism generally decreases away from the Cairngarroch Fault, but only at Eldrig Glen (NX08965075) is a marked decrease noticeable. Here the greywackes are a blue-grey colour and a rare 10 m+ sequence of blue-grey mudstone (G) is present.

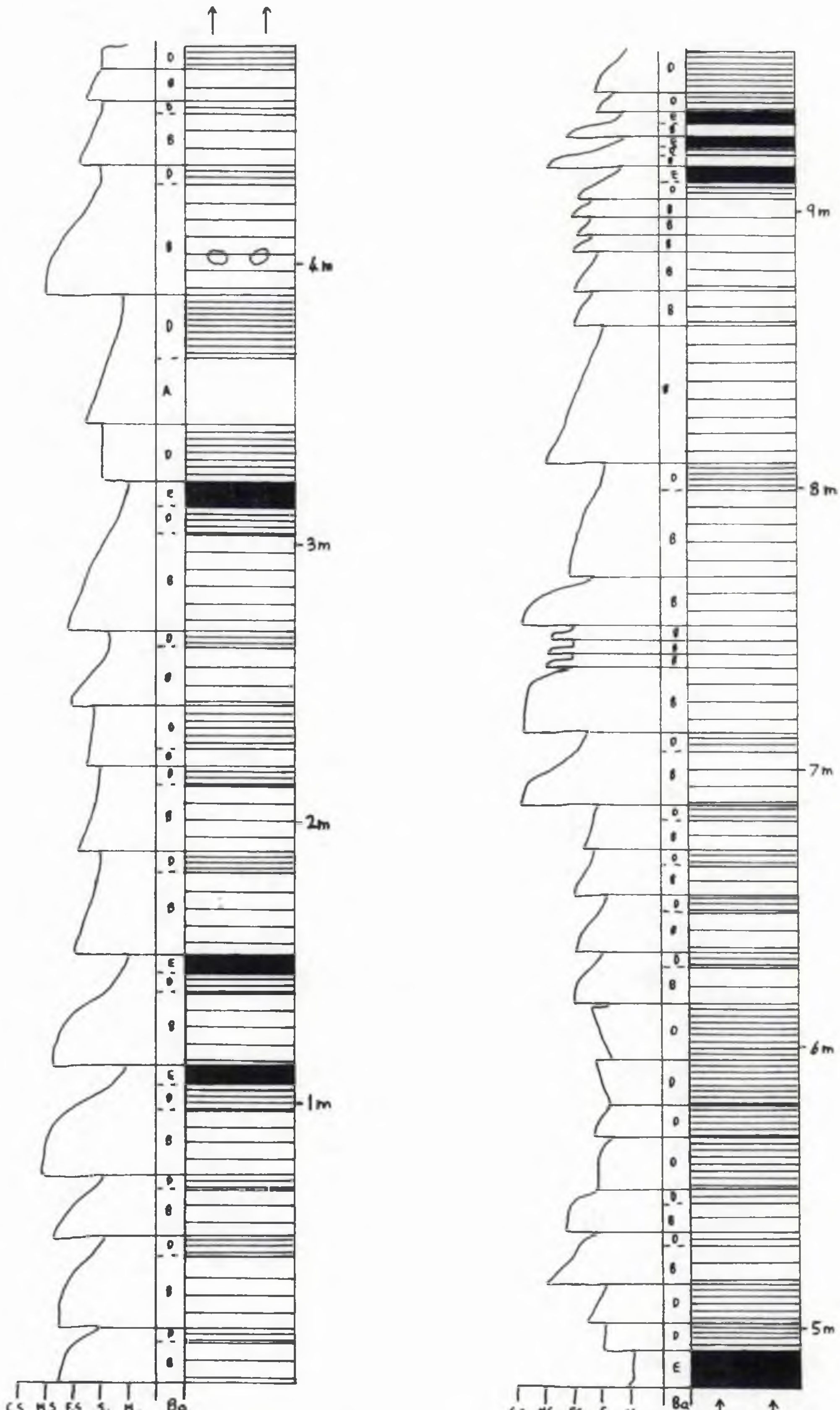


Fig 2.5: Section showing the homogenous base missing turbidites of the Cairngarroch Formation at Cairngarroch Bay (NX04674925). (For explanation of section notation see fold-out after Fig 3.22(B), and hereafter)

Petrographically the turbidites are rich in siliceous material, particularly monomineralic quartz, metamorphic quartzite, and acid igneous clasts, as well as in shale clasts. Where most intensely altered to a hornfels the groundmass consists of fine welded quartz with new growths of biotite though still retains remnants of the original clasts.

Age - this formation has proved unfossiliferous though its strongly siliceous character equates it with the Shinnel Formation to the NE along-strike (Floyd 1982, Stone *et al* 1987). The presence of a major fault along its southern boundary, over which Silurian sediment is found, suggest the Cairngarroch Formation is of late Ashgill age (Fig. 2.2).

2.3.1.2 Moffat Shale Group of the Strandfoot Fault Zone

The Strandfoot Fault Zone (Map A) is characterised by a number of unique and spectacular features not present at other exposed Moffat Shale imbricate zones. These are:-

(1) it is the only place where Moffat Shales are seen to underlie and thus date the structural block immediately S of the Orlock Bridge Fault;

(2) a major shear zone, believed to be a splay of the Orlock Bridge Fault, has preferentially developed along a section of the northernmost and widest of the Moffat Shale inliers; and

(3) at Strandfoot (NX05174813) itself a 'tectonic mixing' has caused Moffat Shales from the base (S) of the Money Head Block to become incorporated in the top (N) of the Float Bay Block immediately to the S.

The Strandfoot Fault Zone and associated Moffat Shales are primarily exposed at two localities: (A) Strandfoot, and (B) Cairnweil Burn (NX08634937). The former was recorded by Peach and Horne (1899, p 187-189), the latter is a new record.

(A) Strandfoot - the Strandfoot Fault Zone is exposed over a 250 m wide section of coast and is split in two by an E-W trending dextral wrench with a throw of at least

200 m (Map A). In the cliffs to the N of this fault are two poorly exposed inliers of Moffat Shales sandwiched between Money Head Formation greywackes. The northernmost of these inliers consists of 10 m of badly sheared and weathered black and grey shales and mudstones. It is clearly faulted to the N against massive, N-younging greywackes (A_4). A 30 m sequence of similar N-younging greywackes occurs to the S though its southern boundary is not exposed. S of this is a second 10 m Moffat Shale inlier though it is much overgrown and access to it is difficult. It consists of thinly bedded black mudstones and shales. The nature of its boundaries is unknown, but coarse, massive greywackes are present to the S before the exposure ends under a covering of drift.

In the foreshore and cliffs S of the wrench fault, five more Moffat Shale inliers are anomalously incorporated into the siltstones and mudstones of the Strandfoot Member at the stratigraphic top of the next tectonic block to the S, the Float Bay Block. All the inliers have steep, N-dipping fault boundaries and appear to form tectonic lenses within the Strandfoot Member. The northernmost inlier is exposed near the high tide mark 10 m NW of a prominent stack (NX05184814) and is a 2 m x 1 m strike elongate lens of black fissile shale with thin bentonite bands. Immediately S of the stack across a 50 cm thick felsite dyke is a 16 m Moffat Shale sequence of black, massive, pyritous mudstones containing abundant poorly preserved graptolite fragments. A third 20 m thick Moffat Shale inlier is present 12 m to the S and is remarkable in containing in cliff section a fault lens (17 m x 12 m) of Strandfoot Member siltstones around which the Moffat Shales bifurcate (Plate 2.1(A)). The inlier consists of flaggy, black and dark grey mudstones and black, fissile shales with intercalated pale, soft bentonites. Large oblate calcareous concretions (17 cm x 12 cm x 6 cm) occur commonly within the sequence and are flattened parallel to bedding. A fourth 2 m thick inlier of intensely sheared Moffat Shales is present on the foreshore a few metres to the S and may be a sheared remnant connected at depth to the inlier to

Plate 2.1(A): Tectonic interlensing of the Moffat Shale Group (MSG) and Strandfoot Member (SFM) in the Strandfoot Fault Zone at Strandfoot (NX05244810)

Plate 2.1(B): The southernmost tectonic inlier of the Moffat Shale Group (MSG) in the Strandfoot Fault Zone (NX05344794) forming the boundary between Strandfoot Member siltstones (SFM) to the NW and Float Bay Formation greywackes (FBF) to the SE.

the N. The most southern inlier in this section occurs 170 m to the S in the foreshore and cliffs at Grid Reference NX05344794 and consists of about 10 m of sheared, fissile, block shales and pale bentonites. The inlier marks the boundary between the Strandfoot Member siltstones to the N and greywackes of the Float Bay Formation to the S (Plate 2.1 (B)). Its boundaries are clearly faulted and the greywackes to the S are intensely sheared and brecciated.

(B) Cairnweil Burn - previously unrecorded Moffat Shales were identified in the Cairnweil Burn and the tributary valley joining it at Gruzy Glen (NX08854942) (Map A, Fig. 2.3). The Moffat Shales are imbricated along with overlying Money Head Formation greywackes. They have an anomalous E-W strike caused by drag from a major dextral wrench with a throw of at least 250 m that trends NW-SE along the tributary valley. A description will be given of the section up the Cairnwell Burn followed by that in the tributary valley providing an almost continuous S to N traverse through the Strandfoot Fault Zone in this area.

The first exposure in the Cairnweil Burn occurs 170 m upstream from its confluence with the tributary valley and consists of a couple of poor outcrops of a coarse greywacke. 20 m beneath the waterfalls (NX08664935) and to the S of the greywackes is the first 10 m broken exposure of black mudstone and shale of the Moffat Shale Group (Figs. 2.3 and 2.6). This is followed by a break in the exposure until a point 4 m beneath the base of the waterfall. After this is a sequence in which coarse, sole marked greywackes (C_1) up to 50 cm thick are interbedded with block shale units (G), with the sand/shale ratio going from low to high in the 4 m to the waterfall. Above this is a 40 m sequence of massive 1 m thick greywackes (C_1 A_4) with a very high sand/shale ratio. These greywackes end abruptly at a steep southerly dipping bedding-parallel fault and are succeeded by an 8 m sequence of massive, well-bedded, black Moffat Shales. These Moffat Shales end at a point where a fence

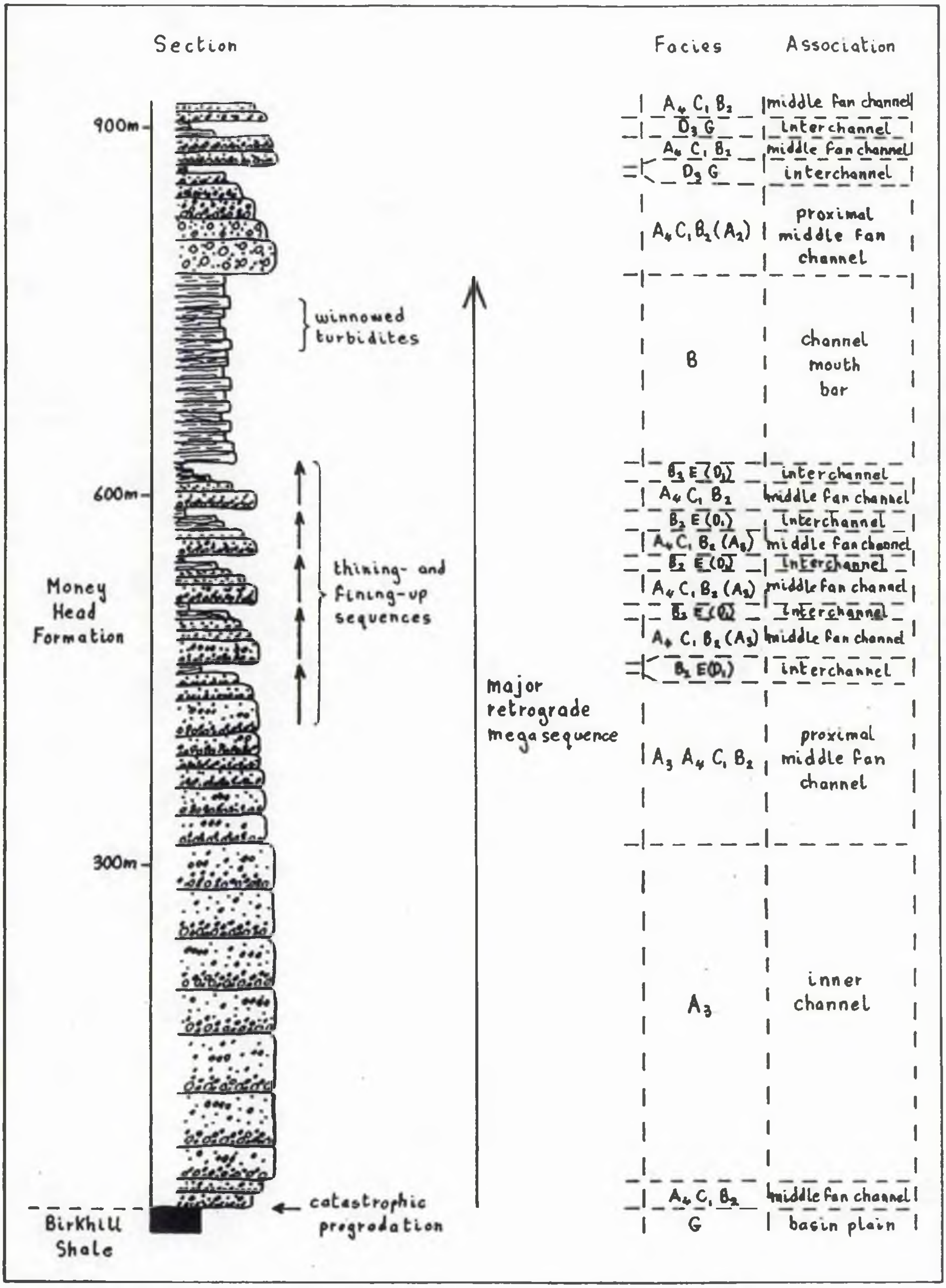


Fig 2.6 (A): Diagrammatic section through the Money Head Formation.

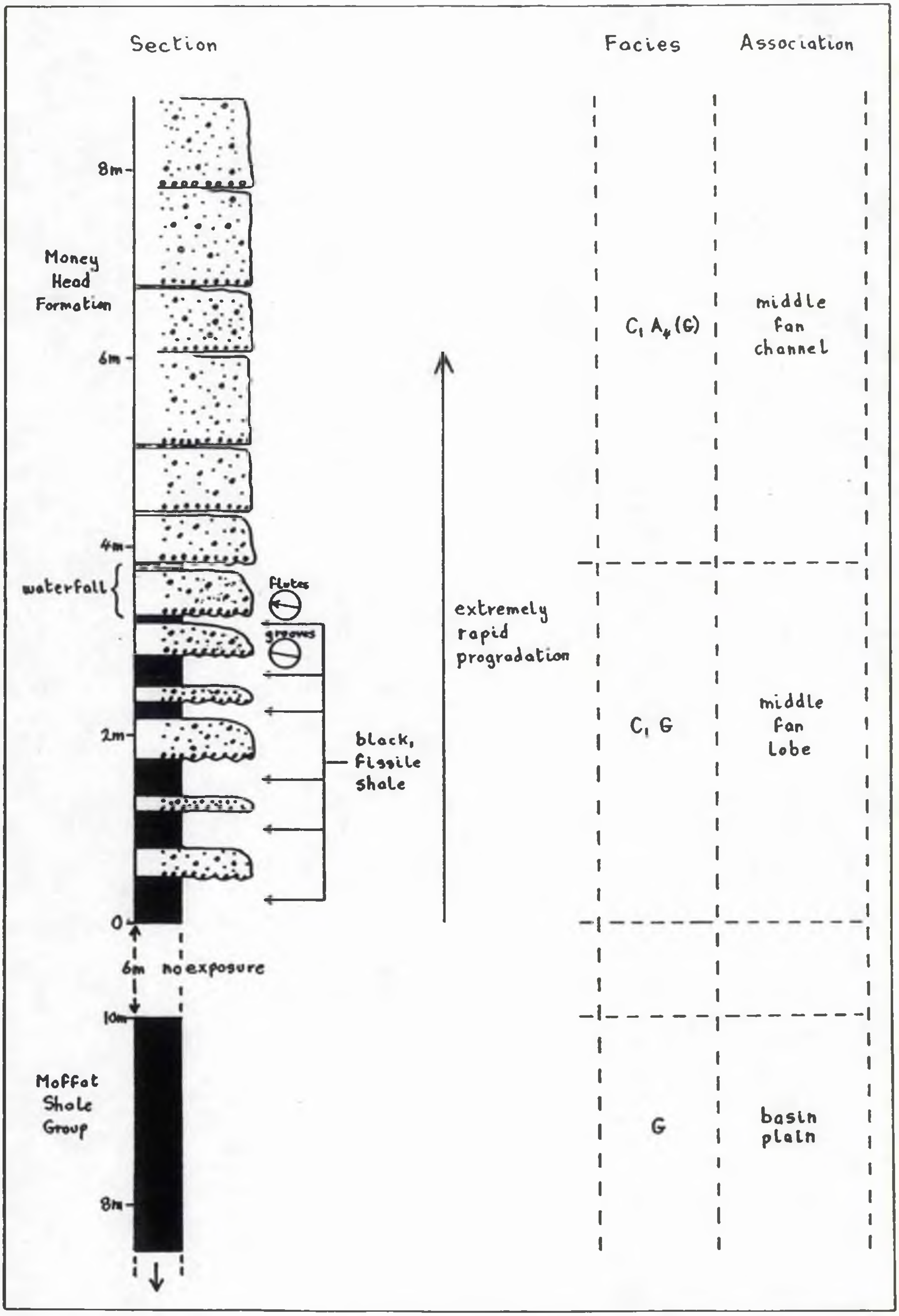


Fig 2.6 (B): Conformable transition between the Moffat Shale Group and Money Head Formation at the waterfall in the Cairnweil Burn (NX08664935).

crosses the burn (NX08554938) and are overlain by a 10m sequence of sheared and brecciated greywackes at the top of which the exposure in the burn ends.

The Cairnweil Burn section is believed to wholly underlie those on either side of the tributary valley. The rocks exposed to the NE of the wrench that runs along the valley are massive greywackes (A_4 C_1) of the Money Head Formation. On the southwestern side of the valley a couple of metres of grey-green mudstones lithologically similar to the Barren Mudstones are exposed near its confluence with the Cairnweil Burn. To the NW of this is a 10 m sequence of badly weathered black Moffat Shales after which there is 100 m of no exposure. At the head of the valley where it bifurcates (NX08704958) a 50 m sequence of intensely sheared black Moffat Shales are part of a shear zone believed to be a splay of the Cairngarroch Fault. This is the most northerly outcrop of Moffat Shales in the Strandfoot Fault Zone and the next exposure in a field 100 m to the NW is of Money Head Formation greywackes.

In general the Moffat Shales at Cairnweil Burn are coherent and not sheared like those at Strandfoot and the Moffat Shale/turbidite transition is well exposed at the waterfall. There is a marked difference in width in the northernmost inlier, at least between the two localities, though the exact relations between them are unknown. The fault zone is expressed topographically across the Rhinns as a linear depression through the drumlins and this, along with a few poorly exposed outcrops in the fields 400 m W of Mid-Float (NX06204835), has been used to extrapolate its position between the two localities on Map A.

Age - graptolite fragments have been found in most of the inliers at Strandfoot, however the intense shearing of the shales means in most cases they cannot be identified. Some identifiable specimens have been collected from the second and third inliers S of the wrench (Appendix 1) and indicate a Lower Birkhill age. Collections by BGS (Appendix 1) from the second inlier S of the wrench yielded specimens co-existent in the *C. vesiculosus* and *Coronograptus cyphus* Zones. However the dominant lithology is of massive black mudstones with rare bentonites which typifies Lapworths (1878) 'vesiculosus Flags'. Along with the restricted fauna this strongly suggests the Birkhill Shales here are of *C. vesiculosus* Zone age.

Despite their greater suitability, the Moffat Shales at Cairnweil Burn have not as yet been collected for graptolites, though some graptolite fragments have been found. The lithologically identified Barren Mudstones at the southwestern end of the tributory valley are the only evidence for Ordovician from the Strandfoot Fault Zone. Thus the age range of the Moffat Shales in the fault zone is believed to be from Upper Hartfell to at least *C. vesiculosus* Zone (Fig. 2.2) and the dominant lithology is Lower Birkhill Shale.

2.3.3 Gala Group

This group consists of all the greywackes and associated turbidite facies (excluding Moffat Shales) cropping out between the Orlock Bridge Fault and the northern boundary of the Hawick Group (Fig. 2.4). It is dominated by thick or massive, coarse-grained greywackes and conglomerates with typically high sand/shale ratios. Sequences of finer and more thinly-bedded siltstones and shales are developed, particularly in the younger outcrop to the S. Petrographically the group has a strongly siliceous character though contains pyroxenous horizons which are particularly common in the oldest sequences along the northern edge of the outcrop. The Gala Group has a Llandovery age extending from *Akidograptus acuminatus* Zone to *Monograptus crispus* Zone with an anomalous *Monograptus griestoniensis* Zone age recorded from Grieston Quarry 8 km SE of Peebles.

2.3.3.1 Money Head Formation

Boundaries, thickness and type locality - the southeastern boundary of this formation is the Strandfoot Fault Zone and the northwestern boundary is the Cairngarroch Fault. A major E-W trending splay extends from the Cairngarroch Fault into the northernmost Moffat Shale inlier of the Strandfoot Fault Zone effectively subdividing the formation into southwestern and northeastern sectors (Map A). The exact relationship between the rocks on either side of this splay is unknown. The formation has a thickness of 900 m and the type locality is the coastal section between Calves Hole and Strandfoot, with the important Moffat Shale/Money Head Formation transition best displayed at the waterfall in the Cairnweil Burn (Figs. 2.3 and 2.6).

Lithology

(A) SW of the splay fault - the succession is dominated by pale, massive, coarse greywackes that develop a distinct pink or orange-brown crust when weathered (Table 2.1, Fig. 2.6). The lower 600 m of the succession is a massive, thickly-bedded (1-10 m+) sequence of coarse to granular greywackes (A_4 C_1 B_2 (A_3)) with very high sand/shale ratios and frequent amalgamation (Plate 2.2 (A)). Mudstone rip-up-clasts are commonly seen towards the base of the beds which typically have a Bouma T_{ae} sequence. The section gets progressively younger northwards and 300 m above the base of the section at a point 100 m NW of Slannax (NX04834833) the first of four bands of thinly interbedded mudstones and sandstones occur (Plate 2.2(B)). These vary in thickness from 3 m to 10 m and in the relative proportions of mudstone and sandstone they contain. However they are distinctive in having a much lower sand/ shale ratio, in being thinly-bedded (typically less than 20 cm) and in being composed almost entirely of turbidite facies B_2 and E with D_1 developed locally. The fine to coarse grained greywacke beds are often lenticular and commonly possess the coarse parallel lamination typical of Facies B beds (see Plate 2.2(B)). Convolute and cross lamination are present in equal proportions in the thinner and finer D_1 greywackes.

600 m above the base of the section at a point 130 m S of Dun Rock the lithology abruptly changes to a more thinly-bedded (less than 1 m) yet equally massive sequence with a very high sand/shale ratio and frequent amalgamation. Beds are fine to coarse grained Facies B greywackes with common internal parallel lamination. This section is 150 m thick and is overlain by a similar thickness of massive, thickly-

Plate 2.2(A): Massive sand units typical of the lower 600 m of the Money Head Formation. Scarty Head (NX04534837)

Plate 2.2(B): Thin-bedded massive sands and mudstones in the Money Head Formation at Slannax (NX48270488). Note convolute lamination in upper mudstone unit and lenticular bedding and coarse lamination in the lower sandstone units.

bedded greywackes (A_4 C_1 B_2) containing a few intercalated intraclast conglomerate beds (A_2) at the northern end of Fox Rattle (NX04614885). Two 20 m bands of thinly-bedded mudstones and siltstones (D_3 G) are exposed in the cliffs to the N (NX04584899) and S (NX0454893) of Anns Cave at the northern end of the section, to the N of which the lithology becomes sheared and brecciated as it nears the Cairngarroch Fault.

Despite its siliceous and lithic rich character the Money Head Formation has a distinctive and variable petrography. The lower 600 m are sporadically enriched in ferromagnesian minerals and in particular pyroxenes. Although these are present in low numbers in the top 300 m of the formation, the turbidites here are instead characterised by being well sorted and winnowed with a low matrix content (less than 15%) distinguishing them as arenites rather than greywackes (Pettijohn 1975). Ore mineral defined laminae are a common feature of these beds whilst the whole formation is rich in metamorphic clasts (particularly quartzite) which often constitute 10% in volume of the sandstone.

(B) NE of the splay fault - the poor and sporadic exposure in this area consists entirely of pale, massive, coarse greywackes excepting 30 m broken exposure of sheared and darkened metamorphased shales at Kennel Plantation (NX08835025). Bedding is only rarely discernible within the outcrops which become noticeably more hornfelsed towards the Cairngarroch Fault.

Petrographically the siliceous and lithic rich greywackes are distinctively enriched in pyroxenes and amphiboles, although in a much less sporadic manner than SW of the splay. Where altered to a hornfels the rock is characterised by a welded quartz groundmass surrounding new growths of biotite. Total recrystallisation is never seen and remnants of the original clasts remain present.

Despite the possibility of a major sinistral movement having taken place along the splay fault, the lithology and petrography either side of it are remarkably similar.

The only differences are the presence of a hornfels to the NE of the fault and the increased occurrence of ferromagnesian minerals in the beds on this side of it. It therefore seems reasonable to regard the rocks on both sides of the splay as belonging to the Money Head Formation.

Age - no graptolites have been found from this formation, but as it overlies Moffat Shales that young at least to the *C. vesiculosus* Zone (Fig. 2.2), it is assumed younger than this. Its pyroxenous nature equates it with the 'Pyroxenous Group' (Walton 1955), Craignell Formation (basic division) (Cook and Weir 1980) and Kilfillan Formation (Gordon 1962) all found to the NE along-strike along the northern edge of the Central Belt.

2.2.3.2 Float Bay Formation

Boundaries, thickness and type locality - the poorly exposed strike fault at Ersbals Caves (NX07954621) forming the southeastern boundary of this formation has been sinistrally displaced at least 100 m by a N-S trending wrench cutting through the foreshore at Salt Pans Bay (NX06934617) (Map A). The northeastern boundary is the Strandfoot Fault Zone and at Strandfoot itself is the E-W trending dextral wrench that displaces the fault zone. Estimating the thickness of the formation is difficult due to the unknown degree to which the faulting (some major) and folding within the block repeat the stratigraphy. However it is believed to be at least 1500 m thick. The type locality is the coastal section between Salt Pans Bay and Strandfoot (Map A).

Strandfoot Member - the southernmost Moffat Shale inlier of the Strandfoot Fault Zone exposed 40 m SE of Goodwifes Cave (NX05344794) forms the southeastern boundary of the member, with the E-W trending dextral wrench at Strandfoot forming the northwestern boundary. The member is at least 200 m thick and occurs at the very top of the Float Bay Formation. The type locality is the coastal outcrop between the two boundaries defined above.

Lithology - much of this formation is severely brecciated and boudinaged as the result of extension during deformation. The lower 90 cm is exposed W of the N-S trending sinistral wrench in Salt Pans Bay (Map A) and consists of boudinaged beds and shear lozenges up to 3 m x 1.5 m of thick, medium to coarse grained greywackes (originally Facies C_1) 'floating' in an argillite matrix of sheared dark grey shales and siltstones ($G(D_3)$). Overlying this is a more coherent 30 m sequence of hardened, light to dark grey shales and mudstones ($G(D_3)$) thinly interbedded with rare, fine to medium grained greywacke beds (E) less than 5 cm thick. Above this a sequence at least 600 m thick extending to Island Buoy (NX06474690) consists of thick (typically *c.* 1 m) medium to very coarse grained greywackes (C_1) with a high sand/shale ratio. In its more massive parts it contains coarse parallel-laminated Facies B_2 type greywackes. This is the dominant facies of the formation which overall develops a progressively lower sand/shale ratio as it gets younger (Table 2.1). The sequence between Island Buoy and Dove Cave (NX05904732) is at least 280 m thick and although the sand/shale ratio remains relatively high, distinct bands up to 15 m thick (though typically less than 5 m) of blue to grey laminated shales and mudstones ($G(D_3)$) and rare thin greywackes (E) are common. At Castle Naught (NX06124725) a 10 m outcrop of black fissile shale, poorly exposed to the S, but younging conformably into brecciated greywackes to the N, is lithologically identical to black Moffat Shales and may be associated with the faulting in Float Bay to the S. The intensely brecciated, boudinaged and folded sequence extending from Dove Cave to the Strandfoot Member has a thickness of at least 300 m. The sand/shale ratio is much lower at approximately 1 and the sequence consists of 60-120 cm thick, medium to very coarse grained, sole marked greywackes (C_1) interbedded with equally thick units of dark grey shales and mudstones (G). Spaced at distances of between 12-100 m apart these shale/mudstone units develop into distinct 12-20 m bands of interbedded fissile shale, mudstone and rare, thin fine greywackes ($G(D_1)$) with numerous calcareous concretions present.

Peach and Horne (1899, p 187-189) correctly interpreted these shale/mudstone bands as interbedded units within the greywacke succession, but wrongly identified them as Moffat Shales.

Petrographically the greywackes of the Float Bay Formation display a monotonous siliceous character being composed of more than 40% quartz with little variability.

Strandfoot member - this consists of a thick sequence of hard, thin to massive mudstones and siltstones (G(D_3)) that are often well laminated and vary from blue to dark grey in colour though commonly weather to light grey or black. Rare, ungraded, medium grained greywacke beds (C_1) less than 10 cm thick are present towards the base of the succession where they are intensely brecciated. Flattened, bedding-parallel calcareous lenses up to 150 cm x 2 cm are commonly present as are more typical oblate and rounded (12 cm x 10 cm x 9 cm) calcareous concretions (See Table 2.1).

Age - graptolites have been collected from three of the shale/mudstone bands in the vicinity of Float Bay (see Appendix 1). These indicated either a *C. vesiculosus* or *C. cyphus* Zone age, with the latter being the more probable.

Peach and Horne (1899, p 187-189) attributed a *Monograptus gregarius* Zone age to graptolites collected from what they interpreted as Moffat Shales cropping out between Dove Cave and Strandfoot. A recent find by BGS (Appendix 1) from the Strandfoot Member 70 m NW of Goodwifes Cave (NX05264805) confirms a *C. gregarius* Zone age for these rocks.

The Float Bay Formation thus has a *C. cyphus* and *C. gregarius* Zone age (Fig. 2.2) and the biostratigraphy supports the sedimentary way-up evidence and structure by indicating the formation youngs progressively northwards. There does not appear to be a substantial age difference between the Float Bay Formation and Money Head Formation (Fig. 2.2).

2.3.3.3 'Stinking Bight beds'

Boundaries, thickness and type locality - the southeastern boundary is the strike fault extending NE from a well defined gully on the coast at Hackle Rock (NX06834552). The northwestern boundary is the strike fault sinistrally displaced by the N-S trending wrench on the foreshore at Salt Pans Bay. The total thickness of the sequence is about 900 m and the type locality is the coastal outcrop between Hackle Rock and Salt Pans Bay (Maps A and B).

This succession has been much affected by both wrench and strike faulting and the exact relationship between the various units is not known. This in conjunction with the extreme variability of the lithologies (Table 2.1) mitigates against giving it formation status.

Lithology - the lower 20 m of the succession are exposed NW of the gully at Hackle Rock and form a massive sequence of medium to dark grey graptolitic shales ($G(D_3)$) interbedded with a few thin (less than 15 cm), fine grained greywackes (E) and a coarse, massive 4 m thick sandy unit (A_4). Conformably above this is a 40 m sequence of thinly bedded shales, massive mudstones ($G(D_3)$) and rare bentonites interbedded with well-graded, medium to coarse greywackes up to 120 cm thick (C_1). Overall the sand/shale ratio is low. The sequence N of this extending from The Hooies (NX06804562) to the sandy beach at Ardwell Bay (NX07004600) is extensively faulted and brecciated, but consists predominantly of thick to massive, medium to very coarse greywackes (C_1A_4) with a high sand/shale ratio and frequent amalgamation. The outcrop at the northern end of the beach at Ardwell Bay (NX07104628) is a folded 40 m sequence of interbedded shales (G) and well-bedded, fine to coarse greywackes (C_1), less than 50 cm thick, that ends after 70 m at an unexposed but topographically evident strike fault. The 600 m thick sequence extending from this fault to Salt Pans Bay is extensively faulted and in places brecciated. It consists predominantly of thick medium sand to granule grade greywackes (C_1 A_4 (B_2)) and coarse, massive sand bodies (A_4) up to 15 m thick. Although the sand/shale ratio is generally very high, towards the N of the outcrop units of interbedded shales (G) and thin (less than 15 cm), fine to medium greywackes (D_1(C_1)) appear, reaching a maximum thickness of 50 m at Tard Stone (NX07004588). The northern outcrop is extensively iron stained imparting a red colour to the exposure, though this staining ends abruptly at the N-S wrench marking the boundary with the Float Bay Formation.

The 'Stinking Bight beds' display typical Gala Group compositional characteristics: they are strongly siliceous (more than 40% quartz) and the most important lithic components are acid igneous clasts (7-8%).

Age - the 20 m thick shale-dominated unit at the very base of the succession immediately N of the gully at Hackle Rock contains a poorly preserved graptalite fauna collected by BGS (Appendix 1). These indicate the age as near the boundary between *C. cyphus* and *C. gregarius* Zone (Fig. 2.2).

(2.3.1.3.) Moffat Shale Group of the Drumbreddan Bay Fault Zone

The Drumbreddan Bay Fault Zone is over 1 km wide and spans the boundary of the Grennan Point and Mull of Logan Blocks (Maps B and A). The fault zone contains from Moffat Shale inliers of mostly Birkhill Shales, the three northernmost of which provide a superb, well exposed example of imbricate faulting and repetition of stratigraphy. The southernmost of the three inliers is on the SE side of the rocky promontory in Drumbreddan Bay (NX07774360) and is exposed SW of a NW-SE trending dextral wrench with a throw of 6 m. The 10 m wide inlier of black fissile shales is visible only at the very lowest tides and even then is extensively weathered and covered with seaweed. The northern and southern boundaries of the inlier are both faulted and to the S a few metres of grey mudstones from the Mull of Logan Formation are exposed before the outcrop disappears beneath a cover of sand. To the N grey mudstones and shales are quickly succeeded by a 70 m sequence of well-bedded N-younging Grennan Point Formation greywackes before these too are covered by the sands and pebbles of a 70 m wide beach.

The second Moffat Shale inlier is exposed at the northwestern end of this beach and extends for 100 m along the southeastern side of the rocky promontory of Grennan Point (NX07704374) before being sinistrally displaced 25 m by a N-S trending wrench. It is remarkable in displaying a conformable transition from Moffat Shales into overlying Grennan Point Formation greywackes with only minor faulting affecting the succession (Fig. 2.7). The Moffat Shales are 9 m thick and consist entirely of black, graptolitic, fissile shales interbedded with bentonite horizons up to 40 cm thick and spaced at less than 20 cm apart. Conformably overlying these, although the boundary has been irregularly sheared by a minor fault, are 3 m of well-laminated and colour banded shales in browns, greys and pale shades (D_3(G)). Groups of four or five, closely-spaced, mm-thick, dark laminae spaced at 3-4 cm intervals enhance the visible banding. Above these though again separated by a minor fault, are 3 m of interbedded grey siltstones (D_1) and thin laminated shales (D_3) up to 4 cm thick which soon grade into strongly sole-marked, medium to coarse greywackes less than 60 cm thick (C_2). This N-younging greywacke sequence continues for 130 m across Grennan Point before ending at a distinct faulted syncline on the southeastern side of Grennan Bay (NX07494376) (Fig. 2.8) marking the southeastern limit of the most northerly of the Moffat Shale inliers. A number of N-S trending sinistral wrench faults displace this 100 m wide inlier by a maximum of 10 m while some of the strike faults within it have late minor sinistral and dextral movements (Fig. 2.8).

Immediately N of the faulted syncline are 20 m of flaggy black mudstones intercalated with rare bentonites and containing a sparce graptolite fauna. These end at a strike fault developed along a 12 cm thick bentonite layer and are succeeded by a 40 m sequence of interbedded black mudstones, fissile shales and common bentonites. A further 12 m of more massive, flaggy, black mudstones outcrop to the N of these

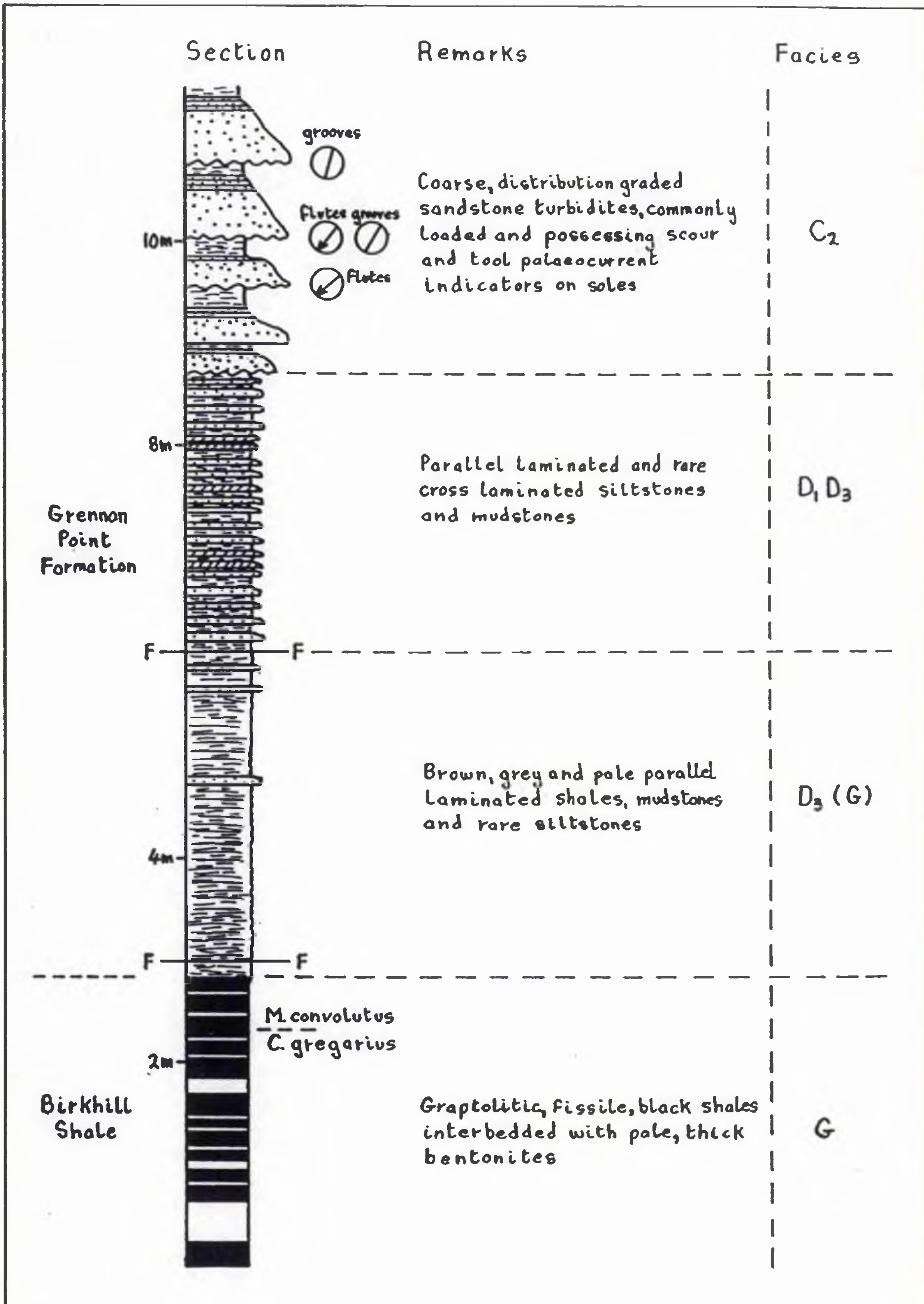


Fig 2.7: Conformable transition between the Birkhill Shale and overlying Grennan Point Formation at the northern end of Drumbreddan Bay (NX07704374).

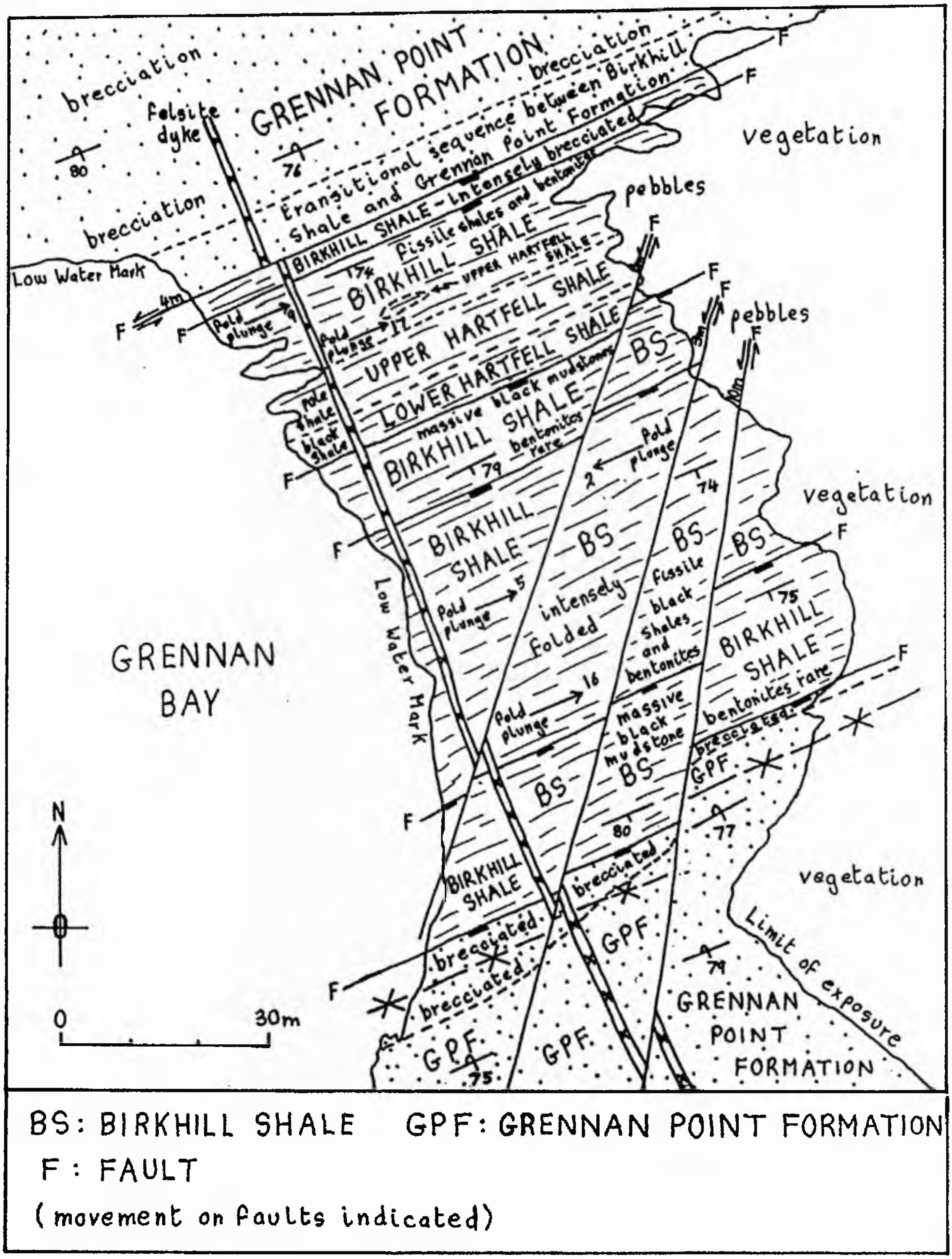


Fig 2.8: Sketch map of the Moffat Shale inlier at Grennan Bay (NX07504385).

beds. This succession ends at a prominent S-dipping fault, N of which are 5 m of sheared black Hartfell Shales, overlain by 7 m of lithologically distinct pale grey and brown weathering Barren Mudstones. These are apparently conformably succeeded by an intensely folded 12 m sequence of black, graptolitic Birkhill Shales containing a few bentonite layers, with a small lens shaped inlier (3 m x 1.5 m) of Barren Mudstones possibly representing an anticlinal core within the shales. N of this a 5 m zone of intensely sheared and brecciated black shales and bentonites contain steeply plunging folds and end at a quartz-veined strike fault that has undergone a late minor sinistral wrench movement. The transition from Moffat Shales to thick Grennan Point Formation greywackes is once again well displayed across the promontory to the NE of this fault (NX07414385), but unlike the other inliers the succession here has been intensely sheared causing brecciation and boudinage of the bedding.

The fourth Moffat Shale inlier is anomalous in occurring 500 m S of the Grennan Point Block at the stratigraphic top of the Mull of Logan Block (Map B). It is exposed on the southeastern side of the sandy bay at Port Gill (NX07794299) and consists of 10 m of sheared black fissile shales faulted against blue-grey mudstones of the Mull of Logan Formation to the S. It most likely represents a faulted sliver of Grennan Point Block incorporated into the Mull of Logan Block during initial thrusting along the boundary between the two.

There is no inland or E coast exposure of the Moffat Shales of the Drumbreddan Bay Fault Zone and their exrapolation to Ardwell (NX11004545) in Maps A and B is an along-strike continuation of their W coast exposure.

Age - graptolites have been collected from the three northernmost Moffat Shale inliers, though none have been found in the fourth inlier due to the extremely sheared and weathered nature of the rock.

The graptolites collected from the southernmost of the three inliers were all poorly preserved and unidentifiable. A re-examination of the Survey collection (Appendix 1) from this area indicated a *Monograptus convolutus* Zone age.

The graptolites collected from the next inlier to the N on the southeastern side of Grennan Point indicated the *C. gregarius* Zone and possibly also the *C. cyphus* Zone. A *C. gregarius* Zone age was confirmed by BGS and two specimens identified in a re-examination of the collection made by Peach and Horne (1899) at this locality indicated a *M. convolutus* Zone age (Appendix 1).

Graptolites collected from the Grennan Bay inlier indicate a *C. vesiculosus* Zone age. While specimens identified in a re-examination of the Survey collection occur in both the *C. wilsoni* and *Dicranograptus clingani* Zones (Appendix 1).

Thus overall the Moffat Shales of the Drumbreddan Bay Fault Zone range in age from the *C.wilsoni* or *D. clingani* Zones of the Lower Hartfell Shale to the *M. convolutus* Zone of the Upper Birkhill Shale (see Fig. 2.2).

2.3.3.4 Grennan Point Formation

Boundaries, thickness and type locality - this formation is bounded to the SE by the Drumbreddan Bay Fault Zone and to the NW by the strike fault extending NE from Hackle Rock. It has a thickness of between 300 m and 600 m, the uncertainty being due to the unknown effect of a number of wrench faults that cut the formation. The type locality is the coastal outcrop between Drumbreddan Bay and Hackle Rock (Maps B and A).

Lithology - the stratigraphic base of the Grennan Point Formation is repeated three times due to imbrication and conformably overlies the Moffat Shales at Drumbreddan Bay (NX07754362), Grennan Point (NX07554380) and NW of Grennan Bay (NX07404385) (Map B). The sequence NW of Grennan Bay is intensely sheared and brecciated, however as just described in the previous section conformable relations are well displayed at the other two localities. Overlying the laminated shales and grey siltstones (D_3D_1(G)) at the base of the succession (Fig. 2.7) is a thick sequence of well-bedded, fine to coarse greywackes (C_2(C_1)) typically between 30 cm and 120 cm thick (Fig. 2.9). These form the dominant lithology of the formation and are superbly exposed on the rocky promontory in Drumbreddan Bay and at Grennan Point. They often display distribution grading and have more complete Bouma cycles than the Gala Group formations to the N, with both parallel-laminated T_b divisions and cross-laminated and convoluted T_c divisions much more common. Thickening-upward cycles of 5-25 m are frequently developed and sand/shale ratios vary from medium to high with rare amalgamation. Sole marks such as flute, groove and load casts are common and in the older part of the succession liquefaction structures and slump folds are evident.

Bands of alternating red, green, pale and/or grey shales variably interbedded with thin turbidites are present at three localities. The first of these occurs 40 m above the base of the succession in Drumbreddan Bay (NX07754362) and consists of 3 m of thickly banded red and green shales (G) overlain by 4 m of grey shales (G) and rapidly succeeded by a thickening and coarsening-upward greywacke sequence (D_1(C_2)). The second is present 80 m above the base of the succession at Grennan Point (NX07524371) and consists of a 5 m sequence of predominantly red (with grey and pale) shales (G), interbedded with fine greywackes (D_1(E)) less than 5 cm thick and spaced at 30 cm intervals. Above this a 20 m sequence of grey shales (G) contains common thin, fine greywackes (D_1) with occasional thick (up to 1 m) medium to coarse greywackes (C_2). The third locality occurs 120 m above the base of the succession at Hole of Grennan (NX07204390) where 5 m of green and pale shales (G) are overlain by 7 m of grey shale (G) interbedded with fine to medium 10-50 cm thick greywackes (D_1(C_2)).

The formation undergoes very little lithological variation throughout its outcrop though Facies C_1 greywackes become of more importance northwards and the

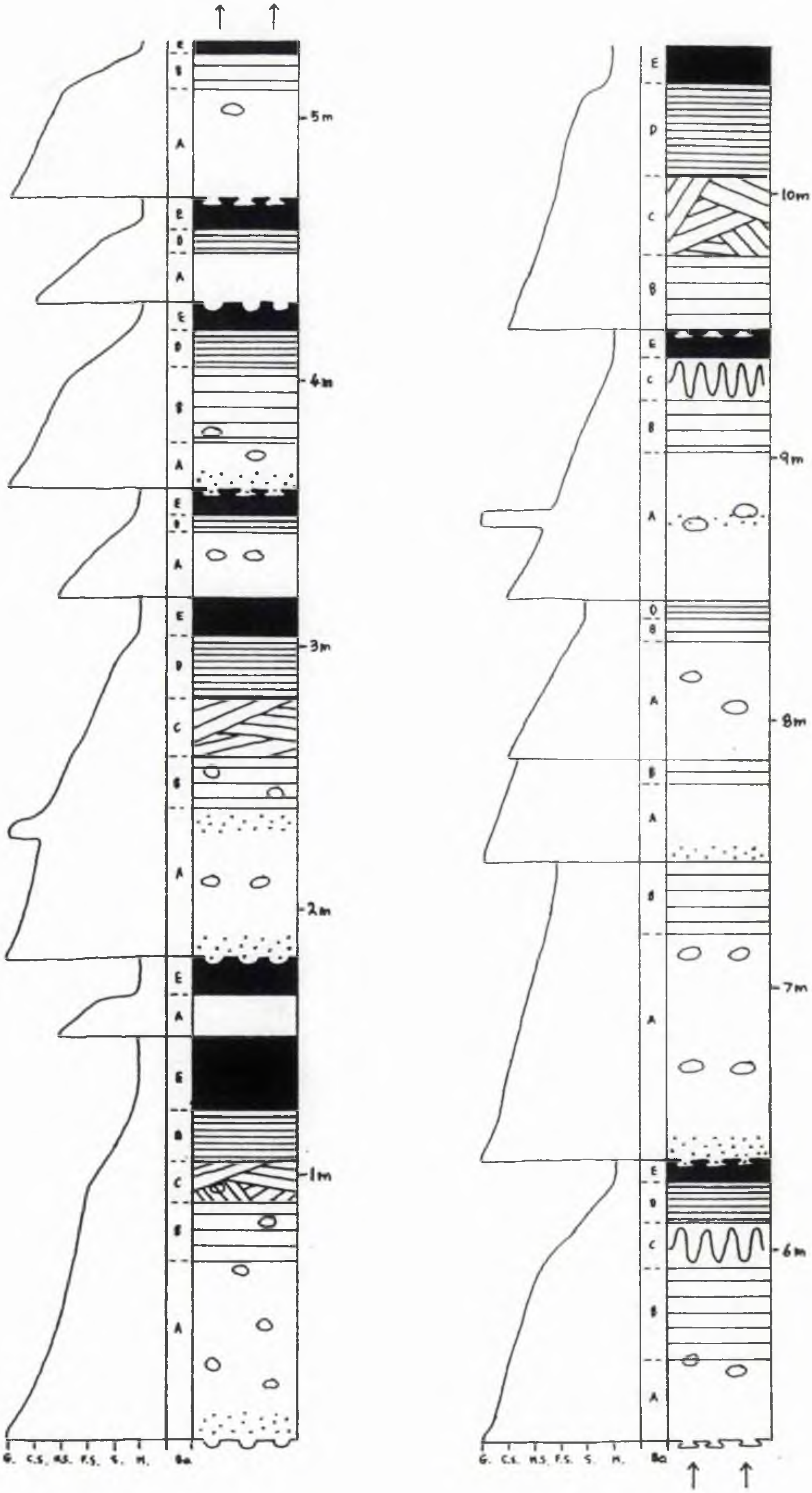


Fig 2.9: 10 m section through the Grennan Point Formation at Grennan Point (NX07524369) showing characteristic mature, distribution graded turbidites.

sand/shale ratio increases with more frequent amalgamation. Iron staining has imparted a distinct red colour to the bedding in the vicinity of Dun Isle (NX06974403).

The composition of the greywackes is strongly siliceous (*c* . 40% quartz) and petrographically the formation is indistinguishable from the Float Bay Formation and the 'Stinking Bight beds'.

Age - the Grennan Point Formation is unfossiliferous, but it must be younger than the *M. convolutus* Zone age attributed to the Moffat Shales it overlies (see Fig. 2.2).

2.3.3.5 Mull of Logan Formation

Boundaries, thickness and type locality - the southeastern boundary of this formation is the Port Logan Bay Fault (Map B). This fault although unexposed is topographically well-expressed extending ENE from the 700 m wide sandy bay N of Port Logan (NX09654090) for 3 km along a low-lying tract of land to Terally Bay (NX12404110) on the E coast. The northwestern boundary is the Drumbreddan Bay Fault Zone (Maps B and A). The formation has a total thickness of at least 1850 m and sub-divides into the following members:-

The Chair Member	-	450 m
Duniehinnie Member	-	550 m
Daw Point Member	-	500 m
Cairnie Finnart Member	-	at least 350 m

The type locality is the coastal outcrop between Port Logan Bay and Drumbreddan Bay.

Lithology

The formation is very well exposed on the W coast and over a large part of the E coast with very little exposure inland (Map B). A detailed description of the W coast section is given (Fig. 2.10, Table 2.1) followed by an examination of its along-strike continuation to the E coast.

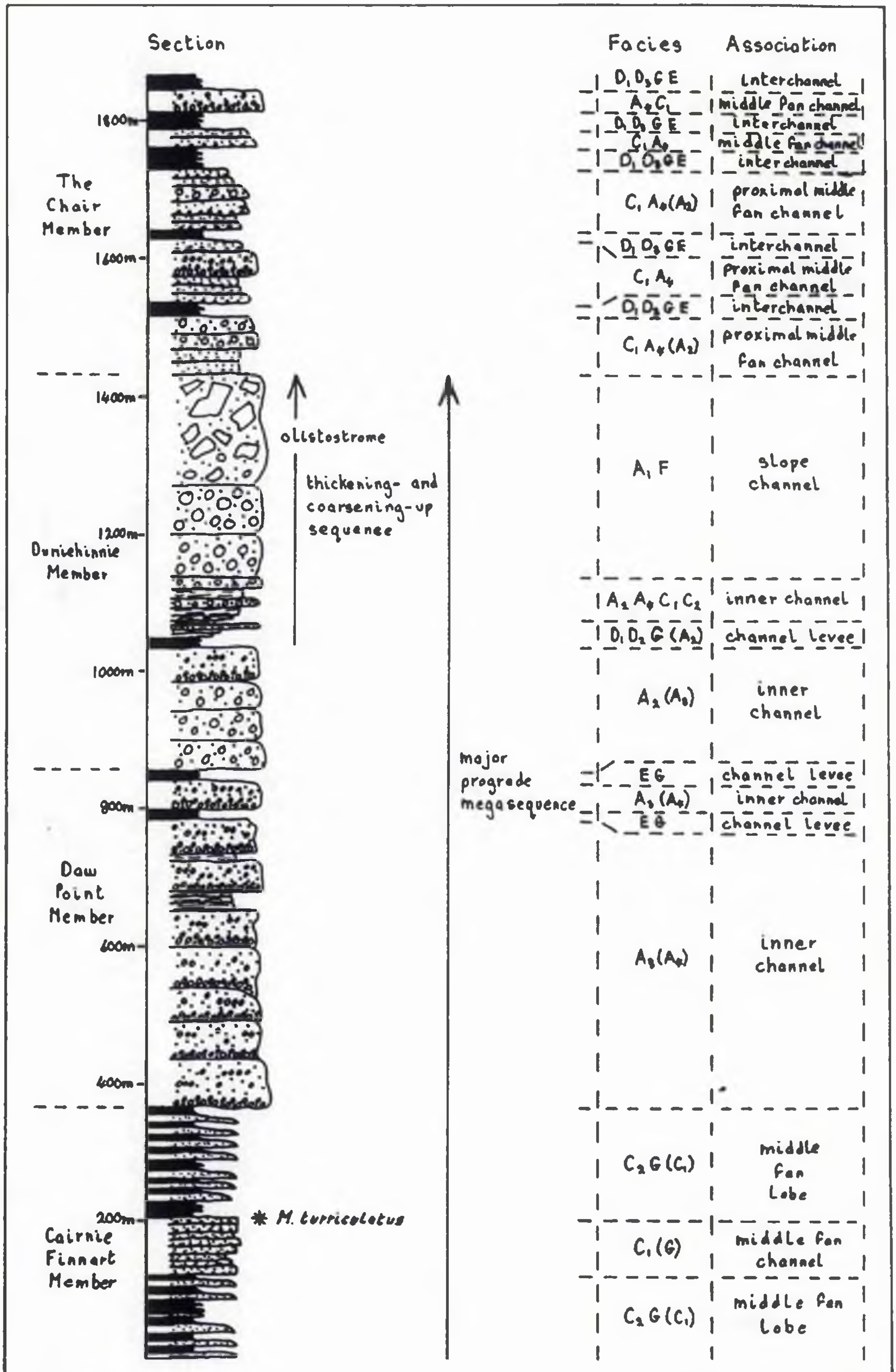


Fig 2.10: Diagrammatic section through the Mull of Logan Formation.

<u>(A) The W coast</u> - the Cairnie Finnart Member forms the base of the formation and is exposed immediately NW of the sandy beach at Port Logan. It consists predominantly of well-bedded, fine to coarse greywackes less than 1 m thick ($C_2(C_1)$) interbedded with grey, green and purple shales (G) and has an overall low to medium sand/shale ratio. A 70 m sequence at Cairnie Finnart (NX08854140) consists of coarser, thicker and more massive greywackes (C_1) with an increased sand/shale ratio. A few bands of grey, red and green shales (G) sparcely interbedded with fine greywackes less than 10 cm thick ($E(D_1)$) are present within this sequence and range from 1 m to 30 m in thickness.

The top of the Cairnie Finnart Member is marked by a 5 m shale unit at Yellnowte Isle (NX08154167) (Fig. 2.10) and is conformably overlain by the coarse to granule-grade massive sands ($A_3(A_4)$) that constitute the Daw Point Member. Minor shearing has occurred along the boundary due to the strong ductility contrast between the two lithologies. Bedding within the Daw Point Member is only rarely discernable and is most clearly visible at Daw Point (NX07704161) and to the N of Otter Rock (NX0745189). The bedding is typically irregular, amalgamated and varies from 1 m to over 10 m in thickness. The section N of Otter Rock also contains a few bands up to 3 m thick of thin shales and siltstones (G) interbedded with coarse greywackes (E) less than 15 cm thick. The massive sands forming the top 10 m of the member are intensely sheared and brecciated and the boundary with the overlying Duniehinnie Member is marked by a relatively minor E-W trending strike fault at Lurghie Point (NX07414198).

The basal 200 m of the Duniehinnie Member extends N from Lurghie Point to Peters Paps (NX07634223) and consists of irregularly bedded intrabasinal conglomerates (A_2) up to 10 m thick with clasts up to 10 cm x 30 cm set in a coarse sandy matrix. In some parts of the succession the beds lose their conglomeratic character and resemble the coarse, massive sands of the Daw Point Member. N of

Peters Paps thinly interbedded fine, base-missing greywackes (D_1D_2) and shales (G) coarsen and thicken upwards through a 100 m sequence of coarse, well-graded greywackes (C_1C_2), massive sands (A_4) and irregularly bedded conglomerates (A_2) into a 250 m sequence of massive, poorly stratified, intrabasinal conglomerates (A_1(F)) containing pebble and boulder clasts up to 50 cm x 80 cm (Plate 2.3).

Compositionally the clasts are 75% greywackes, 25% shale/mudstone and are matrix supported in a coarse sand with their long axes parallel to a rough stratification. Large blocks of massively bedded greywackes up to 15 m x 25 m are present within this conglomerate towards the top of the succession at Duniehinnie (NX07554257) indicating that slumping has occurred. The appearance of sheared turbidites in the succession at the northern end of Duniehinnie marks the conformable boundary with the Chair Member. The shearing again appears due to the major change in ductility across the boundary.

The Chair Member consists of coarse to granule grade greywackes 1-10 m thick (C_1A_4), sporadically interbedded with intrabasinal conglomerates (A_2) containing clasts up to 8 cm x 10 cm. Intercalated shale bands vary in thickness from less than 10 m towards the base of the succession to over 50 m at the top at Parkers Point (NX07784341). These shales and siltstones (GD_3) are typically grey, but are in places banded in red, green and pale colours as at Back Port (NX07754286). Interbedded with the shales are thinly-bedded, medium to coarse greywackes (E) and fine, cross-laminated greywackes (D_1).

The Cairnie Finnart Member has a siliceous petrography, with more than 40% quartz, similar to the formations to the N. However the Daw Point, Duniehinnie and Chair Members are petrographically distinct in being sporadically though consistently enriched in pyroxenes. The average grain size of these members is coarser than that of the greywackes to the N resulting in an increase in the percentage of lithic clasts present, particularly acid and intermediate igneous material, and a corresponding

Plate 2.3: Duniehinnie Member conglomerate/olistostrome 50 m SE of Duniehinnie (NX07604250). The large boulder in the centre of the plate has a visible long axis of 80 cm

decrease in the amount of monomineralic quartz. Metamorphic clasts, particularly quatzite, form an important constituent comprising 8-10% of the thin sections examined.

(B) The E coast - apart from two outcrops of massive sands of the Daw Point member near Logan Botanic Gardens (NX0964266 and NX09904264) and a bedded sequence of the Cairnie Finnart Member 400 m SE of Balgowan (NX11074297) the Mull of Logan Formation is not exposed inland. It is however well exposed on the E coast at Myroch Point (NX12504160) and for 1.5 km between Portacree (NX11854329) and Longrigg (NX11454380). The lithologies are the same as those described on the W coast, however the Duniehinnie Member is absent and instead the Daw Point Member is succeeded by the Chair Member across a NE-SW trending fault, probably a wrench, 450 m NNE of Dryland Croft (NX11644429). If this fault has tectonically excised the Duniehinnie Member it would need to have a sinistral slip in excess of 800 m. No evidence has been found to support it having undergone such a major movement. Another possibility is that the Duniehinnie Member, like many conglomerates (Muttie and Ricci-Lucchi 1975), has a lenticular geometry and does not extend far enough along-strike to reach the E coast. This latter explanation is tentatively favoured (see Map B).

A second major change that has occurred is an increase in outcrop width of the Cairnie Finnart Member for 1 km on the W coast to 3 km (mostly unexposed) on the E coast. A simple tectonic explanation for this is that the E-W trending Port Logan Bay Fault has cut the NE-SW trending Cairnie Finnart Member at an oblique angle.

Petrographically the E coast lithologies display the same characteristics as those on the W coast, although pyroxenes are markedly less common in the Daw Point and Chair Members.

Age - graptolites collected by BGS (Appendix 1) from a dark lamina in a grey shale band 80 m N of Cairnie Finnart (NX08834146) suggest a *M. turriculatus* Zone age.

A derived specimen of the tabulate coral *Propora exigua* found in a 15 m wide zone of sheared mudstones and siltstones in the Chair Member at Back Port (NX07724285) is indicative of the Telychian (*M. turriculatus* to *Monograptus crenulata* Zones) (see Scrutton and McCurry 1987 - (Appendix 5)).

The Mull of Logan Formation is thus most likely to be of *M. turriculatus* Zone age and is very unlikely to be any older than this (see Fig. 2.2).

2.3.3.6 Port Logan Formation

Boundaries, thickness and type locality - the northern boundary of this formation is the Port Logan Bay Fault. This fault is of great significance as the younging direction of bedding changes across it, with the result that all the formations to the S are predominantly southerly younging. The southern boundary is a strike fault that is nowhere clearly exposed having been displaced at least 50 m on the W coast by a N-S trending sinistral wrench exposed on the foreshore 80 m N of Dunbuck (NX09573857) (Map C). The formation has a thickness of at least 800 m and the following three members are intercalated within it:-

Strones Bay Member	-	150 m
Green Saddle Member	-	135 m
Slate Heugh Member	-	120 m

The type locality is the coastal outcrop between Port Logan Bay and the N-S trending wrench N of Dunbuck. Additional type localities for the Strones Bay Member are Grennan Slate Quarries (NX12603938) and the coastal outcrop 250 m ENE of these quarries (NX12853945) where it is more fully exposed.

Lithology

(A) The W coast - the base of the Port Logan Formation is exposed on the seaward side of the pier 300 m W of Port Logan (NX09414053). Apart from three thick hemipelagic members within the succession the S-younging beds change little in their essential character throughout the outcrop (Table 2.1). The dominant lithology

Plate 2.4(A): Part of thickening-upward cycle in coarse-tail graded sandstones in the Port Logan Formation at Quarry Bay (NX09254035)

Plate 2.4(B): Red, green and pale mudstones in the Port Logan Formation at Quarry Bay (NX09254035)

consists of well-bedded, fine to coarse, pale greywackes (C_1C_2) less that 1 m thick (Plate 2.4(A)) with occasional isolated massive units (C_1) up to 3 m thick. The Bouma sequences characteristically developed within the formation are T_{abce}, T_{ace} and T_{abe} with well exposed, ripple marked bedding surfaces forming a distinctive feature of the coastal outcrop. Flute casts, groove marks, longtitudinal ridges and furrows and load structures are commonly present, the load structures showing spectacular large-scale development in a sequence at Needles and Pins (NX09174023). Convolute lamination is frequently present in the beds and prolapsed slump bedding is sporadically developed indicating the highly liquefied state of bedding syn- and post-deposition. Although the sand/shale ratio is low in places, it is usually medium to high with rare amalgamation and thickening-upward cycles of up to 10 m developed (Plate 2.4(A)). Hemipelagic units are present within this succession and apart from the named members are less than 10 m thick. They predominantly consist of dark grey, fissile shales and grey, massive mudstones and siltstones (G) sparcely interbedded with fine, base-missing greywackes (D_1) less than 15 cm thick. Red and green mudstones are present in a few of the units as at Quarry Bay (NX09234031) (Plate 2.4(B)) and disc shaped calcareous concretions up to 8 cm x 6 cm 1.5 cm are developed within some shale horizons.

The oldest of the three members is the Slate Heugh Member which appears conformably within the S-younging succession at Kettle Mouth (NX09223965) above a transitional 20 m thinning- and fining-upward sequence of interbedded greywackes and mudstones. It consists of thinly laminated, blue-grey mudstones and shales (D_3G) interbedded with pale, carbonate-rich siltstones (G) less than 5 cm thick and fine base-missing greywackes and siltstones (D_1) up to 15 cm thick. The upper boundary of the member is marked by the appearance of coarse greywackes (C_1) up to 2 m thick within the mudstone/siltstone sequence and occurs 60 m S of Slate Heugh Bay (NX09258952). This sequence of interbedded coarse, thick greywackes (C_1)

and thick shales (G) is exposed for 50 m before being sinistrally displaced by about 70 m by a NE-SW trending wrench. Across the fault a 30 m sequence of massive greywackes (C_1) conformably grades over a few metres into the Green Saddle Member 50 m N of Brocks Cave (NX09303948). This member is lithologically similar to the Slate Heugh Member, however is distinguished by the presence of interbedded grey cherts up to 10 cm thick. In outcrop it forms a major syncline with its axial trace centred on Green Saddle (NX09303932). In the core of this syncline, 15 m of coarse greywackes (C_1) up to 1 m thick are present marking the upper boundary of the member. The southern limb of the syncline is displaced by a major strike fault in Slouchnamorroch Bay (NX093925), S of which Port Logan Formation greywackes occur.

The Strones Bay Member is in sharp conformable contact with these greywackes 550 m to the S at Strones Bay (NX09513871). Here too the succession is folded by a major syncline and as a result only the basal 50 m of the member are exposed. This sequence consists of interbedded grey, laminated mudstones (D_3G) and base-missing siltstones (D_1) less than 30 cm thick which grade upwards into fine, distribution graded greywackes (C_2) up to 50 cm thick. A number of graptolitic horizons are present within the mudstones.

Petrographically the Port Logan Formation is extremely siliceous with more than 50% quartz and about 30% matrix. The other 20% is of feldspar (predominantly alkaline) with small percentages of assorted lithic clasts, rare garnets and amphiboles.

(B) The E coast and inland - the E coast is relatively well exposed for 1.5 km from Terally Point (NX12664077) to 200 m S of Path Sands (NX12893981). No major lithological changes occur along-strike. The synclinal outcrop of the Strones Bay Member plunges gently E revealing the full thickness of the member in the superb exposure at Grennan Slate Quarries (NX12603938) and on the foreshore S of Path Sands (NX12853945). It consists of laminated, blue, grey and pale shales and mudstones (D_3(G)) interbedded with laminated siltstones (D_1) less than 15 cm thick and fine, well-graded, base-missing greywackes (D_2) up to 80 cm thick. Graptolites are present in thin dark shale horizons within the mudstones.

Age - graptolites have been found at a number of localities throughout the formation (see Appendix 1), but are particularly common in the Strones Bay Member, both at Strones Bay and Grennan Slate Quarries. The graptolites indicate a *M. turriculatus* (post-*Rastrites maximus* sub-Zone) or *M. crispus* Zone age. Specimens collected by BGS (Appendix 1) from the Strones Bay Member indicate a *M. crispus* Zone age.

The Port Logan Formation is thus of *M. crispus* Zone age, though it may have a slightly older *M. turriculatus* (post-*R. maximus* sub-Zone) Zone age towards its base to the N (Fig. 2.2).

2.3.1.4. Moffat Shale Group of the Clanyard Bay Fault Zone

The intensely brecciated 2 km wide Clanyard Bay Fault Zone contains four imbricate Moffat Shale inliers (Map C). The two northernmost of these are at Clanyard Bay (NX10103710) (Peach and Horne 1899, p 183-185) while the two southernmost have not been previously identified. The northernmost of this latter pair is spectacularly exposed at two localities along the sea cliffs extending SW from Clanyard Bay and in the coastal slopes of Breddock Hill (NX09203700) and Cairn of Dolt (NX08903685), as well as inland in the fields W of Low Currochtrie (NX11553750). The southernmost inlier is only exposed inland at High Currochtrie (NX11503695) and at a few other places along-strike. Despite the predominant southerly younging of the greywacke succession the three northernmost Moffat Shale inliers and possibly also the fourth are all N-younging. In this section the coastal inliers are described first in a N to S order, followed by the inland exposure.

(A) Clanyard Bay to Cave of the Saddle (NX08583677) - the northernmost inlier is exposed at the northern end of the pebble beach in Clanyard Bay at Rotten Craigs (NX10073807) (Map C, Fig. 2.11). At its southern end 10 m of anomalous

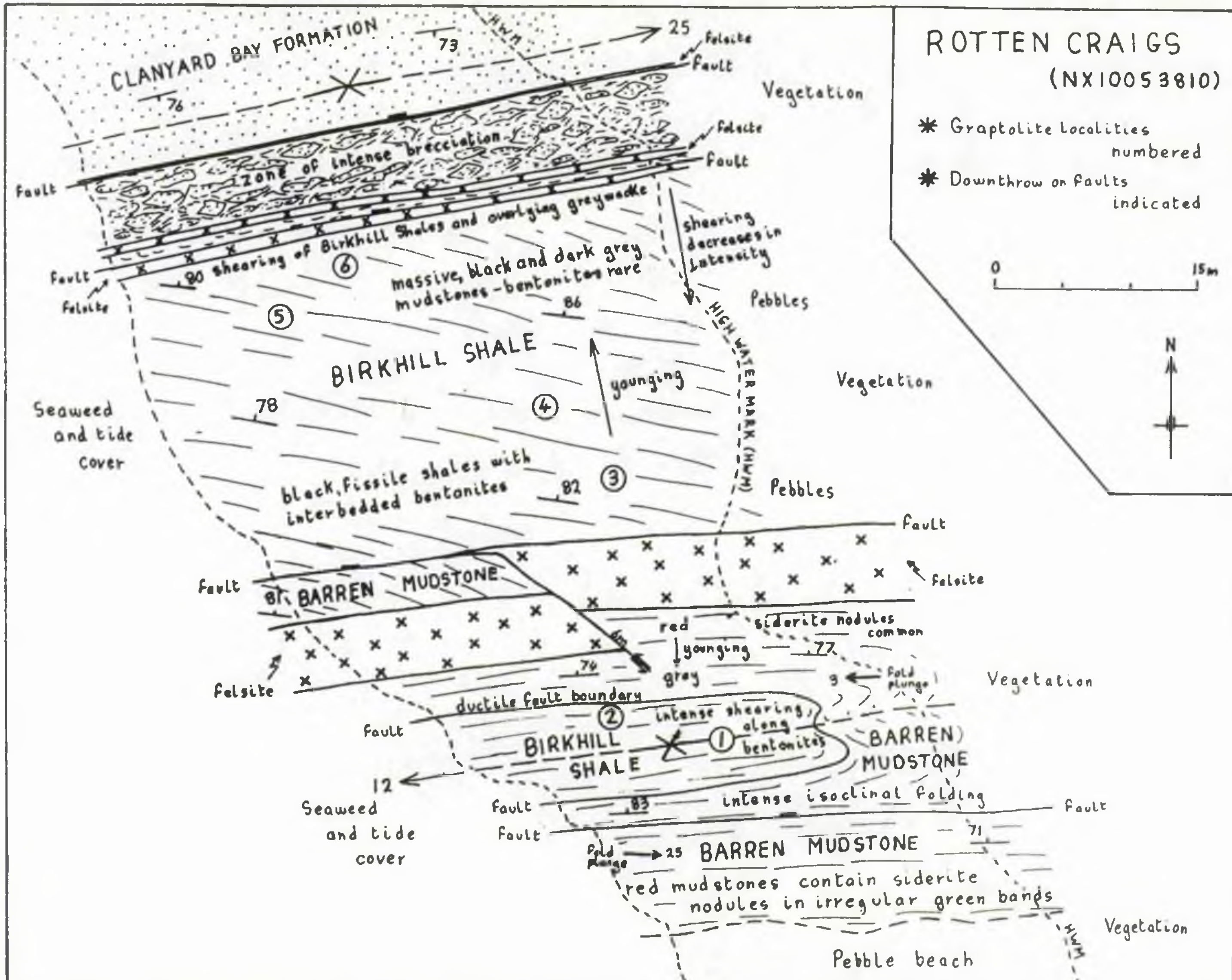


Fig 2.11: Sketch map of the Moffat Shale inlier at the northern end of Clanyard Bay (10053810).

red Barren Mudstones, similar to those 32 km to the NW at Morroch Bay (NX01505250), are exposed and contain rounded irregular shaped spherulitic siderite nodules up to 12 cm x 8 cm in irregular green bands within the mudstone. These mudstones are isoclinally folded and end at a strike fault. Over this fault Barren Mudstones have been ductilely faulted against black Birkhill Shales (Plate 2.5) and then isoclinally folded into a gentle W plunging syncline. Only 3 m of Barren Mudstones are exposed on the faulted southern limb of the fold, but over 8 m are present in the core and on the northern limb and consist of grey, blue and brown mudstones which are red towards their base and contain numerous siderite nodules. The black Birkhill Shales exposed in the core of the syncline are 9 m wide, rich in bentonites and often sheared. The Barren Mudstones on the northern limb of the syncline end abruptly at a strike-parallel 7 m wide felsite dyke that at one point is displaced 6 m by a sinistral wrench. N of this 40 m of sheared and brecciated Birkhill Shales consist of black, bentonitic, fissile shales and massive siltstones and have a discordant E-W strike. These end at two 1 m thick felsite dykes associated with brecciatd greywacke lozenges and over which a major fault throws down to the N. Across this fault 500 m of folded and intensely brecciated S-younging Clanyard Bay Formation greywackes extend N to the boundary with the Port Logan Block.

The second Moffat Shale inlier is exposed for 100 m along the foreshore at Bennan (NX09803773) on the S side of Clanyard Bay 250 m S of the first inlier (Map C). Its southern boundary is marked by a steep N-dipping felsite dyke to the S of which is an intensely folded and brecciated though initially S-younging sequence of Clanyard Bay Formation greywackes. N of the dyke are 25 m of sheared black Birkhill Shales containing numerous thin bentonite bands and in places clearly isoclinally folded. This sequence ends at a prominent strike fault over which 3 m of N-younging Barren Mudstones conformably underlie 2 m of black Birkhill Shale. The Birkhill Shales are cut by a strike fault to the N of which Barren Mudstones are

Plate 2.5: Ductile fault boundary between the Barren Mudstones (pale) and Birkhill Shales (dark) at the northern end of Clanyard Bay (NX10103809)

once again exposed. This sequence is only partially exposed and consists of about 10 m of pale green and grey mudstones interbedded with block shale bands up to 30 cm thick equated with the 'Anceps Bands' at Dobbs Linn (see Williams 1982). Conformably overlying these are 10 m of black Birkhill Shales that are intruded by a prominent 1.5 m felsite dyke to the N of which the exposure ends due to sea cover. A number of NW-SE trending faults cut through the outcrop, but have an unknown effect.

The third inlier is spectacularly exposed 400 m to the S at the practically inaccessible old smugglers cave in Breddock Bay (NX09173720) (Plate 2.6(A)) and at the sea-cave Cave of the Saddle (NX08553675) (Plate 2.6(B), Map C). At the former locality the Moffat Shales have a thickness of about 35 m and appear to young conformably northwards into the Clanyard Bay Formation. The southern boundary of the inlier is covered by vegetation in the cliffs, but is probably a fault as a thick greywacke sequence is visible immediately to the S. The Moffat Shales consist predominantly of black, sulphur-stained, fissile shale, however the top 10 m at Breddock Cave (NX09173720) are composed of massive mudstones with rare bentonites. Apart from a little shearing present at the boundary these appear to young conformably into a 30 m sequence of medium to coarse greywackes (C_1) less than 1 m thick to the N. A 1 m thick band of black, fissile shale is intercalated 5 m from the top of this sequence. Overlying these are 5 m of mudstones and siltstones (GD_3) interbedded with pale, carbonate bands (E) up to 5 cm thick. These end at a fault over which a thick sequence of intensely sheared Clanyard Bay Formation greywackes are exposed. A N-S sinistral wrench in Breddock Bay displaces the whole succession by aobut 20 m with the result that the Moffat Shales are not exposed on the western side of the bay.

At Cave of the Saddle an 80 m fault-bounded inlier of Birkhill Shale is present within a coherently bedded succession of S-younging greywackes and siltstones. The

Plate 2.6(A): Conformable boundary between the Moffat Shale Group (MSG) and Clanyard Bay Formation (CBF) at Breddock Bay (NX09173720) (younging indicated)

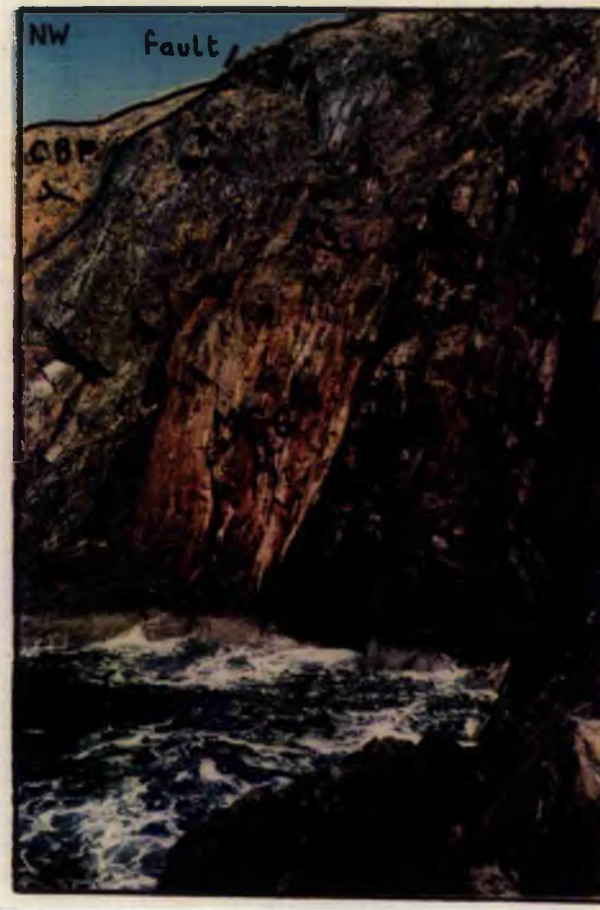


Plate 2.6(B): Fault boundary between the Moffat Shale Group (MSG) and Clanyard Bay Formation (CBF) at Cave of the Saddle (NX08553675) (younging indicated)

Plate 2.7: Massive sandstone unit in the Port Mona Member of the Clanyard Bay Formation at Broad Stone of Portdown (NX09873310)

southern boundary fault of sheared, black, fissile shales, abruptly juxtaposed against a 1 m thick, N-dipping greywacke bed, is accentuated by a large sea-cave eroded along the fault line. The 10 m thick fissile shale sequence is succeeded by 25 m of massive black mudstones with rare bentonites and a few graptolites, suggestive of the 'vesiculosus Flags'. A further 25 m of poorly fossiliferous grey mudstones and siltstones occur to the N of this and end abruptly at a sub-vertical strike fault. N of this fault an 8 m sequence of fissile, black shale is again succeeded by 12 m of massive black mudstone. The northern boundary of the inlier is an inconspicuous quartz-veined shear plane adjacent to a 1 m thick felsite dyke and parallel to bedding (see Plate 2.6(B)). It is succeeded to the N by a 15 m sequence of S-younging siltstones.

This third inlier is primarily exposed at two localities along the coast because of its sinistral displacement by a series of relatively minor NW-SE trending wrenches. It is sporadically exposed along the coastal slopes of Breddock Hill and Cairn of Dolt where its major thrusts and boundaries are superbly displaced in aerial photographs of the area (see Map C). An 80 m x 400 m lenticular outcrop of greywackes is present within the Moffat Shales at Breddock Hill 9NX09203710) suggesting that further localised imbrication of the inlier has occurred. The replacement of a possible conformable northern boundary to the inlier at Breddock Bay by a distinct fault at Cave of the Saddle is possible due to a fault migrating from the greywacke sequence and preferentially developing along the Moffat Shale/greywacke boundary.

<u>(B) Low and High Currochtrie</u> - the two northernmost inliers are not exposed inland but are very well expressed topographically as an E-W trending low-lying valley extending between the hills for 3 km to the E coast at Kilstay Bay (NX12903825). The exposure in the fields around Low and High Currochtrie farms is generally poor but of sufficient quality to define and trace the lithologies. Once again the major thrusts and lithological boundaries are well displayed in aerial photographs. The third

inlier is exposed in the fields W of Low Currochtrie (NX11553750) (Map C). It is of much the same thickness as on the coast and similarly contains a 20 m wide linear outcrop of greywacke within it. The boundaries are not exposed, but the rocks in their vicinity are much more brecciated than at the coast.

The fourth and most southern Moffat Shale inlier is best exposed in a grassy bank 20 m NW of High Currochtrie farmhouse (NX11513696) (Map C) and consists of a 20 m section of black, fissile shale and massive mudstones intruded by a number of 0.5-2 m felsite dykes. An anticlinal inlier of sheared greywackes overlying a core of black, fissile shales is present in a slurry pit 50 m W of this outcrop (NX11463695). Apart from these, only a few other poorly exposed outcrops of Moffat Shales are present NE and SW along-strike. Photogeological evidence suggests this fourth inlier has a true width of about 100 m. Both inliers are cut by numerous, minor NE-SW trending dextral and sinistral wrench faults.

Age - the Moffat Shales at the northen end of Clanyard Bay proved the most prolific in the southern Rhinns at yielding identifiable graptolites (see Appendix 1). Collections were made from six localities within the inlier (see Fig.2.11). These localities and the horizon indicated are given below in a S to N order:-

(1) The centre of the synclinal core of Birkhill Shale exposed south of the 7 m wide felsite dyke (NX10113807) - possibly *C. gregarius* Zone.

(2) Within the synclinal core of Birkhill Shale 1.5 from the northern fault-boundary with the Barren Mudstones (NX10103808) - *C. vesiculosus* Zone.

(3) 7 m N of the 7 m wide felsite dyke (NX10073811) - *C. cyphus* or *C. vesiculosus* Zone.

(4) 15 m N of the 7 m wide felsite dyke (NX10063812) - *C. cyphus* Zone.

(5) 12 m S of the northern boundary of the inlier (NX10053812) - *M. convolutus* or possibly *C. gregarius* Zone.

(6) 5 m S of the northern boundary of the inlier (NX10053813) - *M. convolutus* or *Monograptus sedgwicki* Zone.

BGS (Appendix 1) collected graptolites from six unspecified localities in the same inlier indicating the following horizons: C. *vesiculosus* Zone; *C. cyphus* Zone; near the boundary of *C. cyphus* and *C. gregarius* Zone; and *M. sedgwicki* Zone. In addition a re-examination of the survey collection from the inlier (see Appendix 1) revealed the presence of *M. convolutus* Zone and Ordovician (possibly *Dicellograptus anceps* Zone).

Graptolites collected from the much less prolific Moffat Shale inlier at the southern end of Clanyard Bay 9NX09803770) indicated a *M. convolutus* Zone age (Appendix 1).

At Breddock Bay (NX09153720) the specimens identified (Appendix 1) indicated a *C. cyphus* Zone and possibly *C. vesiculosus* Zone age.

The Moffat Shales at Cave of the Saddle (NX08553675) yielded graptolites indicating a possible *C. gregarius* Zone age (Appendix 1). A re-examination of the Survey collection made from the 'cliffs 250 yards N of Laggantullach Head' (Irvine 1872, p 11) (Appendix 1) probably refers to the Cave of the Saddle outcrop and revealed specimens suggestive of a *C. cyphus* Zone age.

No identifiable graptolites were found from the poorly exposed southernmost Moffat Shale inlier.

Thus the Moffat Shales of the Clanyard Bay Fault Zone range in age from the Ordovician (probably *D. anceps* Zone) to the *M. sedgwicki* Zone of the Llandovery (see Fig. 2.2).

2.3.3.7 Clanyard Bay Formation

<u>Boundaries, thickness and type locality</u> - the northern boundary of this formation is a strike fault displaced at least 50 m by the sinistral wrench cutting the foreshore 80 m N of Dunbuck (NX09573875). The southern boundary is not exposed but is

presumably a strike fault that is once again displaced at the coast by a sinistral wrench, the Nick of Kindram Fault (NX10903208), which has a throw in excess of 2 km. The thickness of the formation is difficult to estimate due to the unknown degree to which imbrication has repeated the succession but is believed to be at least 1050 m though is quite possibly closer to 2000 m. The Port Mona Member, forming the upper part of the formation, has a thickness of at least 800 m. The type locality is the coastal outcrop between the sinistral wrench N of Dunbuck and the Nick of Kindram Fault (see Maps C and D). The formation is intruded by the Portencorkrie granite-diorite pluton (Holgate 1943) which is exposed for 2.5 km along the coast between Laggantalluch Head (NX08443635) and Cuff (NX09383375).

Lithology - the base of the Clanyard Bay Formation is repeatedly exposed due to imbrication throughout the 2 km wide Clanyard Bay Fault Zone. Over most of its outcrop folding and brecciation are intense, yet despite this it is one of the most distinctive lithologies in the Rhinns (see Table 2.1). The transitional contact with the underlying Moffat Shales at Breddock Bay is described in the previous section. The lithology is well bedded and consists of fine to medium, well-graded greywackes ($C_2(C_1)$) less than 1 m thick with a medium to high sand/shale ratio. In places the sequence is more thinly-bedded (less than 30 cm) and is dominated by fine, cross-laminated and rarer duned greywackes ($D_1(E)$), as at Dunbuck (NX09653852). The most distinctive feature though is the sporadic occurrence of 2-100 cm thick units of black, graptolitic, fissile shale (G) within the succession. Also present are distinct 15-40 m sequences of massive blue-grey to dark grey mudstones (GD_3) with occasional thin, fine to medium greywackes and pale, well-graded, carbonate-rich bands(E) less than 12 cm thick.

The Port Mona Member (Table 2.1) consists predominantly of massive, fine to coarse greywackes 0.3-6 m thick with a medium to high sand/shale ratio and rare amalgamation (C_1B_2) (Plate 2.7). The beds are coarse-tail graded and commonly cross-laminated at their tops. S of Port Mona (NX10463262) the member consists of well bedded, fine to medium greywackes (C_1C_2) less than 1 m thick with a medium to high sand/shale ratio that decreases as the succession youngs. 10-40 m thick bands of pale green/grey mudstones and shales (G) interbedded with fine greywackes (E) less than 15 cm thick are present and form the dominant facies in the top 250 m of the succession SE of the strike fault exposed 70 m NW of Craigwhinnie (NX10683230).

The Port Mona Member occurs S of the Portencorkrie granite-diorite pluton and as a result its northern boundary is not exposed. This pluton has an aureole extending from Slouchgarie 400 m SE of Clanyard Bay (NX09523751) to the Nick of Kindram (NX10903208) (see Maps C and D), however generally its effects are limited to slight matrix recrystallisation and the production of biotite. As the igneous margin is approached the rock takes on the appearance of a hard, splintery, biotite-rich hornfels. However only in the immediate vicinity of the margins is it totally reconstituted and particularly at its southern margin with the Port Mona Member 60 m SE of Cuff (NX09383375) where it forms a quartz-biotite-plagioclase-cordierite hornfels.

Away from the igneous margins the greywackes have a siliceous petrography though the base of the Clanyard Bay Formation contains markedly less quartz (30%) than the Port Logan Formation and Port Mona Member (both 50%), and is matrix-rich (40-50%). The Port Mona Member is relatively rich in metamorphic clasts (8-13%).

The sporadic though poor inland exposure of the formation has been sinistrally displaced at least 2.1 km and 1.6 km respectively by the N-S trending Nick of Kindram and Mull Glen Faults (see Maps C and D). The Nick of Kindram Fault appears co-linear with the eastern margin of the Portencorkrie pluton. It is clear however that the extensive exposure in the moors and fields E of the fault/margin has been metamorphosed to a biotite-rich hornfels. The distinct petrographic and lithological changes between the Clanyard Bay Formation (Gala Group) and the Mull of Galloway Formation (Hawick Group) to the S has enabled the inland boundary between them to be traced relatively accurately with the help of aerial photographs despite the limited exposure. This boundary is believed to be a strike fault extending NE form the Nick of Kindram Fault at Kilbuie Moss (NX11303370) to the Mull Glen Fault 450 m SE of Creechan Park (NX13173444) (Map D). The Clanyard Bay Formation is not exposed E of the Mull Glen Fault.

Age - graptolites present in an 80 cm block shale unit within the greywacke succession at Dunbuck (NX09583851) indicated a *M. turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone age (Appendix 1). The same locality yielded specimens to BGS collectors (Appendix 1) indicating an *M. crispus* Zone age. The other black shale units within the succession are inaccessible, badly sheared or thin with the result that no identifiable specimens have been found in them. Apart from these black shale units the greywacke succession has proved unfossiliferous.

The Clanyard Bay Formation is thus of *M. crispus* Zone age (see Fig. 2.2).

2.3.4 Hawick Group

This group consists of all the greywackes and associated turbidite facies (excluding the Moffat Shale and Gala Group inliers described later) cropping out between the unexposed southern boundary of the Gala Group and the Riccarton Line/Fault forming the northern boundary of the Wenlock age Southern Belt (Fig. 2.4). The sequence is dominated by fine to medium grained, pale greywackes typically less than 1 m thick interbedded with pale, green weathering and occasional red mudstones. Petrographically the group has a siliceous character and a distinctive carbonate-rich matrix. The Hawick Group is of late Llandovery *M. griestoniensis* Zone and probable *M. crenulata* Zone age.

2.3.4.1 Mull of Galloway Formation

Boundaries, thickness and type locality - the northern boundary of this formation is unexposed but is believed to be a strike fault sinistrally displaced at least 2 km on the

W coast by the Nick of Kindram Fault. The formation marks the southern limit of exposure on the Rhinns peninsula and as a result its southeastern boundary is not exposed. The (exposed) formation thickness is difficult to estimate due to the unknown degree to which imbrication has affected what is a very homogenous lithology, but it is believed to be at least 1250 m. The Leucarron Member is at least 550 m thick and is underlain in the Cardrain Block by a 450 m sequence and overlain in the Mull of Galloway Block by a sequence at least 250 m thick. The type locality is the coastal outcrop between the Nick of Kindram Fault on the W coast and the bay 450 m N of Portankill on the E coast (NX14123303) (Map D).

N.B. - A 1.5 m thick fault-bounded outcrop of intensely sheared, brecciated and quartz veined black, fissile shale is present in a major fault zone at Portankill (NX14103261) and is believed to be Moffat Shale suggesting the Hawick Group and Moffat Shales are stratigraphically related (see later Section 2.4).

Lithology - the Mull of Galloway Formation (Table 2.1) is composed of pale, fine-grained greywackes and siltstones ($C_1C_2E(D_1)$) generally less than 60 cm thick though occasionally up to 2 m and interbedded with grey mudstones (G) that weather to a pale green colour. The sand/shale ratio is medium to high and the thick grey mudstone interbeds infrequently contain intercalated red mudstones up to 5 cm thick. Longitudinal ridge and furrow sole marks are a common feature, as is the presence of cross-lamination and sand volcanoes, the latter being unique to the Mull of Galloway Formation in the Rhinns. Fining-up and occasional coarsening-up cycles of 4-10 m thickness are sporadically developed throughout the sequence. The succession is remarkably uniform and only in the Leucarron Member is there any marked variation. The northern boundary of this member is the major fault zone at Carrickamickie Bay (NX11953145) which has been sinistrally displaced inland by about 1.6 km by the Mull Glen Fault to cut the E coast at Maryport (NX 14313445). The southern boundary is the Tarbet Fault (NX14053090). The Leucarron Member is characterised by the regular occurrence of distinct channellised sequences up to 12 m thick. These consist of 30-120 cm thick fine-medium greywackes with high sand/shale ratios and frequently amalgamated ($B_2C_1(C_2D_1D_3EG)$) (see Table 2.1). Flute casts and groove marks are present as well as the more typical longitudinal ridges and furrows. Beds frequently have a lenticular geometry and slump structures, channelling and loading features are commonly developed. These features are all superbly displayed in a 12 m thick channellised sequence at Leucarron (NX13303098).

Petrographically the formation is fine-grained and siliceous with about 30% quartz and 7-10% acid volcanic clasts. Its most striking feature though is the matrix which accounts for 35-50% of the rock of which 20-35% is carbonate giving the greywacke its distinctive pale hue. In the vicinity of the Tarbet Fault and over much of the Mull of Galloway Block the lithology is commonly coloured red due to localised iron staining.

This formation is unique in that it is well exposed over both the southwestern coast and over a large section of the northern and eastern coasts of the southern Rhinns (see Maps D and C). Inland exposure is poor and sporadic and in a few places as in the quarries NE of White Craig (NX13033424) and 300 m NW of Maryport (NX13963470) the greywacke has been altered to a biotite-rich hornfels by local intrusions. Correlation between the two coastlines is made difficult by the presence of the two major N-S trending sinistral wrenches, the Nick of Kindram Fault and the Mull Glen Fault. The boundary between the Mull of Galloway Formation and the Clanyard Bay Formation has been detailed in a previous section as striking NE from the Nick of Kindram Fault at Kilbuie Moss (NX11303370) to the Mull Glen Fault 450 m SE of Creechan Park (NX13173444) giving the Nick of Kindram Fault a throw of at least 2.1 km. The most northerly exposure of the Mull of Galloway Formation E of the Mull Glen Fault is at the Old Quarries at Craigburdie (NX13843613) (Map D) indicating a throw of at least 1.6 km for the Mull Glen Fault. This agrees with lithological evidence suggesting the Leucarron Member extends as far N as Maryport Bay (NX1424326) on the E coast.

Age - no graptolites have been found in this formation, however it is lithologically similar to the Kirkmaiden Formation 2.2 km NE along-strike in the Wigton Peninsula which has yielded a *M. griestoniensis* Zone fauna (Barnes *et al* 1987 - (Appendix 2)) (see Fig. 2.2).

2.4 CONCLUSION - REGIONAL CORRELATION

The Southern Uplands-Down-Longford terrane is a 400 km long linear belt with the Rhinns juxtaposed between the main Scottish and Irish outcrop (Fig. 1.1). A detailed stratigraphic as well as structural correlation has been made with the immediately adjacent along-strike exposure in the Ards Peninsula *c.* 25 km to the SE in Ireland, and the Wigtown Peninsula 12-22 km to the NE. This correlation was made in conjunction with Dr. T.B. Anderson and Dr. R.P. Barnes who respectively compiled the stratigraphies within each of the adjacent areas. The detailed results of this correlation are given in Appendix 2 (N.B. - for an alternative correlation between the northern Central Belt lithologies of the Rhinns and Wigtown Peninsula see Kelling *et al* 1987). In this study an attempt was made to correlate the tectonic blocks in each of the three areas as these often equated with the formations defined and the frequent occurrence of Moffat Shales along their base provided biostratigraphic controls. This however proved of only limited value as although some blocks such as the Mull of Logan Block with its distinctive proximal and slumped lithologies could be traced in each of the three areas, others such as the Money Head Block were clearly present only in one. In addition the ages and across-strike widths of the blocks and the numbers present varied along-strike. The overall width of the Central Belt increases from 30 km in the Wigtown Peninsula to over 45 km in the Ards Peninsula and Lecale. The blocks do not therefore form extensive co-

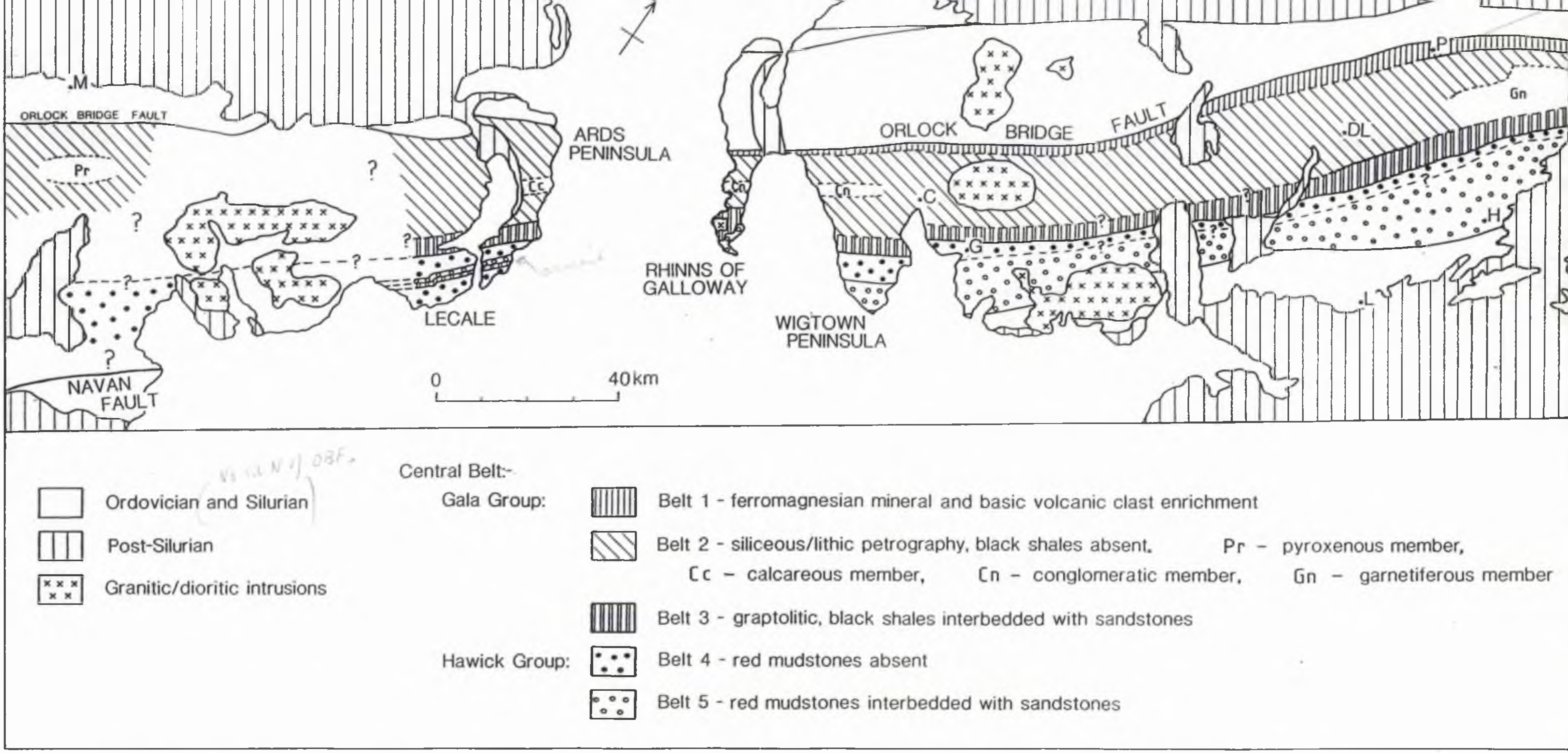


Fig 2.12: Proposed regional lithostratigraphy for the Central Belt of the Southern Uplands-Down-Longford terrane. (Moffat Shale Group not shown).
C - Creetown; DL - Dobbs Linn; G - Gatehouse of Fleet; H - Hawick; L - Langholm; M - Monaghan; P - Peebles

and conglomerates, with interbedded mudstones and silt-stones; sand/shale ratio is high-very high; petrographically are siliceous/lithic with rare ferromagnesian mineral enrichment.			of belt decreases southwestwards							division[2]				
	Siliceous/lithic petrography - no graptolitic black shale horizons, type Gala Group lithology		Local variations in lithology can be used to define members- further definition of red mudstone distribution may enable belt to be split into two	10-20 km	*C. cyphus* Zone-*M. griestoniesis* Zone	Pullans Formation,[5] Tassan Formation,[5] Deerycreevy Formation[5]	Donaghadee, Coalpit Bay, Millisle, Ballywhisken, Ballywalter and Wallace Rock Block Formations[6]	Float Bay Formation, 'Stinking Bight Beds, Grennan Point Formation, Mull of Logan Formation, Port Logan Formation	Garheugh Formation[1] (Garheugh and Corwall Block Formations[7])	Craignell Formation - lithic and siliceous divisions[2]	-	'Intermediate' Group,[3] 'Garnetiferous' Group[3]	Fountainhall Formation,[6] Buckholm Formation[4]	Garheugh Formation
		Conglomerate/ olistostrome						Mull of Logan Formation - Duniehinnie & Daw Point Members	'Blocky Arenite' of Corwall Block[7]					Duniehinnie Member
		Pyroxenous				Tassan Formation -lower[5]								Tassan Member
		Garnetiferous										'Garnetiferous' Group[3]	Buckholm Formation[4]	Buckholm Member
		Carbonate-rich siltstones	? Possible tectonically emplaced Hawick Group rocks				Ballywalter Block - northern section[6]							Ballywalter Member
	Graptolitic, black shales interbedded with sand-stones/mudstones	-	Fissile, black shales up to 100 cm thick	6-7 km	*M. turriculatus* Zone (post-*R. maximus* sub-Zone)-*M. crispus* Zone	? Hope Formation[5]	Rowreagh Formation,[6] Portavogie Formation,[6,8] Tara Formation[8]	Clanyard Bay Formation	?Mochrum Block Formations[7]	?Knockeans Formation - northern section[2,10]	Formation SE of the Ettrick Valley Thrust[9]	-	?Selkirk Formation[4]	Clanyard Bay
Hawick Group - fine-medium grained, pale sandstones <1 m thick, interbedded with green-weathering mudstones; sand/shale ratio is low-high petrographically are siliceous/lithic with a carbonate-rich matrix sandstones/mudstones	Absence of red mudstones	-	Red mudstone deposition is more extensive in Scotland than in Ireland and is diachronous occurring at the base of the Hawick Group in Ireland and the Rhinns and towards the top NE along-strike in Scotland, red mudstones reach a maximum thickness of 200 cm	?8-12 km	*M. griestoniensis* Zone - *M. crenulata* Zone	-	Kearney Formation - upper,[6,8] Ballyquintin Formation,[6,8] Ardglass Formation[8]	(Absent)	Kirkmaiden Formation[7,11]	?Knockeans Formation - southern section[2,10]	-	-	-	Kirkmaiden Formation
	Red mudstones interbedded with			100 m - 11 km+	*M. griestoniensis* Zone - *M. crenulata* Zone	-	Kearney Formation - Millan Bay Member,[6] Kearney Formation - Loughkeelan Member[8]	Mull of Galloway Formation	Carghidown Formation[7,11]	Hawick Group[10,12,13]	Hawick Group[13]	Hawick Group[13,14]	-	Carghidown Formation

[1] Gordan (1962); [2] Cook and Weir (1980); [3] Walton (1955); [4] Kassi (1984); [5] Morris (1986); [6] Anderson (1962); [7] Barnes *et al* (1987); [8] Cameron (1977 and 1981); [9] Toghill (1970); [10] Weir (1968); [11] Rust (1965a); [12] Craig and Walton (1959); [13] Kemp (1986); [14] Warren (1964).

TABLE 2.2 REGIONAL LITHOSTRATIGRAPHY OF THE CENTRAL BELT linear tracts along-strike but rather coalesce and bifurcate to form an anastomosing strike-parallel network.

It is therefore important in developing a regionally applicable lithostratigraphy to correlate distinctive lithological features and define the belts in which they occur, rather than trying to define extensive tectonic tracts that in reality do not exist and provide an oversimplified view of the structure (see Leggett *et al* 1979). This has to a degree already been achieved in the Northern Belt (Stone *et al* 1987, Morris 1987) and in the Southern Belt (Kemp 1986), but has proved of much greater difficulty in the uniform lithologies of the Central Belt (see Stone *et al* 1987, Morris 1987).

It is believed that the Central Belt excluding the Moffat Shale Group lends itself to subdivision into five major lithostratigraphic units, four of which are present in the Rhinns (Fig. 2.12, Table 2.2). Three of these belong in the Gala Group and two in the Hawick Group. The oldest and most northerly unit (Fig. 2.14) is characterised by an enrichment in ferromagnesian minerals and in particular pyroxenes. This was first identified by Walton (1955) in the Peebles area and defined as the 'Pyroxenous' Group. It has since been confirmed in the Gala area - Hazelbank Formation (Kassi 1984), Creetown area - Craignell Formation (basic division) (Cook and Weir 1980), Wigtown Peninsula - Kilfillan Formation (Gordon 1962), and is represented by the Money Head Formation in the Rhinns (see Table 2.2). This enrichment becomes much less pronounced and more sporadic in nature SW along-strike and there is a marked decrease in the width of the belt from 3 km in the Peebles area to 1 km in the Rhinns. This trend continues southwestwards into Ireland where no equivalent ferromagnesian rich rocks are present either in the Ards Peninsula (Anderson 1962) or 100 km SW along-strike in County Monaghan (Morris 1986) indicating this belt is confined to the Scottish outcrop (Fig. 2.12).

The second belt includes all the Rhinns formations from the Float Bay Formation to the Port Logan Formation (see Fig. 2.1) and is much broader than the first belt varying from 10-20 km in width (Fig. 2.12). It is characterised by proximal turbidite facies and a siliceous petrography typical of the Gala Group. Its along-strike equivalents are the Fountainhall and Buckholm Formations in the Gala area (Kassi 1984), the 'Intermediate' and 'Garnetiferous' groups in the Peebles area (Walton 1955), the Craignell Formation (lithic and siliceous divisions) in the Creetown area (Cook and Weir 1980), the Garheugh Formation (Gordon 1962) consisting of the Garheugh Block and Corwall Block rocks (Barnes *et al* 1987 - (Appendix 2)) in the Wigtown Peninsula, the Donaghadee Block to Wallace Rock Block formations in the Ards Peninsula (Anderson 1962), and the Pullans, Tassan and Deerycreevy Formations in Monaghan (Morris 1986) (see Table 2.2). Local lithological and petrographic variation necessitates further subdivision of the belt into possible members (Fig. 2.12). The 'Garnetiferous' group and Buckholm Formation in the Peebles/Gala area could combine to form a garnetiferous member. The lower part of the Tassan Formation in Monaghan could constitute a pyroxenous member. The calcareous siltstones in the northern part of the Ballywalter Block in the Ards Peninsula might be a carbonate-rich member, however they may also be Hawick Group rocks that have been tectonically emplaced with Gala Group lithologies. The slumped deposits and conglomerates of the Mull of Logan Formation in the Rhinns and Corwall Block in the Wigtown Peninsula could combine into a single member or sequence of members. These members remain localised and do not form the extensive linear belts that characterise the main lithostratigraphic units.

The most southern belt in the Gala Group (Fig. 2.12) is characterised by the presence of thin, graptolitic, black shale units intercalated within a greywacke succession of *M. turriculatus* Zone (post-*R. maximus* sub-Zone) and *M. crispus* Zone age and equates with the Clanyard Bay Formation in the Rhinns. This belt is usually present S of the most southern and youngest of the Moffat Shale inliers and has a width (where measurable) of approximately 6-7 km. It has been clearly identified along-strike SE of the Ettrick Valley Thrust near Moffat (Toghill 1970), as the Rowreagh and Portavogie Formations in the Portavogie Block of the Ards Peninsula (Anderson 1962), and as the Tara Formation further S in the Ards (Anderson 1962 - the full significance of this formation will be explained later) (see Table 2.2). It is more tentatively correlated with the Selkirk Formation in the Gala area (Kassi 1984), the northern part of the Knockeans Formation near Creetown (see Weir 1968, p 32; Cook and Weir 1980), and the poorly exposed Mochrum Block rocks in the Wigtown Peninsula (Barnes *et al* 1987 - (Appendix 2)). In Monaghan (Morris 1986) it is unclear whether the black shales associated with the Hope Formation and its underlying formations are intercalated within the succession or are tectonically emplaced Moffat Shales.

Less is known about the Hawick Group than any other major lithostratigraphic unit in the Southern Uplands although its pale, fine-grained, carbonate-rich nature mark it out as one of the most distinctive. It is most fully exposed in the Wigtown Peninsula where it subdivides into the Kirkmaiden Formation in the N with no red mudstones and a sparce *M. griestoniensis* Zone graptalite fauna, and the ungraptolitic Carghidown Formation in the S containing numerous red mudstones (Rust 1963, Barnes *et al* 1987 - Appendix 2)). This presence or absence of red mudstones in the succession provides a basis for subdivision of the Hawick Group (see Fig. 2.12, Table 2.2). Thick red mudstones have been identified NE along-strike from the Carghidown Formation in the southern Hawick Group outcrop W of Gatehouse (Weir 1968), in the Kirkcudbright area (Craig and Walton 1959, Clarkson *et al* 1975, Kemp 1986), and in the Hawick area (Warren 1964, Kemp 1986), however virtually nothing is known about the poorly exposed Hawick Group successions across-strike to the NW of these areas. The exception is in the Creetown area, although from the information published it is difficult to establish if the Knockeans Formation(Cook and Weir 1980) is the along-strike equivalent of the Kirkmaiden Formation or if as the presence of black shales would suggest (see Weir 1968, p 32), it belongs in the most southern Gala Group belt as suggested previously. Probably both these correlations apply although further field study is necessary to establish this and to determine the boundaries.

Despite their proximity the Rhinns possesses no equivalent to the Kirkmaiden Formation of the Wigtown Peninsula as infrequent thin, red mudstones are consistently developed throughout the Mull of Galloway Formation. However SW along-strike in the Ards and Lecale (Fig. 2.12) the most remarkable succession in the Southern Uplands-Down-Longford belt is exposed. In an anticlinal core NW of a major strike fault, Ordovician and Silurian age Moffat Shales are intermittently exposed for 17 km along-strike from Millan Bay in the Ards (J632496) to Coniamstown in Lecale (J494399) (see Anderson 1962, 1987-Fig. 7, Cameron 1977, Barnes *et al* 1987 - (Appendix 2), Anderson and Rickards - in prep.). Conformably overlying the Moffat Shales are 100-155 m of coarse greywackes known as the Tara (Sandstones) Formation which contain thin black shale bands yielding a *M. crispus* Zone fauna (Fig. 2.13). This lithology is clearly equivalent to that in the southernmost belt of the Gala Group. Overlying these is the Hawick Group (Kearney Formation) of which the basal 100-300 m contain thick red mudstones (Millan Bay Member - Anderson 1987-Fig. 7; Loughkeelan Member - Cameron 1977, 1981). Above this red mudstones are absent from the rest of the overlying Hawick rock in the Ards and virtually absent (three localities yield a total thickness of *c* 50 cm) in Lecale. This section thus displays a conformable sequence from the Moffat Shale Group to the Gala Group to the Hawick Group and contains three of the major lithostratigraphic units into which it is proposed to subdivide the Central Belt greywackes (see Fig. 2.13). It clearly has important implications as yet unaddressed for the tectonic interpretation of the terrane. The Hawick Group has not yet been recorded in Ireland SW of Lecale. From the information available there seems a general decrease in the

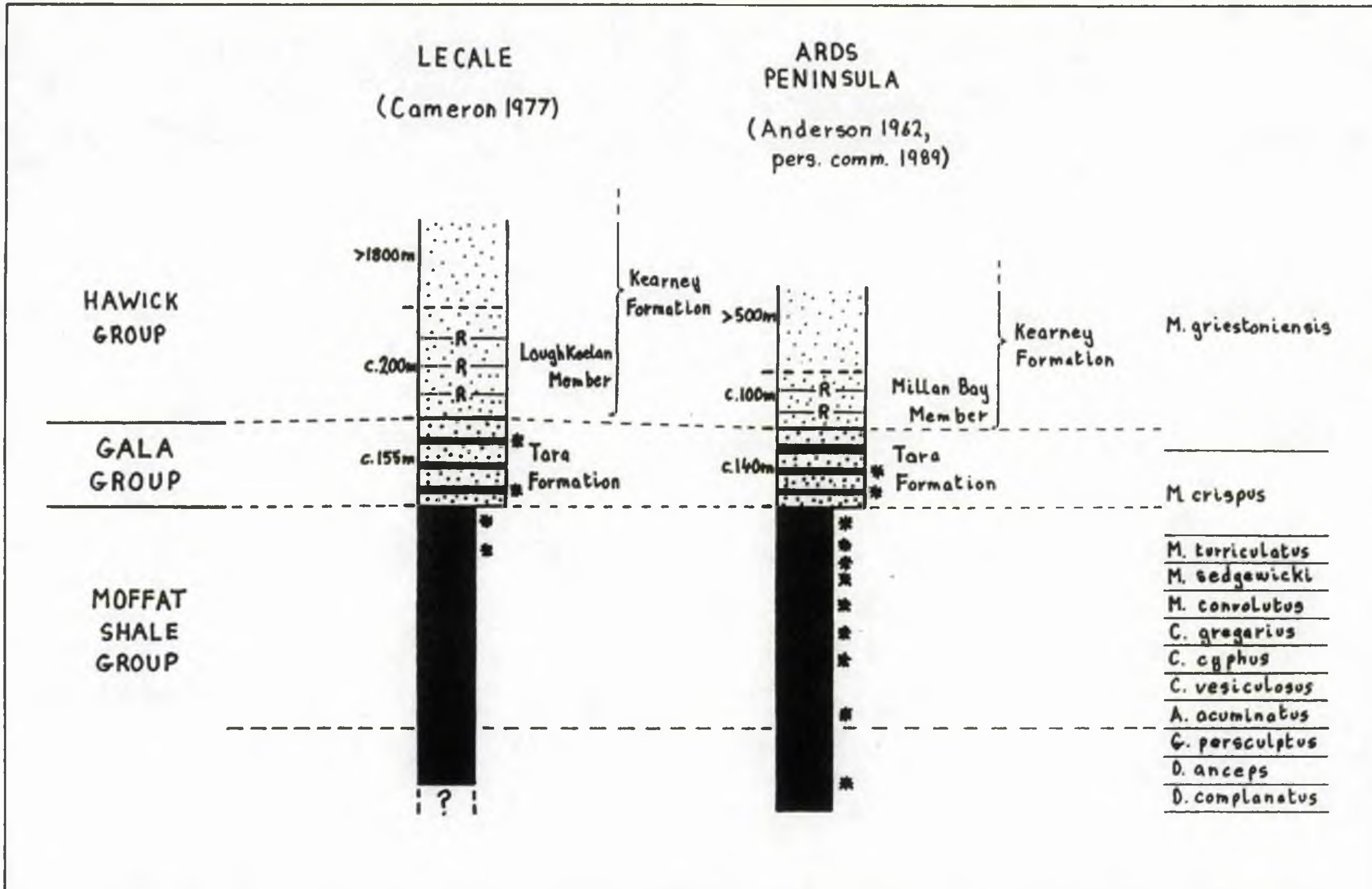


Fig 2.13: Conformable sections through the Moffat Shale Group, Gala Group and Hawick Group in the Ards Peninsula and Lecale. Solid black - graptolitic black shales; stipple-sandstone; R - red mudstone; asterisk - graptolite control.

thickness and importance of red mudstones within the Hawick Group SW along-strike from Scotland into Ireland.

The five belts identified here provide the basis for a regional lithostratigraphy of the Central Belt and can incorporate as members local variations in lithology and petrography.

CHAPTER THREE : SEDIMENTOLOGY

3.1 INTRODUCTION

The aim of this chapter is to examine the sedimentology of the clastic, pelagic and siliceous deposits of the Rhinns and to relate them to the Southern Uplands-Down-Longford terrane as a whole. In view of the controversy currently surrounding tectonic interpretation of the terrane it is not surprising to find renewed interest in its somewhat neglected sedimentological aspects (Kelling *et al* 1987, Kemp 1987), subsequent to the work of Leggett (1980). Foundation studies by Walton (1955) and co-workers Kelling (1962), Gordon (1962), Welsh (1964), Rust (1965b) and Floyd (1975) placed emphasis on examining the petrography of the sandstones and their primary structures such that a significant body of knowledge now exists in these areas. Petrographic analysis of sandstones enables us to determine the tectonic source of the detrital components, but is of little value in determining the tectonic setting of their deposition (Mack 1984, Lash 1985). It is hoped in this chapter to bring together petrographic and other major aspects of sedimentology to bear on the problem of the palaeoenvironment and tectonic setting of deposition.

The chapter begins with a petrographic analysis of the sandstones, followed by an examination of turbidites and their structures as displayed in the Rhinns. Using the turbidite facies scheme of Walker and Mutti (1973) and Mutti and Ricci-Lucchi (1975) the depositional environment of the Rhinns sediments and its development through time is examined. Palaeocurrent data for the area are analysed, followed by a discussion of the significance of some derived coral specimens. At various points throughout the chapter the sedimentology of Rhinns is related to that of the Southern Uplands-Down-Longford terrane as a whole and conclusions about tectonic setting are drawn.

3.2 SANDSTONE PETROGRAPHY

One-hundred and twenty-one samples of sandstone were collected across-strike at approximate 200 m intervals along the 25 km of exposed coastal outcrop. A thin section was taken from each. Only samples of coarse-sand grade were obtained where possible, however in the medium to fine grained Mull of Galloway Formation and very coarse grained members of the Mull of Logan Formation, the closest approximation to a coarse sand grade was obtained. Fifty one of these samples were further selected for point count analysis. These were spaced across-strike at approximately 200-400 m intervals along the 20 km of exposed coastal outcrop forming the W coast of the peninsula, but excluding the aureoles surrounding the Portencorkrie and Cairngarroch Bay intrusives. Initially counts of 1000 points were made on each thin section, but the percentages of constituents did not differ significantly from those obtained by counting 500 points, therefore counts were made of between 500 and 530 points per sample at intervals of 0.2 mm. The constituents were grouped into eight main categories, these being:-

(1) Quartz - subdivided into monocrystalline and polycrystalline quartz including chert.

(2) Feldspar - subdivided into plagioclase and alkali feldspar.

(3) Acid igneous clasts - leucocratic igneous rocks (principally the granitic suite).

(4) Basic igneous clasts - melanocratic igneous rocks, subdivided into spilitic/gabbroic clasts.

(5) Sedimentary clasts - principally shale and siltstone.

(6) Metamorphic clasts - principally quartzite and schist.

(7) Ferromagnesian minerals - principally pyroxene and amphibole.

(8) Matrix - all material less then 0.1 mm plus heavy minerals excluding pyroxene and amphibole, but including

garnet, ores, micas and calcareous material).

In addition numerical details were recorded of component variation within the categories to enable the data to be plotted into classification schemes used by other workers within the Southern Uplands (eg Walton 1955, Kelling 1962, etc) as well as the more widely applicable schemes of Dickinson and Suczek (1979) and Ingersoll and Suczek (1979). The principle source of error in the categorisation scheme used is the differentiation between fine-grained/glassy acid igneous volcanics and chert. This is particularly so where phenocrysts are absent and devitrification has occurred. As a result chert has been included in the polycrystalline quartz category.

Point count results are listed in Appendix 3 along with the means for each formation. The results are discussed in the following sections and represented diagrammatically using ternary plots (Figs 3.1-3.7). The recalculated volumetric percentages of each ternary plot category are listed in Appendix 4.

3.2.1 Classification and texture

Sandstones are classified by the percentage variation of 4 components: quartz (plus chert); feldspar; rock fragments; and matrix. In Fig 3.1 these components have been plotted on a ternary diagram based on the classification scheme of Pettijohn (1975, after Dott 1964), with feldspar and rock fragments combining at one corner. The vast bulk of the sandstones analysed plot within the field of wackes consisting of 15-75% matrix. A few plot as arenites where the matrix content is less than 15%. The relatively low matrix content recorded from some Mull of Logan Formation sandstones is due to the difficulty in obtaining samples of coarse sand grade from very coarse grained members, the increased grain size causing a corresponding decrease in the volume of matrix. In the Money Head Formation the drop in matrix content is not due to sampling difficulties, but is a characteristic feature of the rocks. The mean matrix content of the formation at 20% is the lowest in the Rhinns. The reason for this will be examined later. By replotting the data into the more familiar Q-F-RF classification

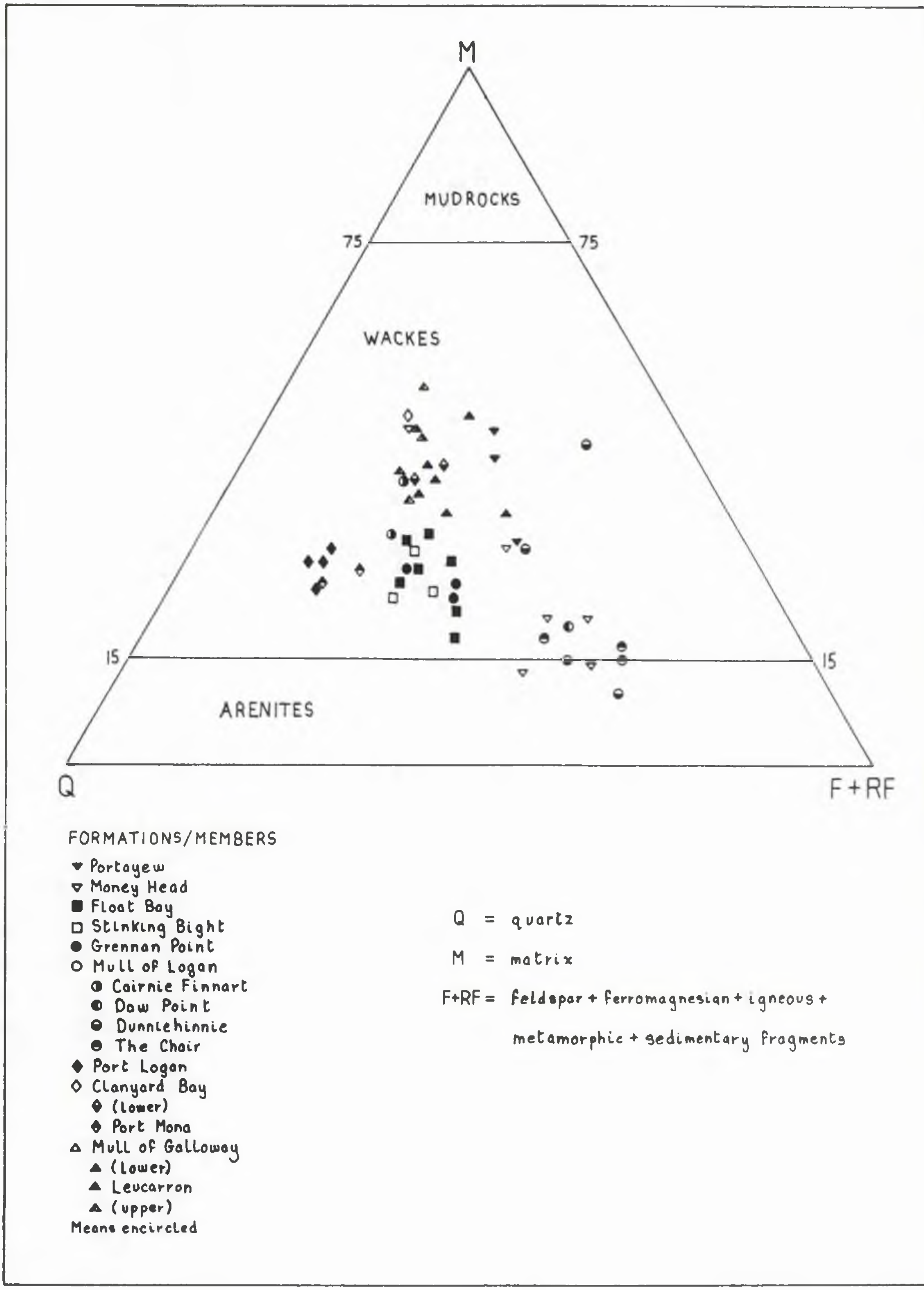


Fig 3.1: M-Q-F+RF diagram, composition fields after Pettijohn (1975, after Dott 1964

scheme of Pettijohn (1975, after Dott 1964) (Fig 3.2) the sandstones are defined as lithic greywackes.

The maturity index is the ratio of quartz to all other rock and mineral fragments (Walton 1955, Pettijohn 1975) and varies greatly in the Rhinns from a value of 0.6 in the Money Head Formation (Plate 3.1) to 3.3 in the Port Logan Formation (Plate 3.2). Although this reflects a general increase in maturity as the formations get younger southwards, it is believed to be partially influenced by differences in the grain size of the samples collected. The provenance index is the ratio of feldspar to rock fragments (Pettijohn 1975) and differentiates between a supracrustal source, yielding rock fragments, and a deep-seated source, yielding feldspar. Values in the Rhinns are in the order 0.4-0.5 indicating a supracrustal source. The more discriminating techniques of provenance determination of Dickinson and Suczek (1975) and Ingersoll and Suczek (1979) are applied to the data in the next section.

It is not surprising to find that rocks compositionally classified as lithic greywackes are also texturally distinctive. The grain size variation between formations, members, beds and within beds is adequately described in the chapter on stratigraphy, however within each thin section a wide range of grain sizes exist indicating poor to very poor sorting. As the clay content of the greywackes is greater than 5% they are defined as immature sandstone using Folks (1968) Textural Maturity Flow Sheet. The greywackes of the Rhinns have grains varying from angular to rounded as defined by Powers (1953), but are typically angular.

3.2.2 Classification and provenance

Emphasis is placed in this study on determining the compositional variation of the greywackes and relating it to provenance rather than attempting to determine distinct petrofacies by which formations can be defined. As a result the ternary plots used are those advocated by Dickinson and Suczek (1979, see also Ingersoll and Suczek 1979) for provenance studies on sandstones, in addition to the Q-M-F plot of Walton (1955)

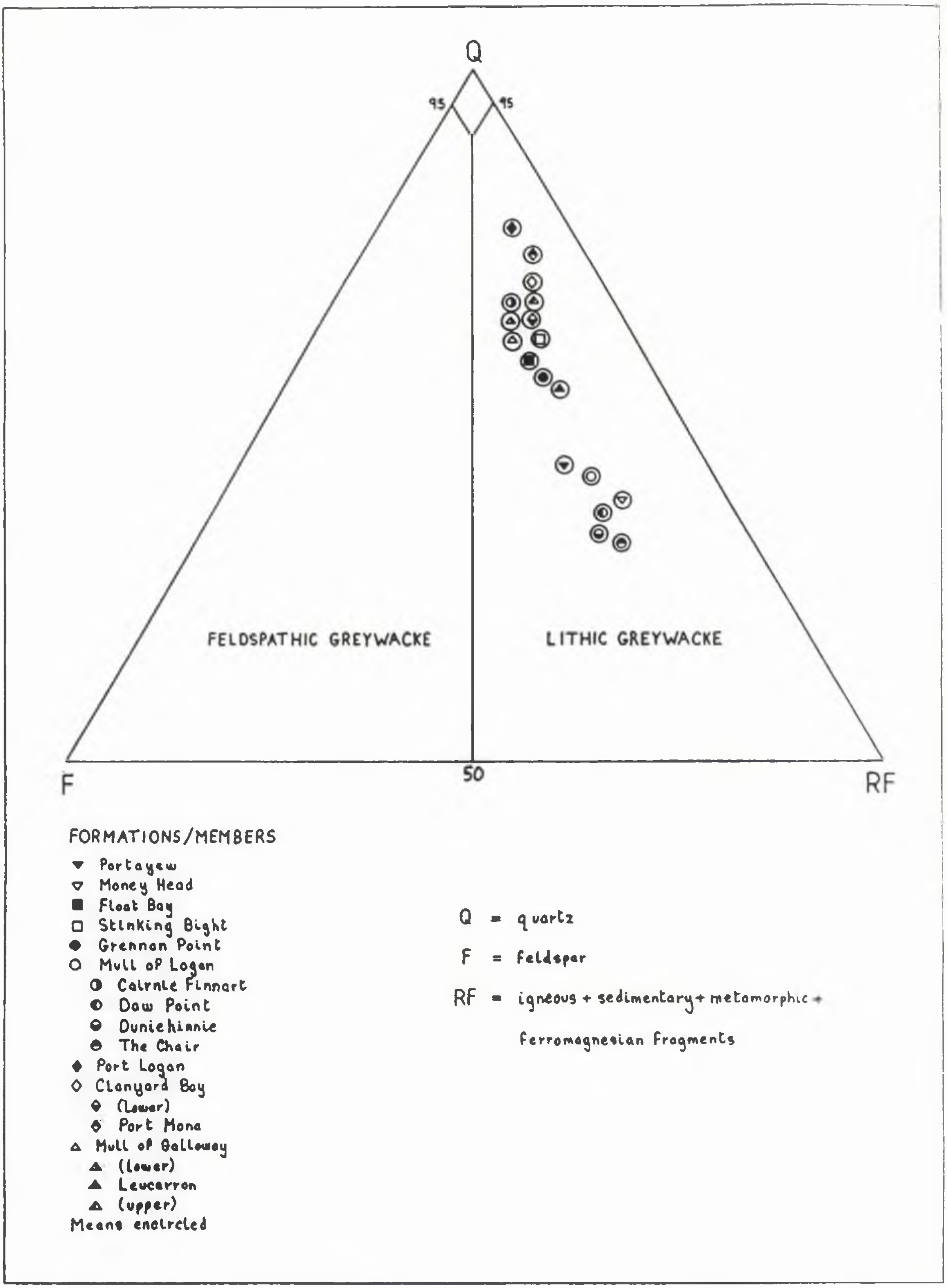


Fig 3.2: Q-F-RF diagram, composition fields after Pettijohn (1975, after Dott 1964).

Plate 3.1: Photomicrograph of Money Head Formation greywacke showing pyroxenes and basic volcanic clasts. Specimen MH2, polarised light, x40

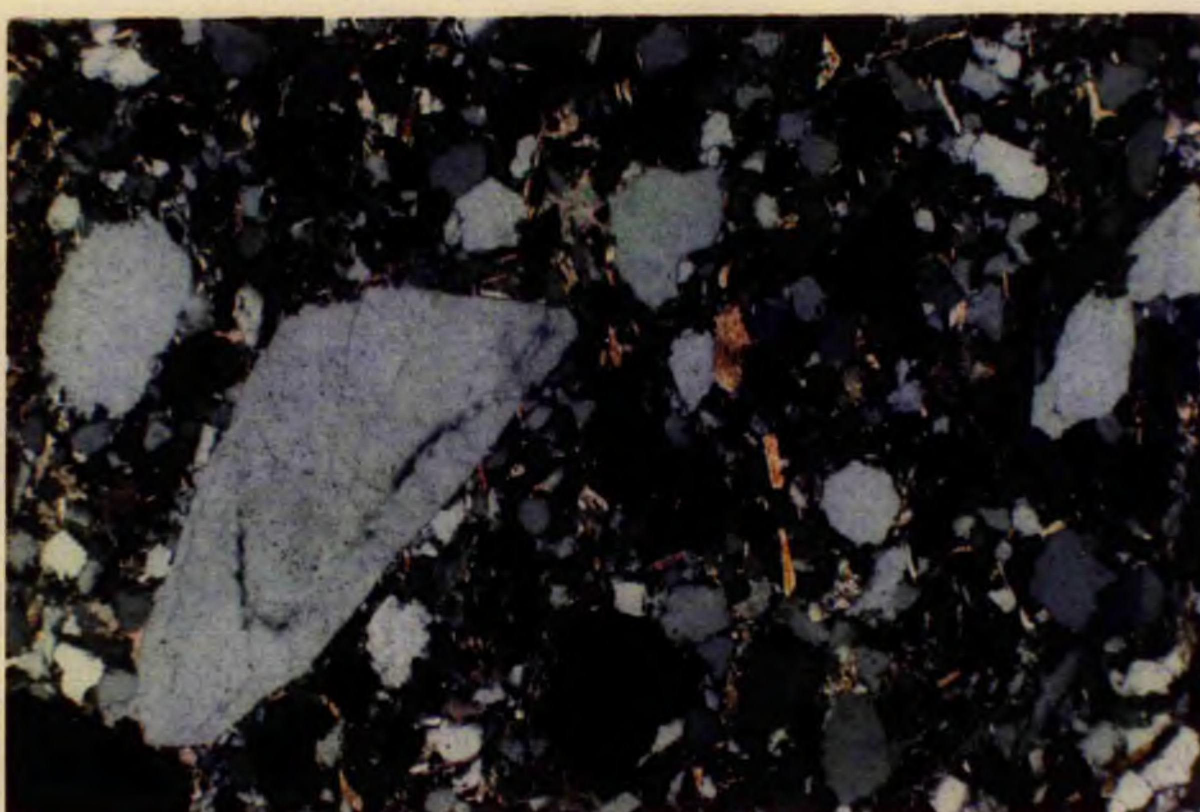


Plate 3.2: Photomicrograph of Port Logan Formation greywacke showing quartz overgrowth and pressure solution effects. Specimen L174, polarised light, x40

which is a standard by which comparision can be made with other petrographic studies in the Southern Uplands. Dickinson and Suczek believe that the 'detrital framework modes of sandstone suites from different kinds of basin are a function of provenance types governed by plate tectonics'. Numerous basins are now known where this is not the case (see Mack 1984, Velbel 1985, Lash 1985) and the real value of Dickinson and Suczek's work lies not in relating sandstone composition to the tectonic setting of its depositional basin but to its tectonic source. These plots also usefully display the compositional variation of the sandstones and their components and to this end the formation means are shown on each of them.

The Q-F-L diagram (Fig 3.3) is similar to the Q-F-RF diagram (Fig 3.2) of Pettijohn's classification scheme (1975, after Dott 1964). Full grain populations are displayed and aspects of grain stability and thus relief, weathering and transport mechanism are emphasised, as well as source rock. The most striking feature is the wide variation in composition of the Rhinns greywackes. The greatest grain stability is evident in the rather quartzose Port Logan Formation and Clanyard Bay Formation, and the least stability in the Money Head, Mull of Logan and Portayew Formations, the former two showing significant enrichment in basic igneous clasts and ferromagnesian minerals (Plate 3.1). There is also a general tendency for the younger southern formations to have greater grain stability than the older northern formations, though the Mull of Logan Formation is an obvious exception to this. Most of the samples plot within the recycled orogen provenance field although some Money Head Formation and Mull of Logan Formation samples tend towards the magmatic arc provenance field. The more quartzose formations have a collision orogen type provenance, while the less stable formations have a subduction complex type provenance (Dickinson and Suczek 1979).

The Q_m-F-L_t diagram (Fig 3.4) displays the full grain population and relates to the grain size of the source rock, as fine grained rocks yield more lithic fragments of

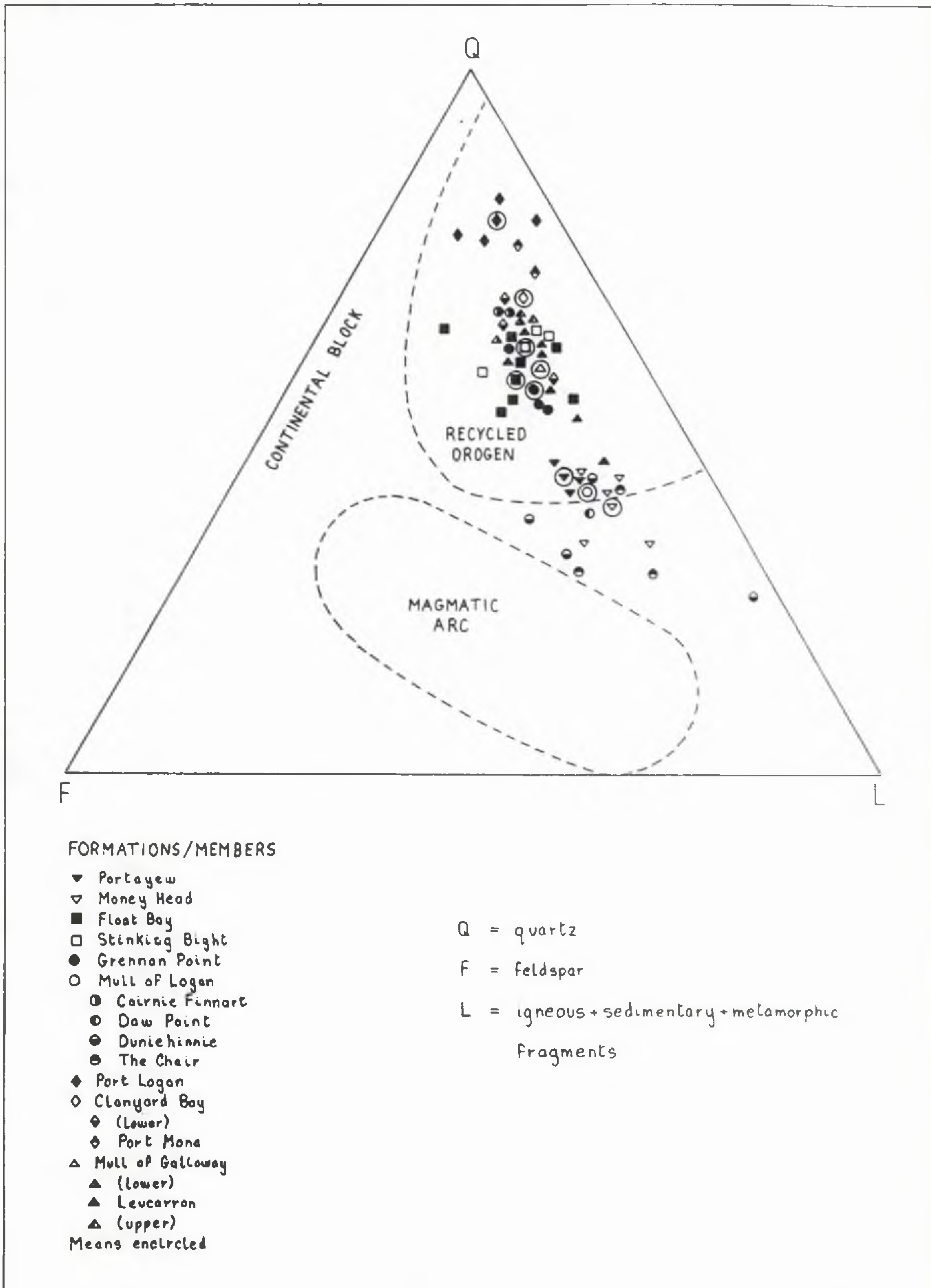


Fig 3.3: Q-F-L diagram, provenance fields after Dickinson and Suczek (1979).

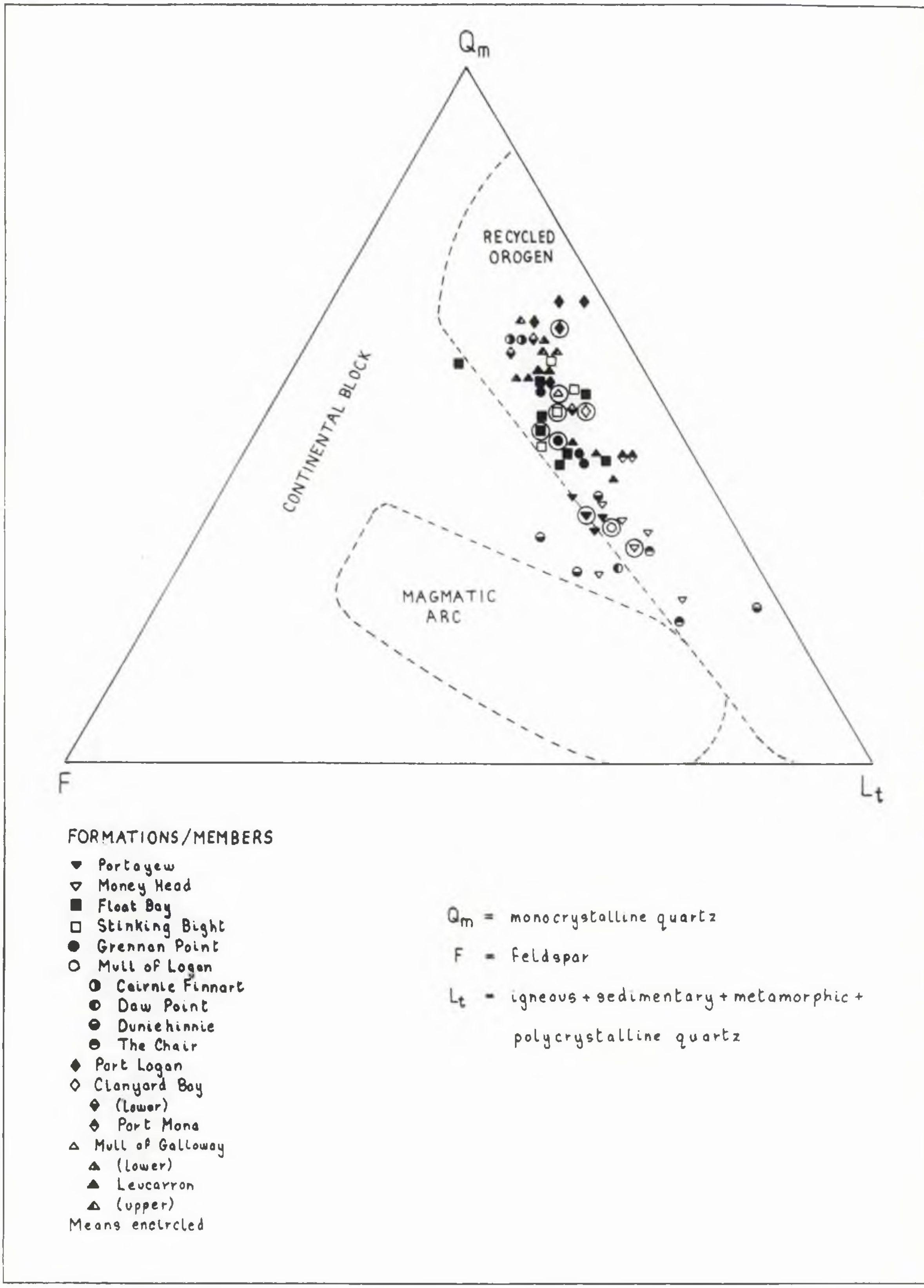


Fig 3.4: Q_m-F-L_t diagram, provenance fields after Dickinson and Suczek (1979).

sand size. Polycrystalline quartz is plotted at the same pole as the lithic fragments. The general relations displayed in the Q-F-L plot are retained here through a closer grouping of samples is noticeable due to the greater proportion of polycrystalline quartz in the Port Logan Formation and Clanyard Bay Formation. Most samples plot once again in the recycled orogen provenance field despite a relatively high feldspar content that causes some samples to plot close to the magmatic arc provenance field. The Rhinns formations generally have collision orogen and foreland uplift provenance types, though the more lithic rich Mull of Logan, Money Head and Portayew Formations tend towards a subduction complex type provenance (Dickinson and Suczek 1979).

The Q_p-L_v-L_s diagram (Fig 3.5) displays a partial grain population revealing the character of the polycrystalline components of the sandstone. It is useful for differentiating the different types of magmatic arc and recycled orogen provenances. Most samples plot towards the L_v pole either within the field for magmatic arc sources or close to it. This is rather surprising when the Q-F-K and Q_mF-L_t diagrams (Fig 3.3 and 3.4) each indicate the samples had a recycled orogen provenance. This would suggest that the difficulty encountered during point counting in differentiating between fine grained/glassy acid igneous clasts and cherts has caused the plots to offset away from the Q_p pole towards the L_v pole. If this is the case then the samples should plot closer to the Q_p pole indicating a subduction complex source, as do the Port Logan Formation and some Clanyard Bay Formation samples. Whichever be the case the high L_v/L_s ratios of between 1.1 and 4.3 for the Rhinns formations, as displayed on the diagram, indicate the greywackes are unlikely to have either a foreland uplift or collision orogen source as defined by Dickinson and Suczek (1979).

The Q_m-P-K diagram (Fig 3.6) displays a partial grain population revealing the character of the monocrystalline components of the sandstones. It demonstrates the predominance of plagioclase feldspar over alkali feldspar in the samples indicating a probable magmatic arc source for the feldspars, although the high quartz content rules

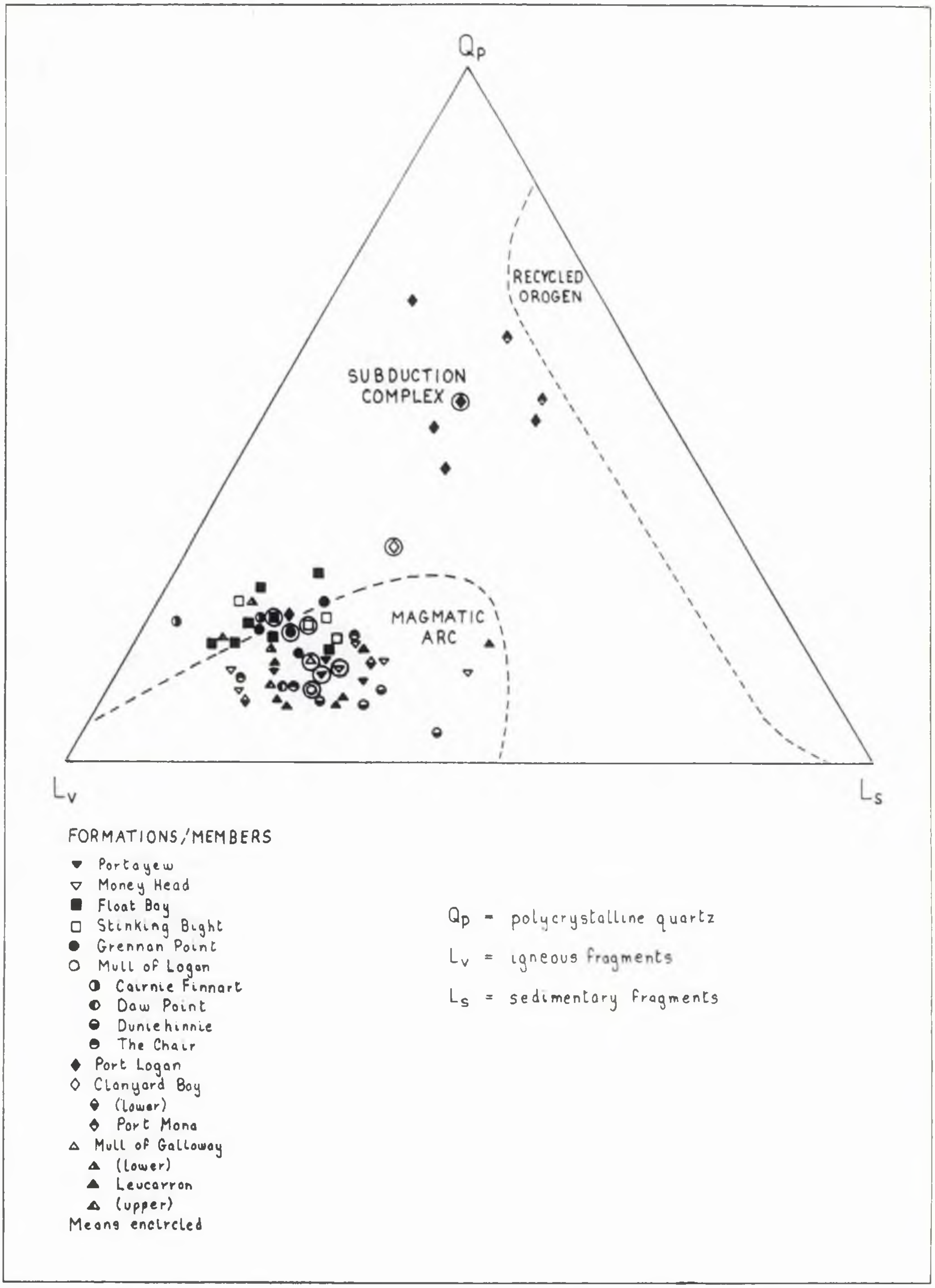


Fig 3.5: Q_p-L_v-L_s diagram, provenance fields after Dickinson and Suczek (1979).

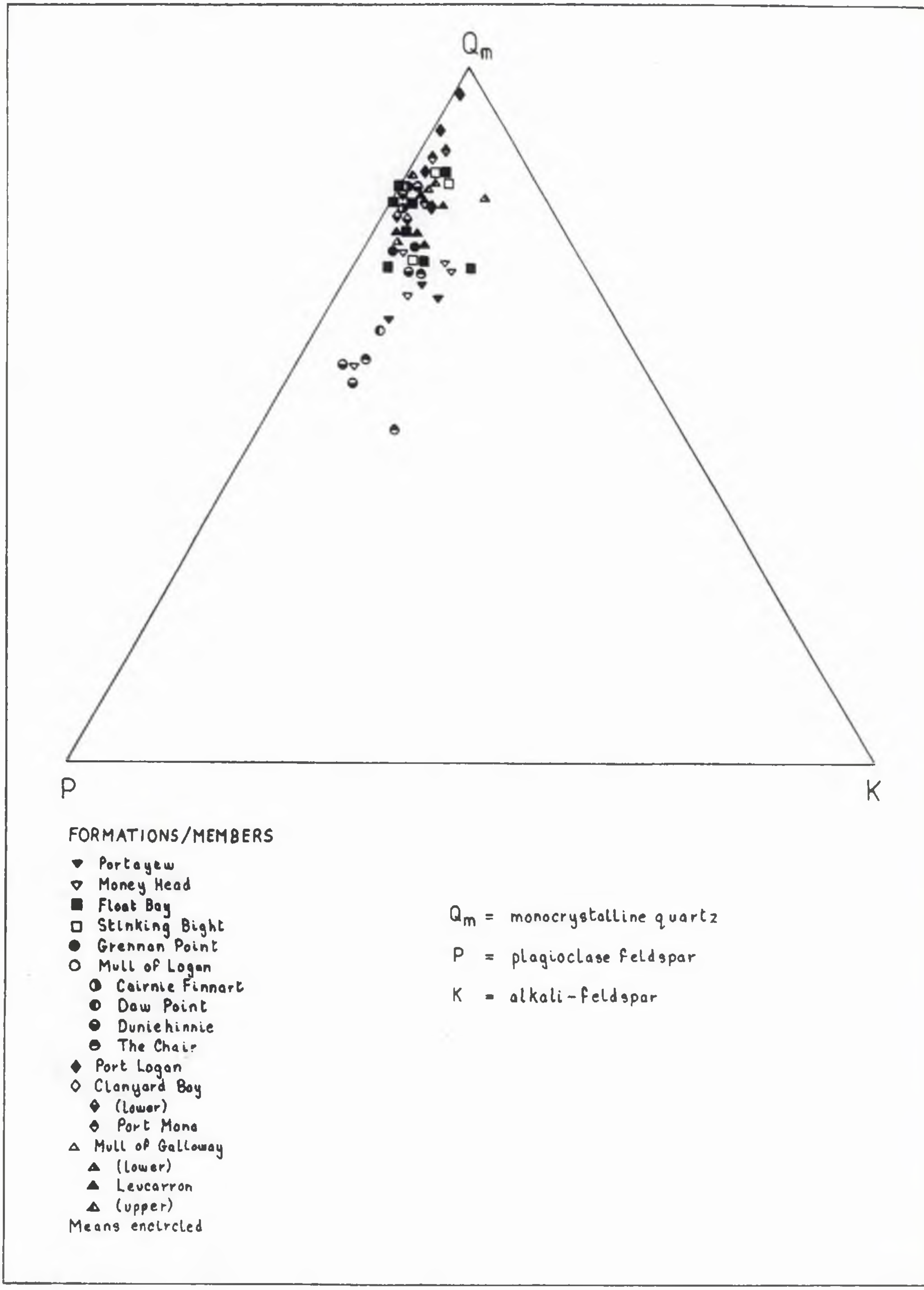


Fig 3.6: Q_m-P-K diagram.

out a magmatic arc provenance for the samples as a whole, excepting possibly for the Portayew, Money Head and Mull of Logan Formations. The plagioclase/total feldspar ratio for each formation ranges from 0.7 to 0.87 further supporting a volcanic source for the feldspars (Maynard *et al* 1982).

The Q-M-F diagram (Fig 3.7) of Walton (1955) has been used in most subsequent petrographic studies of Southern Uplands greywackes (eg Kelling 1962, Gordon 1962, Welsh 1964, Floyd 1975, Hepworth 1982 etc) and as such is important for comparing the petrography of different areas. The Rhinns samples group rather well when plotted on it remaining distant from the F pole of basic igneous clasts, feldspar and ferromagnesian minerals and trending towards the siliceous Q pole. This plot will be discussed more fully in the section dealing with the petrography of the Southern Uplands as a whole.

Despite the general siliceous character of the Rhinns greywackes, the most striking feature of the petrography is the degree of compositional variation they display. This variation is not only evident between formations, but also within formations and between members. It is most strikingly displayed in the Mull of Logan Formation where the quartz-rich Cairnie Finnart Member is conformably overlain by the relatively quartz-poor and volcanics enriched Daw Point, Duniehinnie and Chair Members. In this section this change is made conspicuous by a sudden influx of detrital ferromagnesian minerals. A similar change though in reverse occurs within the Money Head Formation where the lower 600 m are enriched in volcanics and ferromagnesian minerals (Plate 3.1) and are overlain by a 300 m sequence from which they are depleted. This latter change is not picked out by the point count analysis. In addition the Port Logan Formation and Port Mona Member of Clanyard Bay Formation are distinctly more quartzose than the other formations (Plate 3.2). Due to the difficulty in differentiating fine grained/glassy acid igneous clasts from chert, the Q_m-F-L_t diagram (Fig 3.4), in which polycrystalline quartz is grouped with the lithic fragments, is the

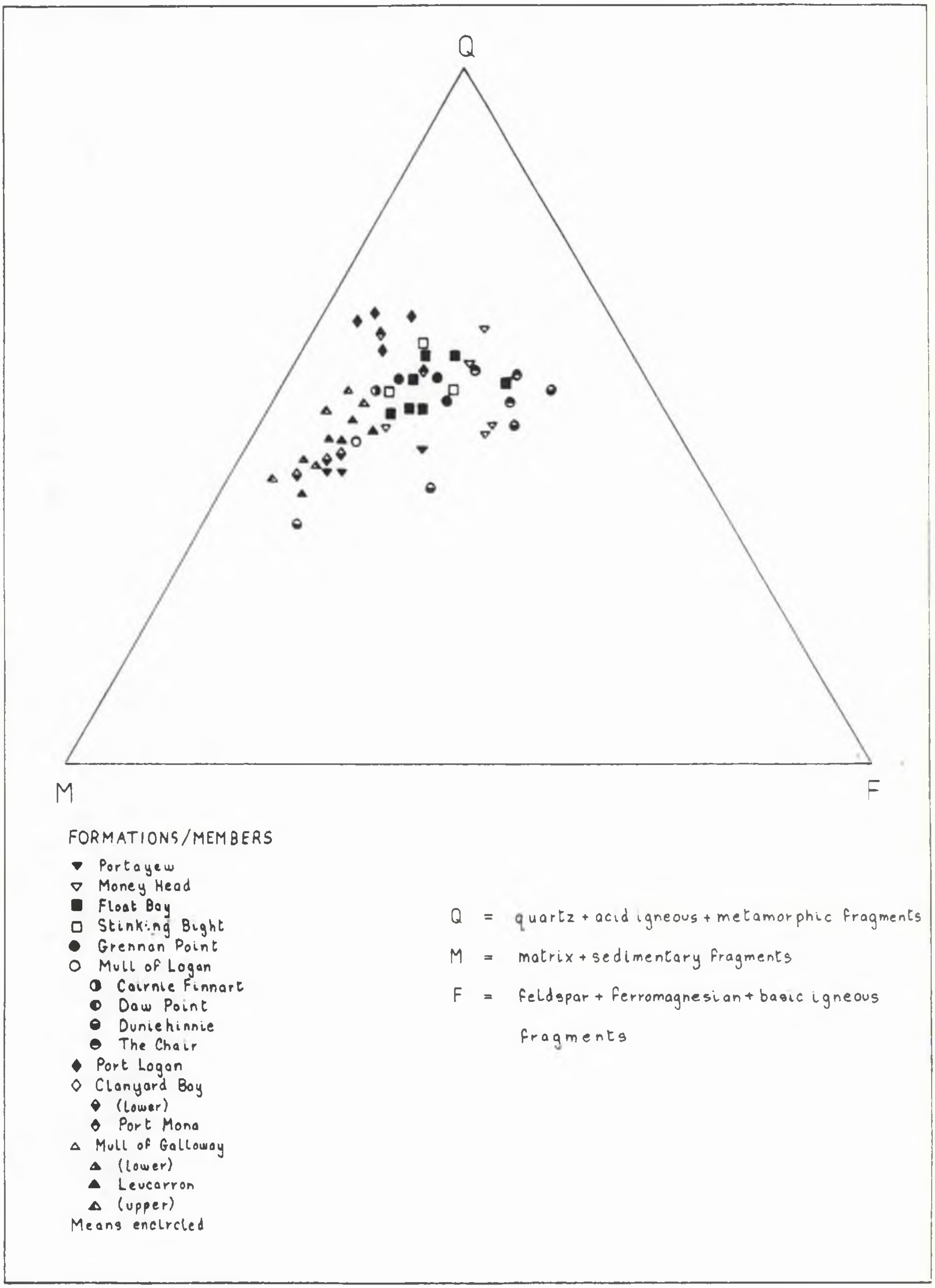


Fig 3.7: Q-M-F diagram

most reliably accurate plot of the full grain population. It differs from the Q-F-L diagram (Fig 3.3) only slightly by causing the Port Logan Formation and Port Mona Member of the Clanyard Bay Formation to shift a proportionately greater distance away from the Q_m pole towards the L_t pole than the other formations. This has the effect of grouping the formations into two distinct clusters. Cluster A consists of the Portayew Formation, Money Head Foramtion and Mull of Logan Formation, excluding the Cairnie Finnart Member, and has an excess of lithic fragment, particularly igneous clasts, over monominerallic quartz. In general in thin section these rocks are distinctively enriched in ferromagnesian minerals (Plate 3.1). Cluster B consists of all the remaining formations plus the Cairnie Finnart Member of the Mull of Logan Formation and is more siliceous with monomineralic quartz in excess over lithic fragments (Plate 3.2) Ferromagnesian minerals are present but rare in thin section. These clusters suggest the Rhinns greywackes had two distinct sources.

Most of the point count samples from the Rhinns plot within the recycled orogen provenance field of Dickinson and Suczek (1979) although a number of Cluster A samples plot between the recycled orogen provenance field and magmatic arc provenance field. Dickinson and Suczek (1979) subdivided their recyclced orogen provenance into three types: subduction complex; collision orogen; and foreland uplift. The samples from Cluster A are closest to a subduction complex provenance, whereas the Cluster B samples tend towards a collison orogen or possible foreland uplift provenance. The Q_p-L_v-L_s diagram (Fig 3.5) is used for separating the different types of recycled orogen provenance and the high L_v/L_s ratios displayed in it virtually rule out the possibility of the Rhinns samples having a collision orogen or foreland uplift source, and support either a subduction complex or magmatic arc source. As the quartz content in the samples is much too high for a magmatic arc provenance, a subduction complex source is the most likely. This would be consistent with the magmatic arc source suggested for the feldspars (Fig 3.6). In conclusion, the data suggest Cluster A has a source in a subduction complex with significant subsidiary input from a magmatic arc, whereas Cluster B has a source in a more mature subduction complex with possible subsidiary input from a collision orogen or foreland uplift source. These comments refer only to the composition and provenance of the sandstones in the Rhinns and should not be used to infer the tectonic setting of their basin of deposition.

3.2.3 Summary of the petrography of the formations

3.2.3.1 Portayew Formation

The Portayew Formation is relatively quartz poor (25%), but resembles the Mull of Galloway Formation in having a high matrix content dominated by secondary carbonate material. Partial replacement of the matrix and all but the quartzose grains is extensive. Whether any of this carbonate had a primary origin is difficult to assess, though no detrital carbonate grains have been positively identified. The proximity of the samples to the granitic and dioritic intrusions of Cairngarroch Bay (NX04454953) and their presence in the brecciated Portayew Fault Zone (NX03955007), along with their inability to be traced NE or SW along-strike, make localised metasomatism related to an igneous source seem likely. Feldspar content is a very typical 11%, though basic clasts are uncommon and ferromagnesian minerals very rare. The most common lithic components are acid igneous clasts.

3.2.3.2 Cairngarroch Formation

Although broadly retaining its sedimentary character, the Cairngarroch Formation is throughout its outcrop a hornfels, having been thermally metamorphosed by the Cairngarroch Bay intrusives and their along-strike equivalents. The degree of alteration increases as the intrusives are approached southwards. In the N the clasts remain relatively unaltered, though much of the matrix has been reconstituted into a welded quartz with abundant new growths of biotite. Total recrystallisation is only encountered at the margins of the intrusions. The unaltered clasts consist mainly of quartz, acid igneous fragments and metamorphic quartzite. Basic igneous clasts and ferromagnesian mineals are both relatively rare and the feldspar content, reflecting this, is rather low.

3.2.3.3 Money Head Formation

This distinctive formation is characterised by having both a low quartz and low matrix content and subdivides petrographically into two divisions. The lower 600 m are enriched in ferromagnesian minerals and basic igneous, acid igneous and sedimentary clasts, particularly shale (Plate 3.1). Occasionally units within the sequence fail to display this igneous enrichment and instead have higher concentrations of metamorphic quartzite and shale. By contrast the upper 300 m are most notable for their greatly reduced matrix content defining them as arenites rather than wackes. They have few basic igneous clasts or ferromagnesian minerals but contain a significant proportion of all other lithic fragment types. Concentrations of ore minerals in sub-parallel laminae (Plate 3.3) in association with the low matrix content, indicate these sandstones have undergone winnowing. A full description of these winnowed sediments and their significance is given in a later section. Feldspar content throughout the formation is about 10% and is dominantly plagioclase.

3.2.3.4 Float Bay Formation

The Float Bay Formation, 'Stinking Bight beds' and Grennan Point Formation display a remarkably similar if somewhat nondescript petrography. The differences in composition of each formation are negligible. The formations are characterised by a high quartz content (41-44%) of which only about 5% is of polycrystalline quartz, with matrix being the second most important constituent at 26-27%. Lithic clasts amount to 20% of the total rock and are mostly acid or intermediate igneous, with metamorphic fragments quite common and sedimentary clasts present in small numbers. Ferromagnesian minerals are present, but are very rare. Feldspars amount to a typical 10-11%, with plagioclases (albite composition) outnumbering alkali felspars (mainly

Plate 3.3: Photomicrograph of a dark lamina of ore minerals, (principally pyrite and ilmenite) in a fine-grained winnowed turbidite from the Money Head Formation. Specimen CR2, ordinary light, x40

Plate 3.4: Photomicrograph of Mull of Galloway Formation greywacke showing carbonate enrichment and possible detrital carbonate clast (upper left quadrant). Specimen L139, polarised light, x40

orthoclase with rare microcline) by about 3 to 1. Detrital garnets, spinels and zircons are sporadically present, though rare.

3.2.3.5 'Stinking Bight beds'

(Essentially the same as the Float Bay Formation)

3.2.3.6 Grennan Point Formation

(Essentially the same as the Float Bay Formation)

3.2.3.7 Mull of Logan Formation

This formation subdivides markedly into two distinct petrographic types. The Cairnie Finnart Member is quartz rich (45%) and has a lower than average feldspar content at 8% consisting predominantly of plagioclase. The matrix content of the rocks is high at 37%, though a corresponding paucity in the number and diversity of lithic clasts exists. Sedimentary and metamorphic clasts are rare, though acid igneous clasts are relatively common with a signficant number of basic igneous clasts also present. Ferromagnesian minerals are virtually absent from the rocks sampled.

By contrast the Daw Point Member, Duniehinnie Member and Chair Member, conformably overlying the Carnie Finnart Member are most notable for their relative enrichment in ferromagnesian minerals and low quartz content. They show a major increase in the percentage composition of lithic fragments, with acid igneous, basic igneous and metamorphic clasts all common. Sedimentary clasts also form a significant proportion of the sandstone matrix of the conglomeratic Duniehinnie Member. In line with the high percentage of basic igneous clasts present the feldspar content is also high at 13-14% and is dominantly plagioclase, though orthoclase, including microperthite, and microcline are also quite common. The amount of matrix present is very variable, particularly in the Duniehinnie Member, but overall tends to be low. Significantly the composition of the clasts of the intrabasinal conglomerate/olistostrome forming the Duniehinnie Member is the same as that of the sandstone matrix in which they are embedded.

3.2.3.8 Port Logan Formation

This distinctive, highly siliceous formation is more mature and better sorted than any other in the Rhinns (Plate 3.2). Over half the rock consists of quartz, of which one fifth comprises polycrystalline fragments. Correspondingly there is a marked decrease in the percentage of all other components present, excepting matrix. Metamorphic and acid igneous clasts are the most common lithic fragments, although the total lithic component amounts to only 11%. Feldspar content is low at 6%. Ferromagnesian minerals, particularly amphiboles, are occasionally present and there is a marked though sporadic occurrence of subhedral garnets in the lower half of the succession. Interpenetration of quartz grains and the development of suture contacts are frequently observable pressure solution features resulting from compaction.

3.2.3.9 Clanyard Bay Formation

Distinct petrographic differences exist between the Port Mona Member and the rest of the Clanyard Bay Formation. Although both contain just over 30% of monomineralIic quartz, the Port Mona Member is endowed with a further 19% of polycrystalline quartz, as opposed to 2% in the rest of the formation. The total lithic content of both amounts to about 14-15%, though consists mainly of metamorphic fragments in the Port Mona Member, while acid igneous fragments predominate in the rest of the formation. The other lithic clast types are present in much smaller quantities. Ferromagnesian minerals are rare and the feldspar content is low, particularly in the Port Mona Member where it amounts to just 5%. Feldspars are mostly plagioclase and have an albite composition. A high proportion (one third) of the matrix is carbonate in all but the Port Mona Member and is possibly the result of carbonate metasomatism related to the nearby Portencorkrie granite-diorite intrusion.

3.2.3.10 Mull of Galloway Formation

The Mull of Galloway Formation is immediately recognisable by the high proportion of matrix it contains (44%), two thirds of which is secondary carbonate material (Plate 3.4). Partial replacement of the matrix and all but the quartzose grains is extensive. This carbonate enrichment can be traced along-strike throughout the Southern Uplands and is a characteristic feature of the Hawick Group. Although no detrital carbonate grains have been positively identified in the Rhinns, the stratigraphically controlled nature of its distribution suggest that, unlike the metasomatic carbonate of the Portayew Formation, it has a detrital origin and has subsequently recrystallised and redistributed, partially replacing the other components. Quartz is the second most important constituent (34%) and acid igneous clasts the only common lithic fragments. Feldspar content at 7% is low, though is typical of the younger Rhinns formations. Ferromagnesian minerals are virtually absent from the samples. The Leucarron Member is petrographically the same as the rest of the formation.

3.2.4 Southern Uplands Petrography

After examining the petrography of the Rhinns it is essential to relate it to the region as a whole. A brief description of the petrography of the Northern Belt, Central Belt and Southern Belt is given, with emphasis placed on correlation within the Central Belt.

3.2.4.1 Northern Belt

Greater petrographic variation exists in the Northern Belt than elsewhere in the Southern Uplands and as a result its petrography has recieved more attention and is known in greater detail than in the belts to the S. The Northern Belt subdivides into two broad tracts separated by the strike-fault variously named the Carrickateane Fault, Killantringen Thrust or Leadhills Line. To the NW the greywackes are dominated by quartz, felsic igneous and metamorphic detritus, though a subsidiary petrofacies, containing andesitic minerals and lithic fragments named the Galdenoch petrofacies (Morris 1987), is found locally within it. Most of the greywackes have a recycled orogen provenance with palaeocurrent data indicating either northwesterly derivation or 'axial' (NE-SW) flow, excepting the Galdenoch petrofacies which has a magmatic arc provenance and a possible southeasterly derivation (Morris 1987).

The greywackes SE of the strike-fault are dominantly composed of fresh andesitic material, lithic fragments and blueschist detritus, but grade southeastwards into acid clast greywackes containing felsic igneous intrusive and extrusive detritus. In the extreme SE Morris (1987) defines the sporadically developed quartz dominated Shinnel Formation petrofacies. Most of the greywackes have a magmatic arc provenance with the increasing felsic content reflecting erosion of the arc and exposure of its plutonic/metamorphic root zone (Morris 1987), however the Shinnel Formation has a recycled orogen provenance. Southeasterly derivation has been claimed for these greywackes (Morris 1987, Stone *et al* 1987, but see Leggett 1987). The interbedding of volcaniclastic and sliciclastic greywackes is known to occur at a few localities (see Stone *et al* 1987, Morris 1987).

The Portayew Formation and Cairngarroch Formation of the Rhinns fall compositionally somewhat between the greywackes of the Shinnel Formation petrofacies and the acid clast greywackes immediately to their N, but have greater affinities with the latter.

3.2.4.2 Central Belt

Despite the pioneer work on Southern Uplands petrography by Walton (1955), less is known about the petrography of the Central Belt than the Northern Belt. Table 3.1 shows a general correlation of the available point count data on the Central Belt and the formation means have been plotted onto a Q-M-F diagram (Fig 3.8) for immediate comparative purposes.

Walton (1955) defined a Pyroxenous Group immediately S of the Northern Belt boundary in the Peebles area. This contains significant amounts of both felsic igneous and andesitic lithic and mineral fragments and is most easily distinguished by its high ferromagnesian mineral content. Kassi (1984) identified the same petrofacies

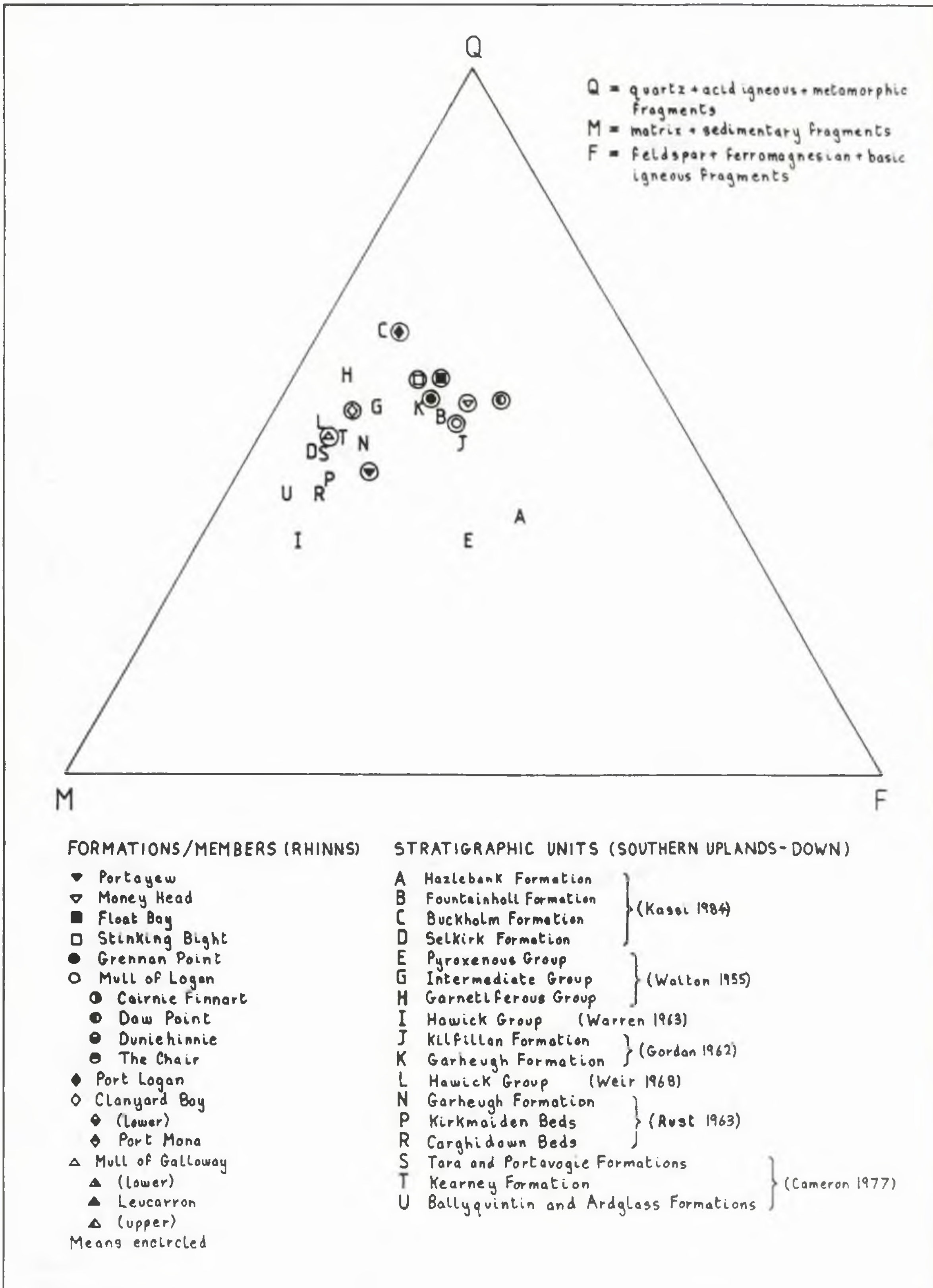


Fig 3.8: Q-M-F diagram for Central Belt formations.

(A) GALASHIELS - KASSI (1984) (N-45)

	HAZELBANK FORMATION	FOUNTAINHALL FORMATION	BUCKHOLM FORMATION	SELKIRK FORMATION
Q	23.1	31.7	43.7	30.0
F	10.4	15.1	5.5	5.4
A	12.3	16.4	13.6	14.5
B	22.7	5.0	1.5	1.7
Mt	1.5	2.5	5.4	1.7
S	2.2	1.4	0.9	0.8
Fm	4.3		-	0.1
M	23.4	27.8	29.4	45.9

(B) PEEBLES - WALTON (1955) (N-37)

	PYROXENOUS GROUP	INTERMEDIATE GROUP	GARNETIFEROUS GROUP
Qm	22.5	34.1	40.3
F	8.6	6.8	3.7
Qp+A+Mt	10.2	18.2	17.0
B	18.2	4.5	2.3
S	3.4	1.9	1.8
Fm	5.0	0.2	-
M	30.2	34.1	34.8

(C) HAWICK-WARREN (1963) (N-13)

	HAWICK GROUP
Qm	16.8
F	7.1
Qp+A+Mt	16.3
B	5.2
S	1.3
Fm	-
M	53.2

(D) WIGTOWN PENINSULA (NW) - GORDAN (1962) (N-60)

	KILFILLAN FORMATION	GARHEUGH FORMATION
Q	27.5	34.9
F	10.0	8.4
A	17.4	13.9
B	14.8	9.3
Mt	1.9	2.7
S	5.3	6.9
M+Fm	22.9	24.0

(E) GATEHOUSE - WEIR (1968) (N-58)

	HAWICK GROUP
Q	20.0
F	3.0
A	18.0
B	1.0
Mt	12.0
S	1.0
M+Fm	4.3

(F) WIGTOWN PENINSULA (SE) - RUST (1963) (N-45)

	GARHEUGH FORMATION	KIRKMAIDEN FORMATION	CARGHIDOWN FORMATION
Q	36.1	32.4	26.3
F	6.8	3.7	3.1
A	9.6	8.8	12.7
B	6.4	6.7	7.2
Mt	1.4	0.9	1.4
S	8.5	10.6	19.5
M	31.2	36.5	29.8

(G) RHINNS OF GALLOWAY - McCURRY (see APPENDIX 3) (N-51)

	MONEY HEAD FORMATION	FLOAT BAY FORMATION	'STINKING BIGHT BEDS'	GRENNAN POINT FORMATION	MULL OF LOGAN FORMATION	PORT LOGAN FORMATION	CLANYARD BAY FORMATION	MULL OF GALLOWAY FORMATION
Q	29.9	41.7	44.1	40.9	28.8	54.6	41.5	33.2
F	10.9	11.3	9.6	10.9	12.5	6.0	6.4	6.8
A	15.1	8.7	7.9	9.1	13.4	4.0	5.3	8.9
B	11.0	7.6	7.0	7.7	10.0	1.6	3.2	3.1
Mt	7.5	3.0	3.6	4.1	7.1	4.1	5.0	4.0
S	4.2	0.4	1.1	1.3	2.7	1.2	1.0	0.6
Fm	1.3	-	-	0.1	1.1	0.2	0.1	-
M	19.9	26.9	26.8	26.2	23.9	28.4	37.7	43.1

(H) LECALE - CAMERON (1977) (N-17)

	TARA/ PORTAVOGIE FORMATIONS	KEARNEY FORMATION	BALLQUINTIN/ ARDGLASS FORMATIONS
Q	30.2	30.5	20.2
F	5.8	8.0	1.9
A	9.3	14.0	10.6
B	2.2	1.3	5.7
Mt	6.0	3.1	8.8
S	4.2	4.3	8.6
Fm	0.7	1.3	0.3
M	41.8	37.6	4.4

Q: Quartz; Qm: Monocrystalline Quartz. Qp: Polycrystalline Quartz. F: Feldspar. A: Acid Igneous. B: Basic Igneous. Mt: Metamorphic. S: Sedimentary. Fm: Ferromagnesian Minerals. M: Matrix. N: Number of samples. Dashed lines separate regional lithostratigraphic belts defined in Section 2.4 and Table 2.2

TABLE 3.1 - REGIONAL CORRELATION OF POINT COUNT FORMATION MEANS FOR THE CENTRAL BELT

immediately NE along-strike in the Gala area, however when it is traced SW along-strike to the Money Head Formation of the Rhinns, *via* the Craignell Formation (basic division) NE of Newtonstewart (Cook and Weir 1980) and the Kilfillan Formation S of Glenluce (Gordon 1962), the andesitic detritus decreases in quantity and becomes increasingly sporadic in distribution. This trend of increasing maturity to the SW along-strike is confirmed by the absence of any significant andesitic detritus in the equivalent Irish outcrop.

The rest of the Gala Group, with a few localised exceptions, is compositionally equivalent to the Intermediate Group of Walton (1955) and is dominated by felsic igneous lithic and mineral fragments. The rather homogenous Float Bay Formation, 'Stinking Bight beds' and Grennan Point Formation of the Rhinns typify the older, northern formations of this petrofacies. The increase in maturity and better sorting evident in the Port Logan Formation and Clanyard Bay Formation to the S is duplicated regionally and is related to a decrease in felsic igneous detritus and corresponding increase in metamorphic detritus in the younger formations. Locally within this petrofacies lenticular belts with a markedly different petrography occur. Both the lower part of the Tassan Formation in County Monaghan (Morris 1986), and Daw Point, Duniehinnie and Chair Members of the Mull of Logan Formation in the Rhinns, plus the Alticry Member of the Corwall Formation, 20 km NE along-strike in the Wigton Peninsula (Kelling *et al* 1987), have a petrography of mixed felsic igneous and andesitic lithic and mineral fragments. The latter belt may extend as far as an outcrop of the Craignell Formation (basic division) NE of Creetown (Cook and Weir 1980). Similarly the Garnetiferous Group (Walton 1955) and Buckholm Formation (Kassi 1984) in the Peebles-Gala ara are distinguished by the high concentration of garnets they contain, although they are dominantly composed of felsic igneous and metamorphic detritus.

The Hawick Group displays remarkably little petrographic variation throughout its outcrop. It is relatively mature and well sorted, similar to the younger Gala Group formations, but is dominated by a high carbonate content of presumably shallow marine origin, often redistributed and partially replacing the felsic igneous and metamorphic detritus. The presence of 'red mica', i.e. mica with a thin coating of haematite, is often taken as a diagnostic feature of the Hawick Group (eg. Rust 1965a, Kemp 1986), however red micas are rare in the Mull of Galloway Formation in the Rhinns and virtually absent from the Hawick Group in Ireland (hence Kemp's (1986) misinterpretation of the positon of the Hawick Group in Ireland, *cf* Barnes, Anderson and McCurry (1987)- Appendix 2). In Scotland they occur most commonly immediately N of the Southern Belt and become rarer northwards (see Barnes - in press). The Hawick Group has not been identified in Ireland SW of the Ards Peninsula and Lecale.

Palaeocurrent data for the Central Belt generally indicates either northwesterly derivation or 'axial' flow predominantly from the NE. An analysis of palaeocurrent data from the Rhinns tells a somewhat differnt story and is described later in Section 3.5.

3.2.4.3 Southern Belt

Petrographically the Southern Belt is remarkably homogenous and has a composition comparable to that of the Hawick Group. The quartzose greywackes are relatively mature and composed of felsic igneous and metamorphic lithic and mineral fragments. In addition to large amount of detrital carbonate with bioclasts, including corals, bryozoans and brachiopods occur. It is apparently more micaceous in the NW (Lumsden *et al* 1967) where it contains rare 'red micas' (Barnes - in press), but overall displays little compositional variation. Palaeocurrent flow was predominatly from the NE, though northwesterly derivation is evident in the Langholm area (Kemp 1987). The position of the Southern Belt in Ireland is equivocal.

3.2.4.4 Summary

The distribution and trends displayed by the principle clastic petrofacies in the Southern Uplands are shown in Fig 3.9. Any tectonic interpretation of the terrane has to explain the high degree of petrographic variation in the Northern Belt and Gala Group of the Central Belt and the relative homogeneity of the Hawick Group and Southern Belt. Overall there is an increase in maturity southeastwards with andesitic detritus an important constituent of many northwestern formations, while virtually absent from the SE, and the reciprocal being true with regard to carbonate detritus which is abundant in the southeastern formations and rare or absent in the NW. The Gala Group - Hawick Group boundary is of major importance in demarcating these changes. There is also some evidence of a southwesterly increase in maturity in the Central Belt, though this is perhaps not surprising as it matches the dominant palaeocurrent flow direction (see Section 3.5).

3.3 THE SEDIMENTS OF THE RHINNS AND THEIR STRUCTURES

The sediments composing the Rhinns are conglomerate, sandstone (including siltstone), shale, mudstone, chert and bentonite. By far the bulk of the sediment consists of interbedded sandstone and shale and is often referred to as 'flysch' (Studer 1827, Dzulynski and Walton 1965). The sandstones typically define as lithic greywackes in the classification scheme of Pettijohn (1975, after Dott 1964) (see Section 3.2.1 and Fig 3.1) and are here referred to as greywackes (see Dzulynski and Walton (1965) for discussion of term).

The poor sorting of the greywackes and the structures they contain indicate that the vast bulk of Rhinns sediments have been deposited in sediment gravity flows. These are defined by their grain support mechanism and are of four main types (Middleton and Hampton 1973):-

(1) Turbidity currents - particles are suspended by the upward component of turbulence

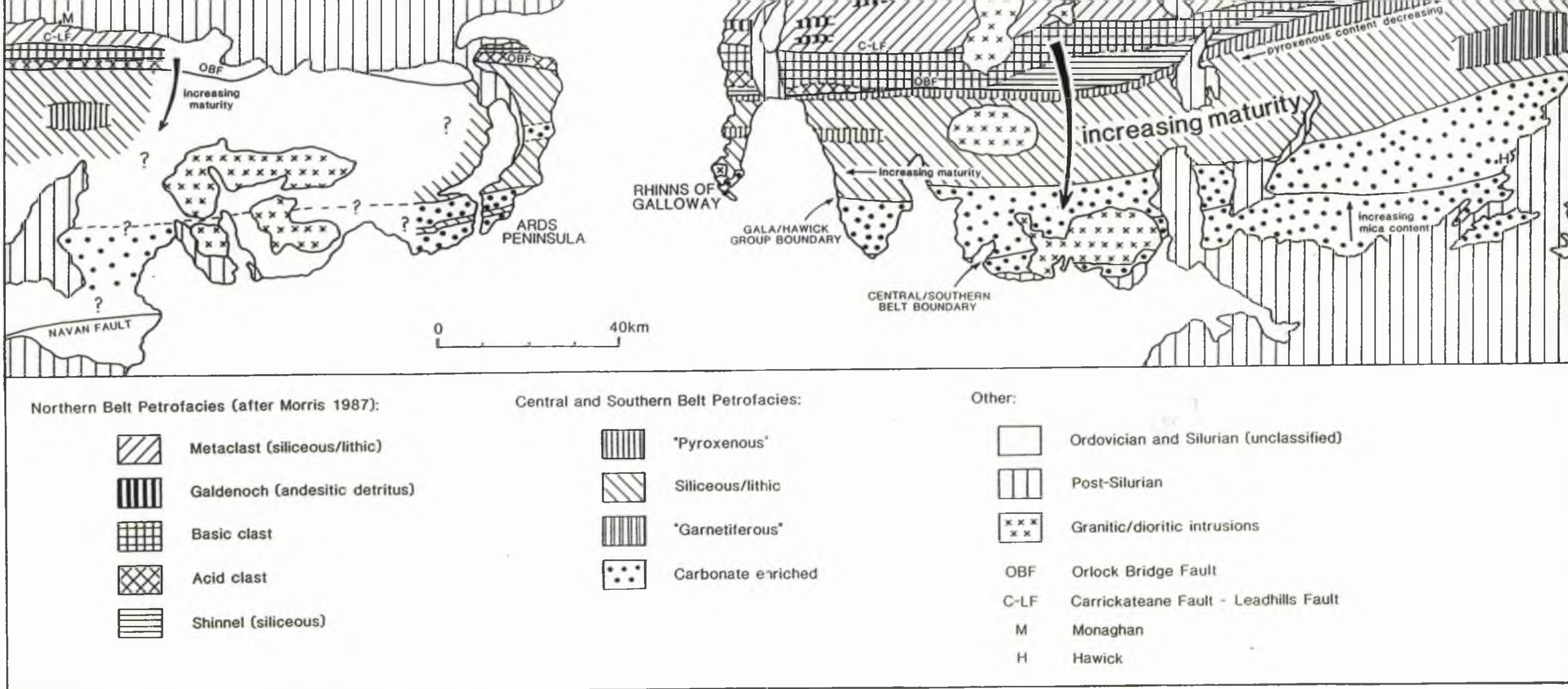


Fig 3.9: Regional petrofacies of the Southern Uplands-Down-Longford terrane. Northern Belt after Morris (1987)

and the mass moves down slope because its density is greater than that of the ambient fluid.

(2) Liquefied flows (fluidised sediment flows) - grains are suspended in their own upward moving porewater to form a liquified sand layer in which flow 'freezes' from the bottom upwards as pore fluids are progressively lost.

(3) Grain flows-grains are supported by the dispersive pressure of grain to grain collisions during movement down slope.

(4) Debris flows - grains are supported by a matrix of clay grade material and fluid that has enough cohesion to prevent the grains from settling, but no so much that the mass itself cannot flow.

In reality a bed is often acted upon by more than one grain support mechanism during its deposition and often a number operate together at the same time (for an example of this see Scrutton and McCurry (1987) - Appendix 5).

Turbidity currents were the dominant type of sediments gravity flow operative in the Rhinns and their deposits are referred to as turbidites, though the extent to which these are purely the product of flow by turbulent suspension is questionable. Bouma (1962) described an "ideal" sequence of structures expected in a turbidite (Fig 3.10), these are from base to top: T_a-massive, graded unit, T_b-parallel laminated, T_c-cross or convolute laminated, T_d-parallel laminated silt/mud, T_e-homogeneous mud. This 'Bouma sequence' reflects a decrease in flow strength with time: an upper flow regime in which surface waves are in phase with bed undulations producing the T_a and T_b divisions, is replaced by a lower flow regime in which surface waves are out of phase with bed undulations producing the T_c and T_d divisions (Middleton and Hampton 1973). The T_e division can be of either turbiditic origin or the result of hemipelagic and pelagic sedimentation. In reality the full Bouma sequence is rarely encountered in the Rhinns, but acts as a useful 'ideal' to which the turbidites can be compared.

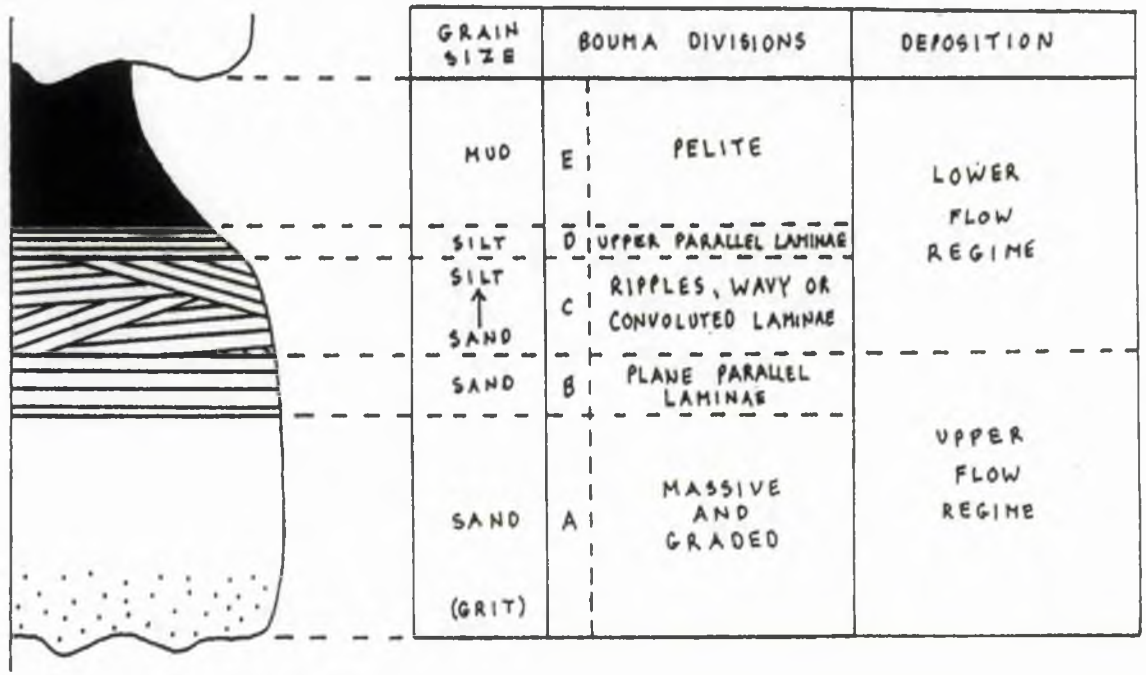


Fig 3.10: Ideal sequence of structures in a turbidite unit (based upon Middleton and Hampton 1973 - Fig 2, after Bouma 1962).

As well as possessing a distinctive set of internal structures, turbidites also have distinctive external sole markings. The Rhinns turbidites possess most of the common types of structure and as these are discussed and figured widely in the turbidite literature (see Dzulynski and Walton 1965) they are described only briefly below. The distribution of these structures is indicated in the stratigraphic descriptions (Chapter 2) and Table 2.1. Rarer structures and those of particular significance in the Rhinns are described more fully.

3.3.1 External current structures

(1) Flute marks - these are common throughout the Rhinns, though tend to be confined to the channelised sequences in the Mull of Galloway Formation (Plate 3.5). They range up to 350 mm x 300 mm in size, and 85 mm deep, though are generally much smaller, and are typically isolated and triangular (Dzulynski and Walton 1965). Linguiform and bulbous types are common in the more mature formations to the S where they sometimes combine into longitudinal, transverse or rare diagonal alignment patterns. They are usually found in association with other sole markings.

(2) Longitudinal ridge and furrows - these are associated with low concentration turbidity currents (see Stow 1986 for definition) and are rare in the coarser grained formations N of the Port Logan Bay Fault, excepting the Cairnie Finnart Member of the Mull of Logan Formation, and are common to the S of it, particularly in the Mull of Galloway Formation. The ridges are 5-40 mm apart and 1-4 mm high and usually have associated cuspate bars. They are typically straight and parallel sided, though a 'scaly' pattern is frequently seen and 'fleur-de-lys' structures occasionally present, the latter particularly so in the channelised sequences of the Mull of Galloway Formation suggesting rapid flow under upper flow regime conditions. The cuspate bars represent a deepening of the furrow, suggesting an origin similar to flute marks with which they are often found in association (see Dzulynski and Walton 1965).

Plate 3.5: Flute casts on a turbidite sole in the Leucarron Member of the Mull of Galloway Formation at Slouchanamars (NX13703094)

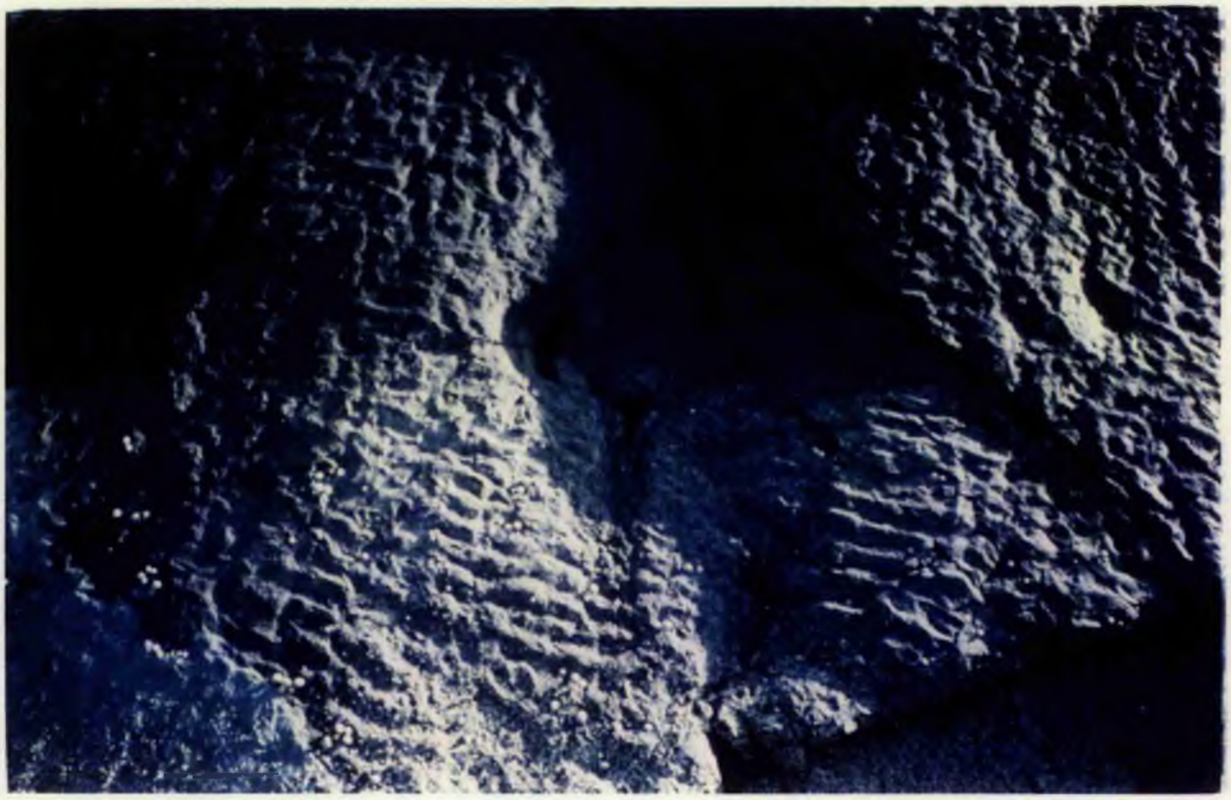


Plate 3.6: Sinuous ripples on the upper surface of a turbidite in the Port Logan Formation at Needles and Pins (NX09114028)

(3) Groove marks - these are common in all the Rhinns formations, though are usually associated with the coarser, more massive beds. They are very variable in size, but occur up to 120 mm in width, 35 mm in depth and over 3 m in length. Often a number of groove marks occur together on a bed and are divergent by up to 30^{o} indicating that current direction was not constant during each flow event. In the Rhinns groove marks are frequently found in association with isolated flute marks (*cf.* Hsu 1959), though this does not necessarily mean they formed at the same time under the same flow conditions. Mudstone rip-up-clasts are by far the most likely tools, though rare pebble grade bioclasts, as recorded from the 'Stinking Bight beds' (see Scrutton and McCurry 1987 - Appendix 5) are a possible alternative. Grid marks have only been recorded from a few localities in the Rhinns.

3.3.2 Internal current structures

(1) Graded bedding - grading is a diagnostic feature of turbidites and is of three main types of which two are common in the Rhinns and the third present locally (Fig 3.11). In distribution grading the whole grain size distribution becomes progressively finer from the base to the top of a bed and is produced by low concentration turbidity currents. In coarse-tail grading only the very coarsest grains in the bed are graded and is caused by high concentration turbidity currents. In inverse (reverse) grading the coarsest sand grains occur above the base of the bed and is produced by very high concentration sediment gravity flows. As might be expected coarse-tail grading is dominant in the coarser and more thickly-bedded northern formations of the Gala Group, while the younger more mature formations to the S tend to show distribution grading, although grading is much less distinctive in these finer grained lithologies. The two main types of grading are not incompatible and gradations exist between them, though overall coarse-tail grading is the more dominant in the Rhinns. Inverse grading is typical of some of the very coarse massive units found in the Money Head Formation

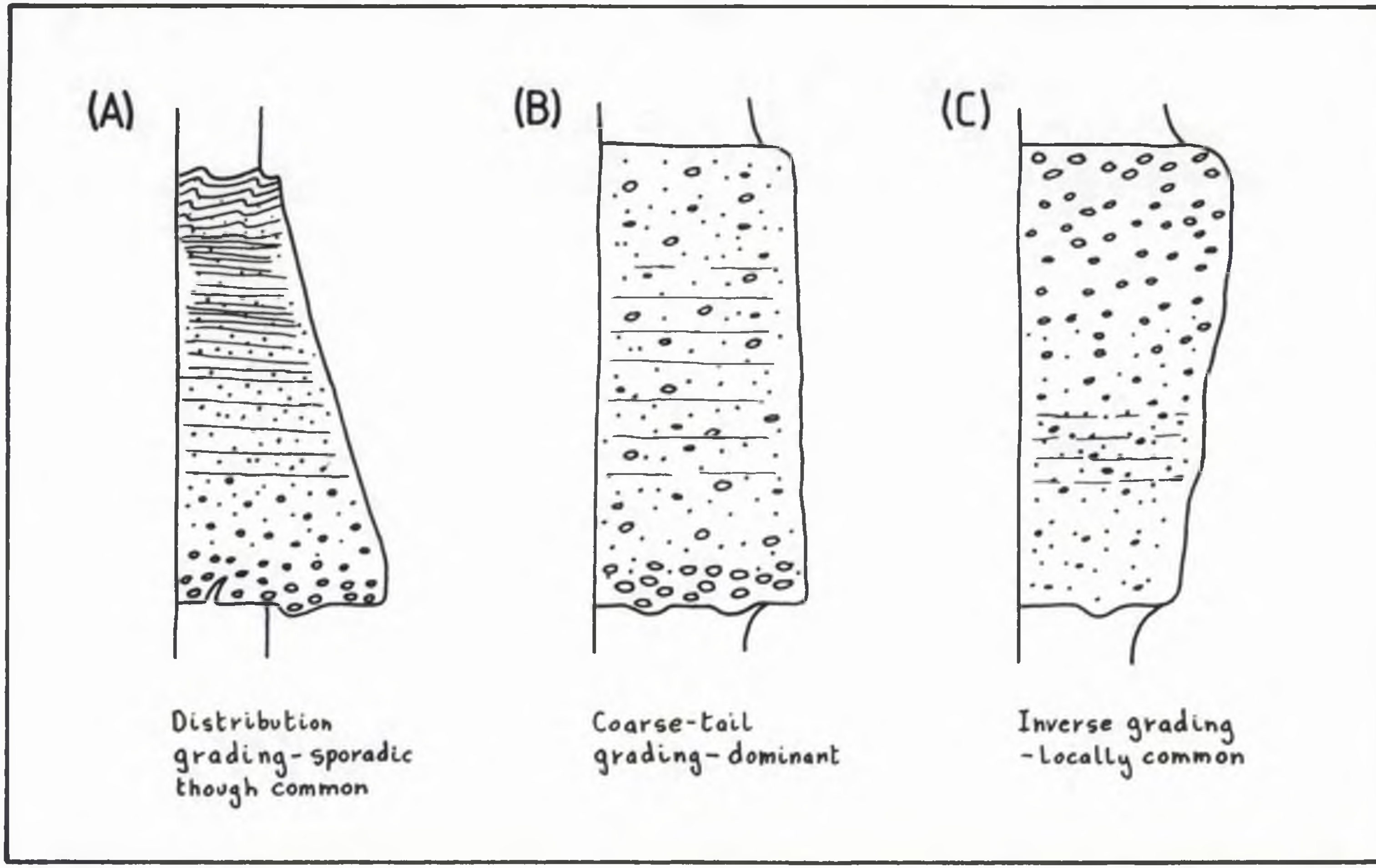


Fig 3.11: Distribution (A), coarse-tail (B) and reverse (C) grading as found in the Rhinns (after Middleton 1967).

and Mull of Logan Formation and its significance is duscussed more fully later (see Section 3.3.4).

(2) Planar parallel lamination - this is present in the T_b and T_d divisions of the Bouma sequence and is observed in all the Rhinns formations, though most extensively in the Mull of Galloway Formation. All sizes of laminae (up to 10 mm) occur in the T_b division, but are invariably less than 1 mm in the T_d division. Coarser laminae are often diffuse and ill-defined in thin section, but appear to result from the parallel orientation of size sorted grains. The mineralogical enrichment of layers gives rise to colour differences with dark laminae generally the result of an increase in clay mineral content, though in places caused by ore mineral enrichment.

(3) Ripple cross lamination - this occurs in the T_c division of the Bouma sequence and is found throughout the Rhinns, but particularly in the more mature southern formations. It is superbly displayed in the exposed bedding surfaces at Needles and Pins (NX09154020) in the Port Logan Formation (Plate 3.6). Climbing ripple-drift cross lamination is ubiquitous and is typically inclined at an angle of less than 20° and in size is generally less than wavelength 150 mm, height 30 mm. Ripples are either sinuous transverse or crescent crested (it is not possible to clearly distinguish whether the latter type are lunate or linguoid) and give rise to Kappa-cross-stratification (Allen 1963). The current directions indicated by the ripples are extremely variable and often differ substantially from those indicated by sole structures.

3.3.3 Liquefaction and load structures

Liquefaction and load structures are well developed and often spectacular in form in the Rhinns. They are concentrated in the Port Logan, Clanyard Bay and Mull of Galloway Formations, but are also common in the basal units of the Grennan Point Formation exposed in the vicinity of Drumbreddan Bay (NX07704360).

Load structures are very common and take a variety of forms. At their simplest they consist of downbulges of sandy material from the base of an overlying turbidite into the mudstone top of the turbidite beneath. In places these sands have detached from the overlying turbidite and are encased in the mudstone beneath forming sandstone balls. Flame structures in which mudstone projects in narrow upward tapering 'flames' into the overlying sandstone are closely associated with the loading. These features are superbly displayed in the Grennan Point Formation as exposed on the rocky promontory in Drumbreddan Bay (NX07704360). They are post-depositional and the result of density instability causing heavier sandy material to sink into lighter, unconsolidated muds beneath. This effect may be enhanced by differential loading or partial or complete liquefaction of the sediment induced by earthquake shock waves as described below.

A special type of load structure is sometimes produced by ripple marks, as in the Grennan Point Formation at Drumbreddan Bay (NX07744364), where well formed sinuous transverse ripples are apparently present on the amalgamated base of a 40 cm thick turbidite. These have resulted from the differential loading caused by ripples on the upper surface of the turbidite. Similarly in a rare 30-80 cm thick dune-bedded sandstone in the Clanyard Bay Formation at Dunbuck (NX09613854) differential loading has 'transferred' the dune structure to the base of the bed severely disrupting the sandstone bed underneath (Plate 3.7). However the most spectacular loading structures occur in the Port Logan Formation at Needles and Pins (NX09174023) (Plate 3.8) where a coarse 25-105 cm thick sandstone bed has liquefied and 'sunk' into an underlying 1 m thick, coarse sandstone forming massive pillow structures whose depth of 20-80 cm often exceeds width. Both the upper and lower surface of the bed are highly disturbed though the beds underneath show only minor disturbance. The cuase of the loading is not known as the overlying bed has been removed by erosion, but it has clearly had a major effect on at least two beds and seismic shock seems the most likely explanation. Here as in many instances in the Rhinns the loading structures have developed between two coarse sandstones rather than at a more typical sandstone-

Plate 3.7: Gravity loading of a dune structure in the top bed has caused the dune to transfer to the base of the bed thereby deforming the underlying beds. Clanyard Bay Formation - Dunbuck (NX09623853)

Plate 3.8: Large-scale pillow structures from a liquefied sandstone bed in the Port Logan Formation at Needles and Pins (NX09174024) have 'sunk' into an underlying massive sandstone unit, yet have little effect on the beds beneath

mudstone interface indicating the pore fluid content of the sands was very high suggesting rapid deposition. A large-scale pillow structure of a different type is present near the base of the Grennan Point Formation at Hole of Grennan (NX0734386) and is illustrated in Fig 3.12.

Sand volcanoes are abundant in the Mull of Galloway Formation and indeed are only found in the Hawick Group within the Central Belt. They have a widespread distribution within the sporadic beds of fine grained distribution graded turbidites and form cones on the bedding surface with a maximum diameter of 60 mm and height 20 mm. These cones are generally well weathered and only rarely is the shallow summit crater still preserved. Vents connecting with the cones have not been observed in the Rhinns though the small size of the latter would suggest they do not extend lower than the bed in which they are found. These sand volcanoes are formed by the sudden escape of pore fluid from a liquefied bed.

Convolute lamination is commonly observed in the T_c division of the Bouma sequence where it is either solitary (see Plate 2.2 (B)) or more rarely associated with, and usually above, ripple-drift cross lamination. It forms distinct planar layers of about 7-8 cm thickness, though up to 20 cm in the Grennan Point Formation, and consists of a complex pattern of irregular anticlines and synclines that rarely become more angular and overturned in one direction. These convolutions result from the liquefaction of cross or parallel laminae induced by one, or a combination, of current drag, loading or seismic shock. Although present in all the Rhinns formations it is usually associated with distribution graded or base-missing turbidites and so is more common in the southern formations. Plate 2.2(B) shows a rare exception to this association with convolute lamination present between massive sands of the Money Head Formation.

Coherent slumps of liquefied sandstone beds are present in the Port Logan Formation, the channelised sequences of the Mull of Galloway Formation and the base of the Grennan Point Formation. The beds affected are fine to coarse grained, massive

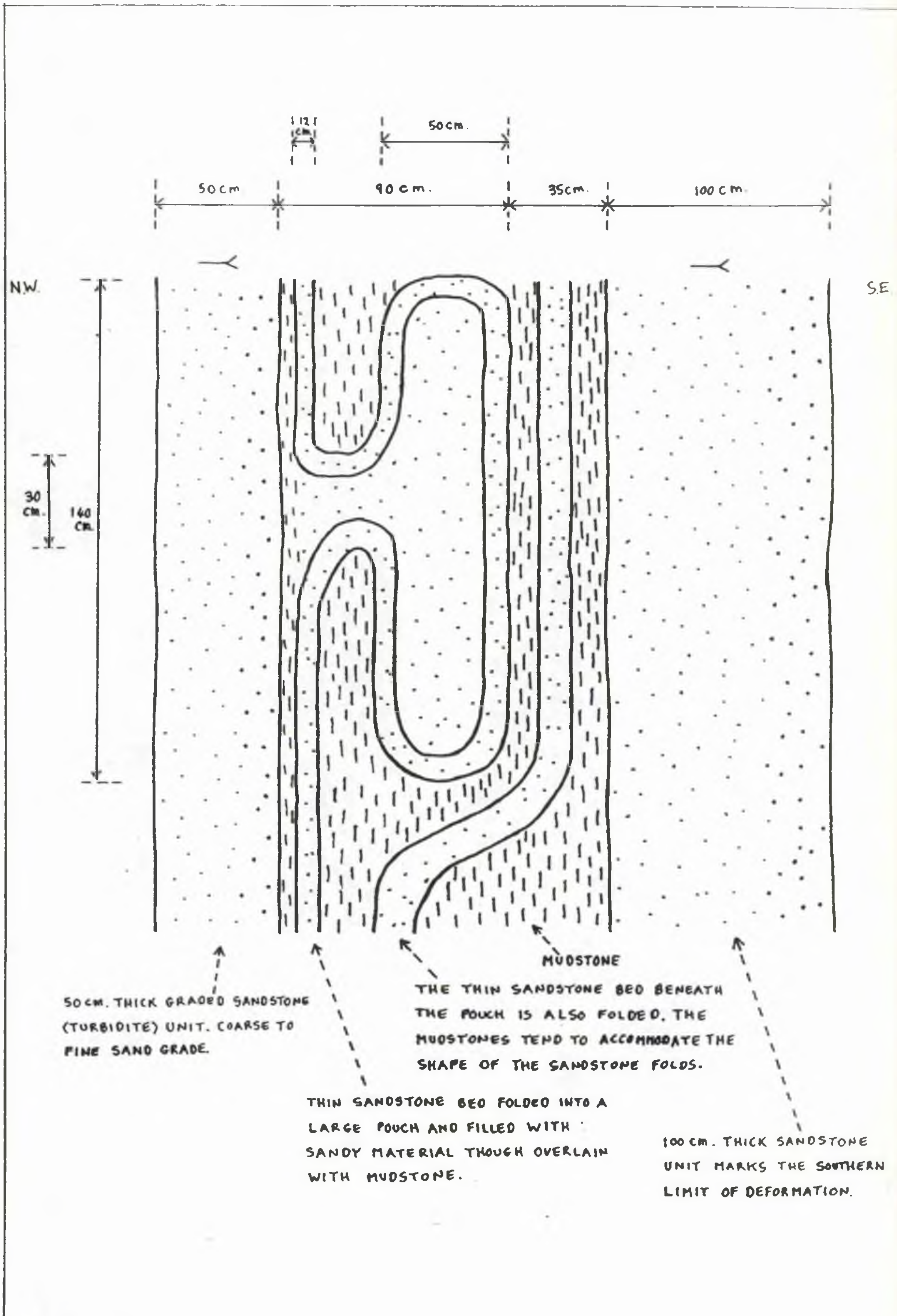


Fig 3.12: Sketch of pillow structure (vertical section) exposed at Hole of Grennan (NX07134386) (scale approximate).

sandstones and are usually less than 50 cm thick. The most common feature found is prolapsed bedding (Wood and Smith 1959) as superbly displayed at Scrangie (NX09134018) in the Port Logan Formation (Plate 3.9(A)) and Leucarron (NX13303098) in the Mull of Galloway Formation (Plate 3.9(B)). Pull apart structures are well exposed in a further slump at the latter locality (Fig 3.13) and 'plastic glide' where the whole bed has undergone folding and pull apart due to thrusting (Dzulynski and Walton 1965) is regularly observed, as on the point 150 m N of Cairnywellan Head (NX09034002) in the Port Logan Formation. In most of the slumps the flow direction can be clearly discerned, though in beds strongly folded by plastic glide it is much less obvious. Many of the slumps are overlain by a thin, fine grained erosional turbidite (Plate 3.9(B)) and some were themselves erosional (Fig 3.13).

3.3.4 Structures related to bedding form (plus trace fossils)

A number of structures (below) are best described in relation to the form of bedding they are associated with:-

(1) Massive, pebbly sandstone structures - massive, pebbly sandstone beds, typically Facies A_4, C_1 and sometimes B_1 in the Walker and Mutti (1973) and Mutti and Ricci-Lucchi (1975) turbidite facies schemes, are very common in the Rhinns and dominate the Money Head Formation and Daw Point Member and Chair Member of the Mull of Logan Formation. They contain a very distinctive set of structures to which little attention has been paid in the Southern Uplands literature, Walton (1967) and Kemp (1987) being rare exceptions. The beds are very coarse and massive and are typically 1-4 m thick, although they reach thicknesses much greater than this and often have thin mudstones along their tops (see Plate 2.2(A)). Bedding surfaces are sharp and distinct however the lower surface is sometimes erosional or amalgamated and is often overlain by the coarsest granule or pebble grade fraction of the clasts (Plate 3.10(A)). Inverse grading, although common, rarely extends over the whole bed and instead affects small sub-units, often repeatedly, and is associated with normal coarse-tail grading (Fig

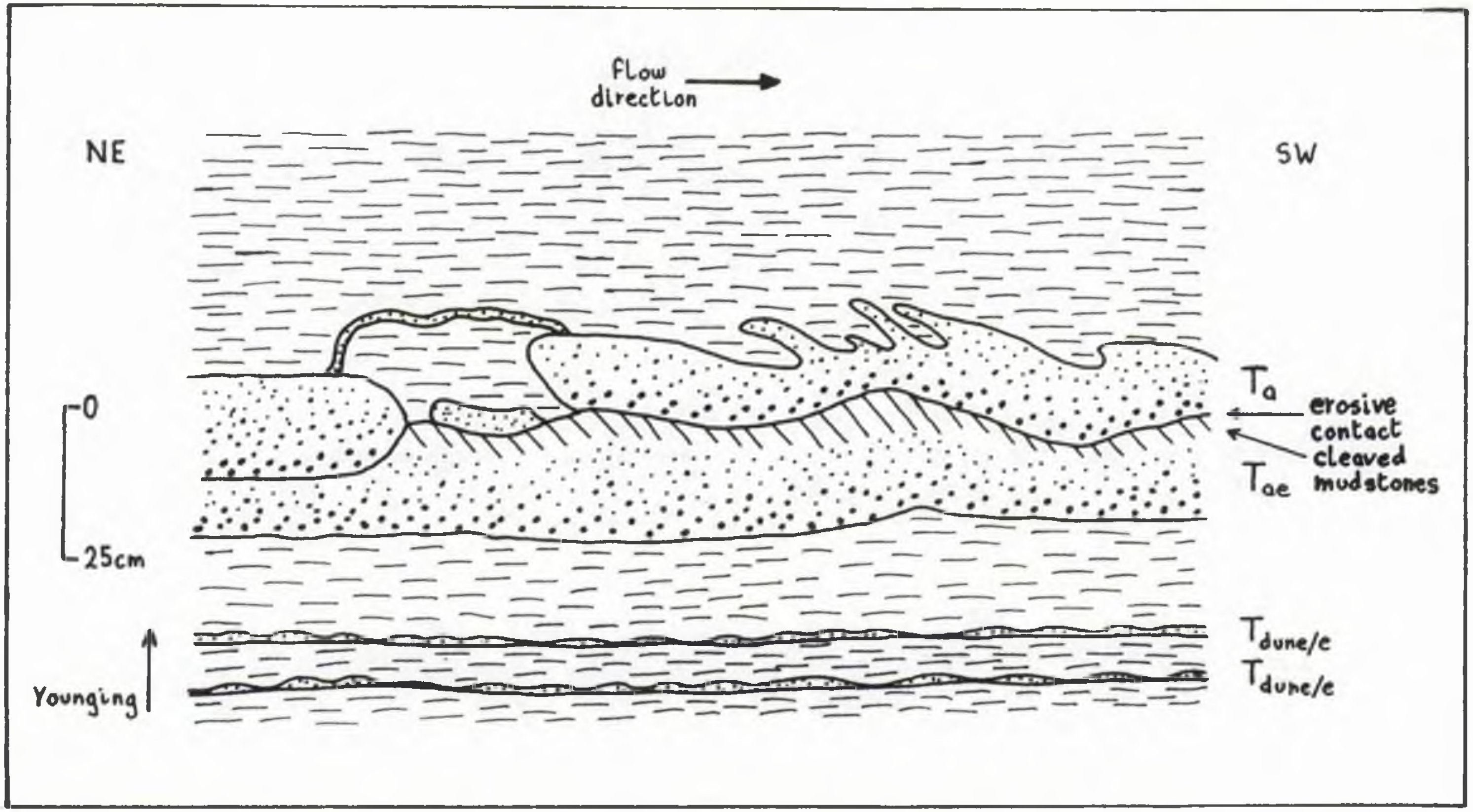


Fig 3.13: Pull-apart slump structure in the Leucarron Member of the Mull of Galloway Formation at Leucarron. Stipple - sandstone; dash - mudstone; Bouma sequencing indicated.

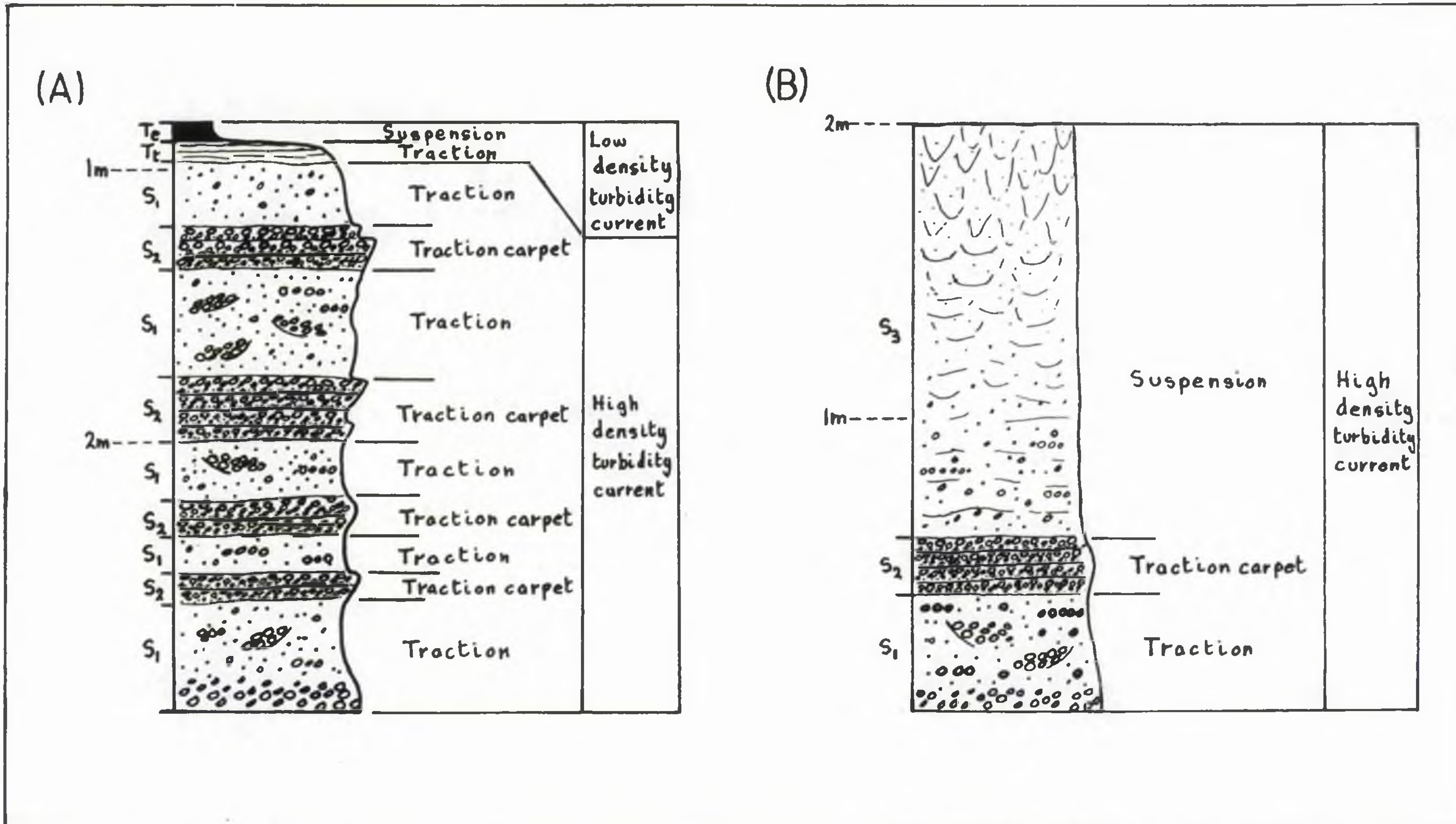


Fig 3.14: (A) Typical massive pebbly sandstone bed from the Money Head Formation at Scarty Head (NX04494843); (B) Lowe sequence - idealised sequence of divisions deposited by a single high density turbidity current (after Lowe 1982). (For explanation see text).

Plate 3.9(A): Prolapse structure in the Port Logan Formation at Scrangie (NX09134018). Flow: down to left

Plate 3.9(B): Prolapse structure in the Leucarron Member of the Mull of Galloway Formation at Leucarron (NX13303098). Flow: to right

Plate 3.10(A): Erosional amalgamated bedding contact and irregular 'pockets' of granule grade clasts in the Daw Point Member of the Mull of Logan Formation (NX11674422)

Plate 3.10(B): Irregular stratification of granule grade clasts and mudstone clasts in the Daw Point Member of the Mull of Logan Formation (NX11674422)

Plate 3.10(C): Loading and water escape structures in the Daw Point Member of the Mull of Logan Formation (NX11674422)

Plate 3.11: Sediment creep structure in the Money Head Formation at Slannax (NX48270488). Although the top of the bed is displaced the base of the bed appears unaffected

3.14(A)). Commonly this grading gives rise to a coarse, though sporadic, stratification of granule-pebble grade clasts (Plate 3.10(B)) and is in places associated with rather enigmatic irregular or linear shaped 'pockets' of similar sized material (Plate 3.10(A)). Mudstone rip-up-clasts are a typical feature of the bed and, although much larger than the other clasts, are deposited sporadically throughout it. Liquefaction structures, mostly convolute lamination, loading and water escape structures (Plate 3.10(C)) are present but rare.

These beds have been interpreted as the product of high density turbidity currents. Lowe (1982) has gone a long way to elucidating the processes at work in these flows and the structures produced by them and in so doing has effectively developed a 'Lowe sequence' (Fig 3.14(B)), a high density equivalent of the Bouma sequence. Initially (S_1 stage) the high density turbidity current is slightly unsteady but fully turbulent and deposits some of its load by traction to form a sand bed in which tractional bedforms, like parallel or dune stratification, may develop (see later). At this stage the current is locally erosive and the scours produced trap the coraser clasts forming the irregular 'pockets' observed. As flow unsteadiness increases (S_2 stage), the suspended sediment concentrates towards the surface of the bed giving rise to grain to grain collisions. Eventually dispersive pressure replaces turbulence as the main buoyancy mechanism and a traction carpet forms producing inverse layering in the flow (see Bagnold 1954). Sediment fallout from suspension continues to load the traction carpet until it eventually freezes, thus depositing an inversely graded layer.

The process then repeats itself and a new traction carpet forms. In this way a whole series of inversely graded layers are deposited in the bed. At high suspended sediment fallout rates (S_3 stage) there is no time for traction or a traction carpet to develop and deposition is by direct suspension sedimentation. This produces a liquefied layer and liquefaction structures, particularly water escape structures develop in it.

Like the Bouma sequence, the Lowe sequence is an ideal and one or more of the stages may be absent or may repeat within the sequence. In the massive pebbly sandstone beds of the Rhinns, the S_3 stage is rare while the S_1 and S_2 stages are common and often repeat in the same bed. However the S_1 stage tends not to show extensive development of tractional bedforms and instead these form in separate beds in which they are the dominant feature (see structure (2)). The scarcity of the S_3 stage in the Rhinns indicates that the flows did not decelerate rapidly which would suggest they were relatively unconfined. The repetition of the S_1 and S_2 stages in many of the beds may be due to slight undulations in the topography of the slope down which flow and deposition occurred.

(2) Massive, coarse lamination - this is present in the coarse, massive sandstone beds of 10-100 cm thickness typical of Facies B_2 in the Walker and Mutti (1973) and Mutti and Ricci-Lucchi (1975) turbidite facies schemes. These beds are closely associated with the massive pebbly sandstone beds described in (1) above and their distribution is similar. The coarse laminae may be either plane parallel or inclined and they extend throughout the bed, which is itself markedly lenticular at outcrop scale (see Plate 2.2(B)). They are defined by both compositional and clast size variations.which, apart from rare discontinuous layers of granule and pebble grade clasts, occur in otherwise structureless beds. These laminae equate with the tractional bedforms, eg dune cross stratification, defined by Lowe (1982) in the S, stage of a high density turbidity current. Why these tractional features should be rare in the S_1 stage of the massive, pebbly sandstone beds described in (1) and yet be the dominant feature of massive, coarse sandstone beds is not clear, but is probably related to the decrease in grain size of the latter.

(3) Sediment creep structures - these enigmatic structures are present at Slannax (NX05864829) in the Money Head Formation and are illustrated in Fig 3.15 and Plate 3.11. At outcrop level they are seen affecting a sequence of four C_1 and B_2 facies

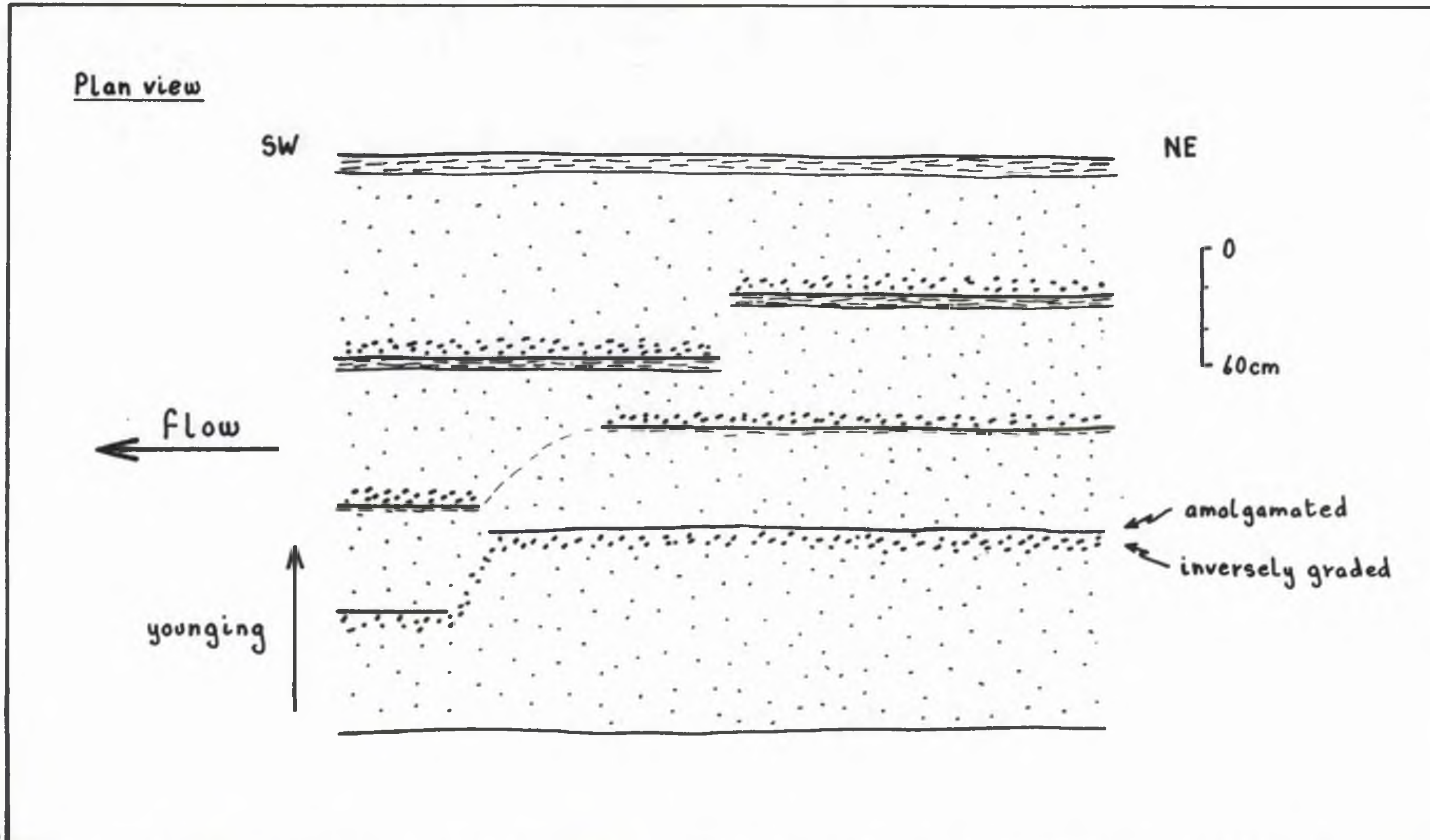


Fig 3.15: Sediment creep structure in the Money Head Formation at Slannax (NX05864829). Heavy stipple - coarse to granule grade sandstone; light stipple - coarse sandstone; dash pattern - mudstone.

massive sandstone beds, downfaulting them internally by about 20-25 cm, though the uppermost and lowest bedding planes of the sequence remain intact and undeformed. The fault contacts are sharp and well defined although there is evidence that at least one acted as a dewatering conduit. These structures can best be explained by the process of sediment creep (Watkins and Kraft 1978). Although this process 'has not often been described from the deep sea ... it is probably a widespread phenomenon' (Stow 1986). Load induced stress on a gentle slope causes slow strain of the sediment which begins to slowly glide down a decollement developed at depth (Fig 3.16). Tensional faults develop which may act as dewatering conduits. Eventually rupture may occur and a slide or slump form (for an example of deformation by sediment creep see Hill, Moran and Blasco 1983). As the upper bedding plane of the sequence at Slannax is not displaced, it would suggest that internal redepositon of the bed took place after tension faulting. Prolapse structures within the bed indicate movement towards the downthrown side of the fault.

(4) Trace fossils - these are surprisingly rare in the Rhinns and have been found at only three localities. Two of these were in the Port Logan Formation at Scrangie (NX09114017) (Fig 3.17(A)) and 80 m S of the Cave of Carlin Bed (NX09173974) (Fig 3.17(B)). Both consisted of the ichnogenus *Gordia*. The former specimen was preserved as a positive epirelief on the mudstone top of a sandy turbidite while the latter was a negative epirelief on the top of a siltstone bed. Both specimens were smooth, unbranched, curved irregularly and had diameters of 1-2 mm (Scrangie specimen) and 2-3 mm (Cave of Carlin Bed specimen). The third specimen was a very poorly preserved specimen of *Nereites* and was found in a thick red mudstone sequence at Back Port (NO7724287) in the Chair Member of the Mull of Logan Formation. The specimen was 3 mm wide and had lobes of 3 mm in length with 3-4 developed every centimeter. Peach and Horne (1899, p 216) found specimens of *Protovirgularia* in the Leucarron Member of the Mull of Galloway Formation at St Medans Cave

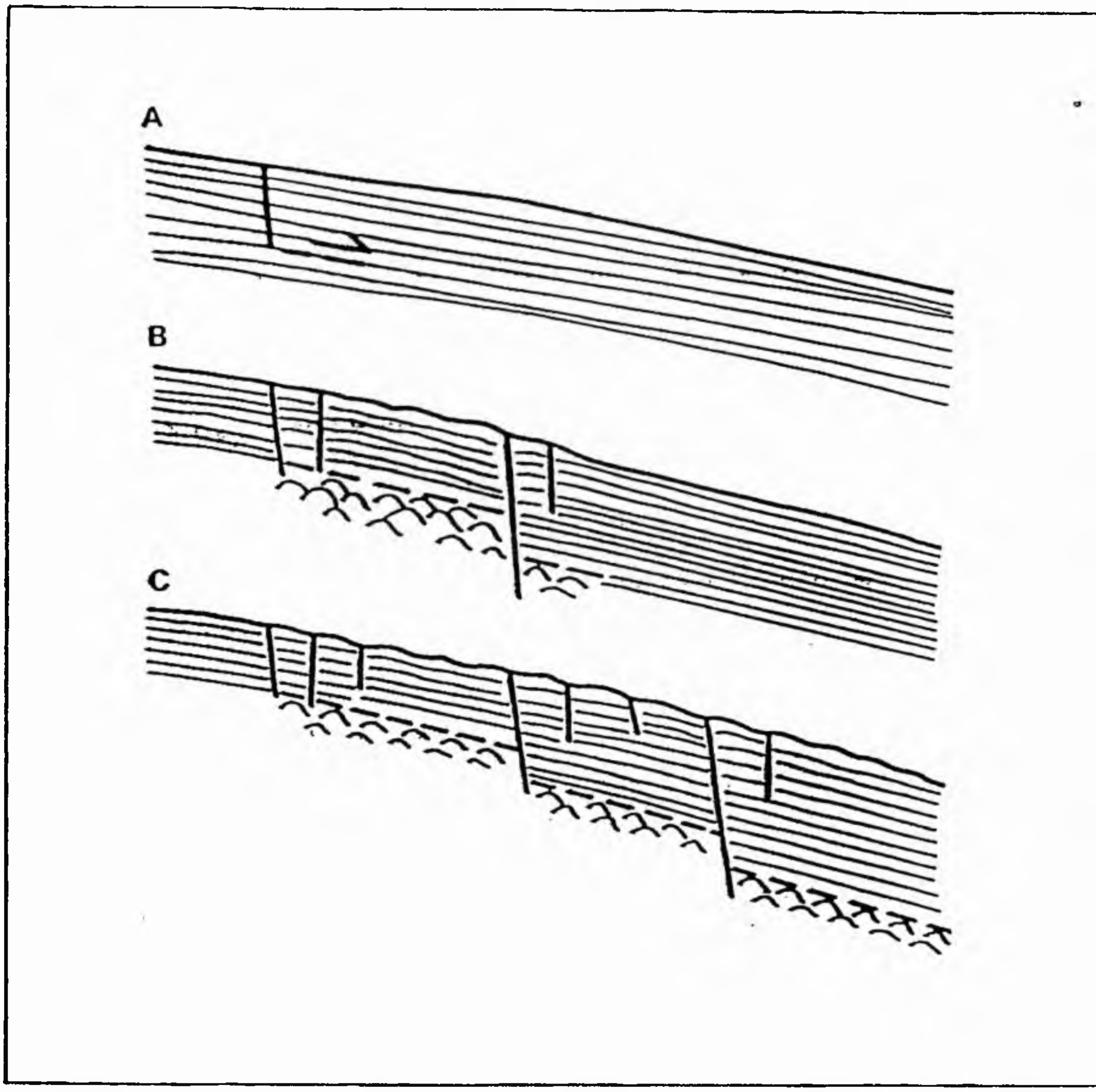


Fig 3.16: Model for sediment creep on a gentle submarine slope (after Hill 1983 - pers. comm. in Stow 1986). The three stages (A to C) show the propagation of an internal decollement zone, its vertical displacement along zones of tension, and the development of sediment waves in a horizontally stratified sediment column.

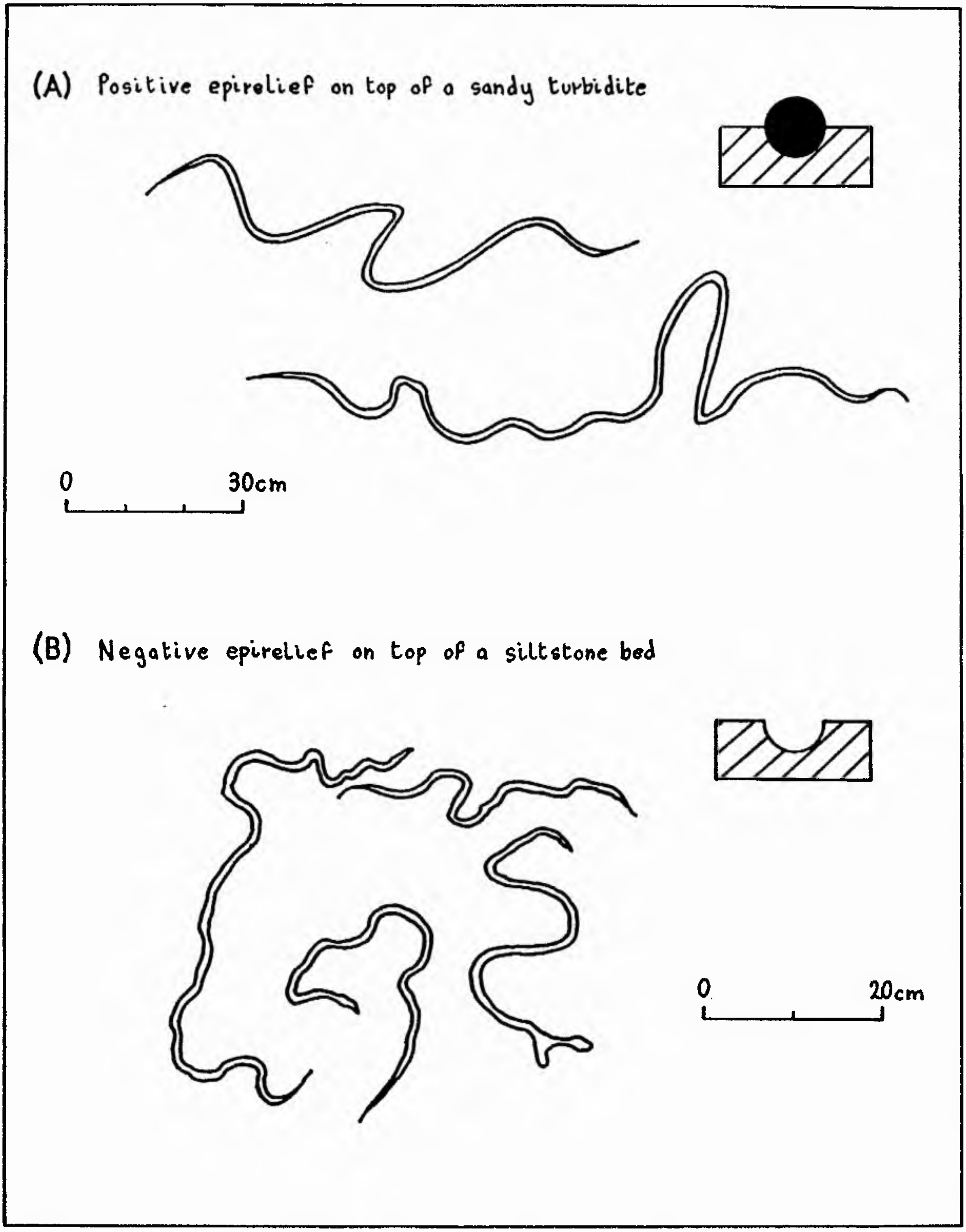


Fig 3.17: Sketches of the ichnogenus Gordia from (A) Scrangie (NX09114017) and (B) Cave of Carlin Bed (NX09173974).

(NX14413161). Recent re-examination of these specimens by Strachan (pers. comm.) confirms their identifications. All these specimens are indicative of a deep water palaeoenvironment (Seilacher 1964).

3.4 DEPOSITIONAL ENVIRONMENT OF THE SEDIMENTS

Sediment gravity flows are deposited in three different marine settings, these being slopes, submarine fans and basin plains (Stow 1986). Similar types of deposit are grouped together into facies and each setting is characterised by a distinctive assemblage of facies as defined by Mutti and Walker (1973) and Mutti and Ricci-Lucchi (1975). Their conclusions are based on the study of turbidite sequences in the Northern Appenines and Southern Central Pyrenees and they interpret their facies in terms of rather 'idealised', though nonetheless real, submarine fan systems as illustrated in Fig 3.18. Depositional systems at active margins and many passive margins are more complex than this and the Mutti and Walker (1973) and Mutti and Ricci-Lucchi (1975) model has required adaption, particularly with regard to trench-forearc deposition (see Underwood and Bachman 1982). In this thesis, terms such as middle fan, inner fan, etc, are used in relation to facies association, but following Underwood and Bachman (1982) do not necessarily imply deposition in a simple fan system.

In order to reconstruct the environment of deposition of the sediments of the Rhinns it is necessary to examine five aspects of the sediments (Stow 1986): scale, preservation and bathymetry; palaeocurrents; horizontal facies distribution; vertical facies sequences; and environmental facies associations. The first of these has been largely dealt with, while the second is examined in the next section (Section 3.5), the final three are dealt with below. The aim of this section is to give a dynamic account of the sediments, their vertical sequences and associations in order to understand their depositional processes. Each formation will be examined in turn from oldest to youngest and will be described and interpreted in terms of turbidite facies and facies

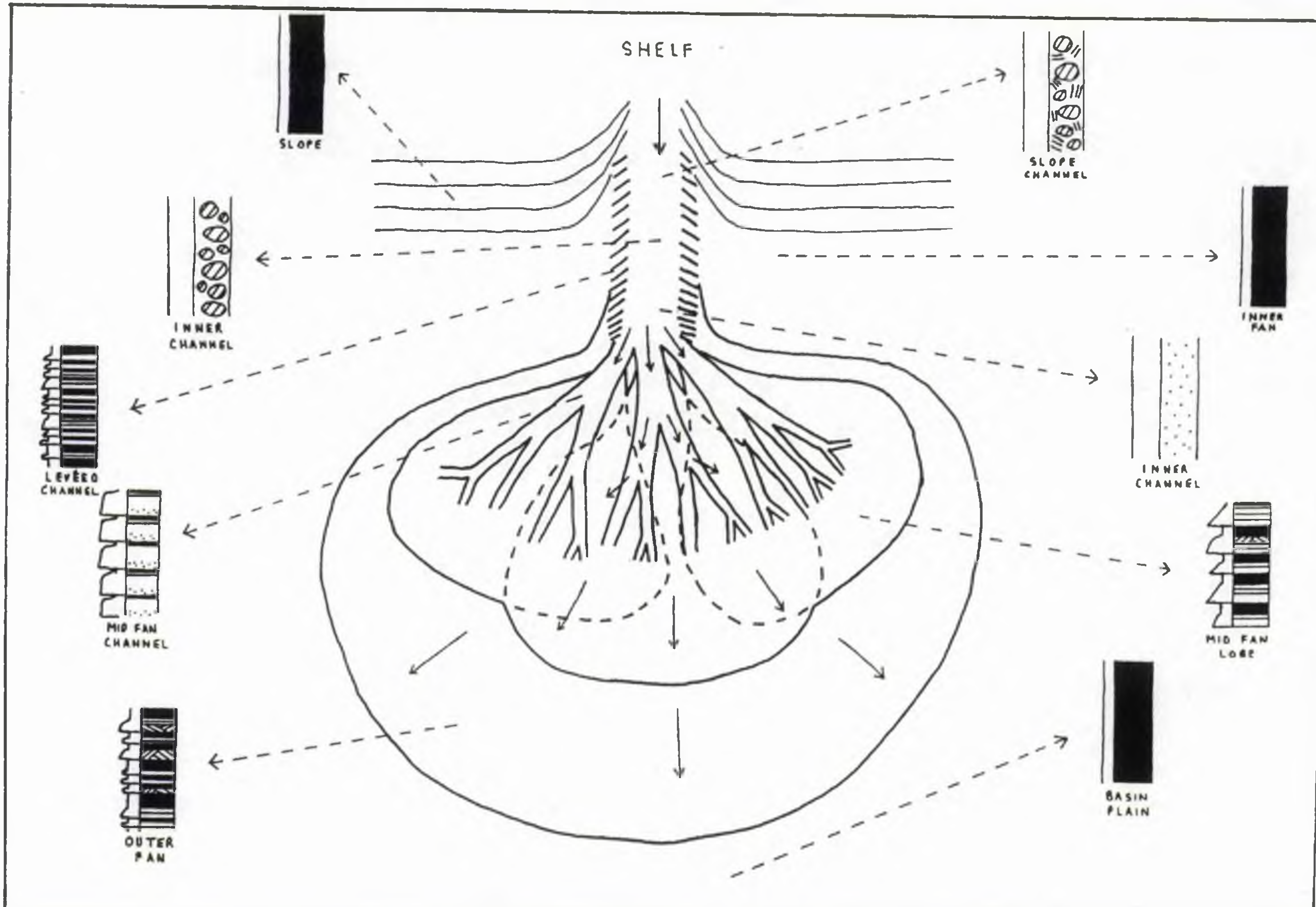


Fig 3.18: Idealised turbidite fan environment and associated deposits (based upon Mutti and Walker 1973 and Mutti and Ricci-Lucchi 1975).

asssociations. The main characteristics of each facies are detailed in Table 3.2 and the distribution of facies environments illustrated in Fig 3.18. The distribution of facies in the Rhinns is indicated in the chapter on stratigraphy (Chapter 2) and in Table 2.1. Before examining the depositional environment of the Rhinns sediments it is necessary to discuss the four sediment types so far not examined and their environmental significance.

3.4.1 Additional sediment types and their environmental significance

3.4.1.1 Shales and mudstones

Shales and mudstones are abundant in the Rhinns and, apart from the black shales of the Moffat Shale Group, display only a very weak fissility if at all. They comprise the topmost T_e division of the Bouma sequence or are bedded between the individual turbidites and typically are less than 40 cm thick, though may comprise sequences of many metres thickness, reaching a maximum in excess of 35 m in the Moffat Shale Group. They are typically grey in colour and consist of clay and silt grade material, mostly of clay minerals and colourless micas, although quartz and rare feldspar grains can sometimes be identified. The sediments are not laminated and result from pelagic and hemipelagic deposition from suspension.

A number of colour varieties exist determined by the percentage of free carbon (dark grey or black), iron bearing compounds (red and green) or green phyllosilicate minerals (green) present. Black or dark grey shales are abundant in the Moffat Shale Group and are pelagic carbonaceous deposits formed under anaerobic bottom conditions. These conditions are believed to have resulted from marine transgressions that increased primary productivity of organic carbon in surface waters, thereby inducing an expansion in the oxygen minimum layer (Leggett 1978). Graptolites are commonly preserved in the shales as carbonaceous films or more rarely pyritic replacements. Microcrystalline and cryptocrystalline pyrite are both present occurring as isolated, euhedral grains and aggregates.

Facies and sub-facies	Characteristics	Dominant deposition mechanism
A	Massive, thick-bedded, coarse sandstones and conglomerates	
A_1 Disorganized conglomerates	Pebble-boulder deposits in a sandy matrix, bedding 1-15 m thick, irregular and internally structureless	Debris flow
A_2 Organized conglomerates	As for A_1 but bedding more regular and may be normally or inversely graded, horizontally stratified or show a preferred clast orientation	Debris flow and high density turbidity flow
A_3 Disorganized pebbly sandstone	Coarse - v. coarse sandstones with granule/pebble clasts, bedding 50 cm-10 m + thick, irregular and internally structureless, the sand/shale ratio is v. high and amalgamation is common	Grain flow
A_4 Organized pebbly sandstone	As for A_3 but bedding thinner, typ. 30-300 cm, and more regular with internal stratification of granule/pebble clasts and coarse-tail grading, scour and tool marks developed on soles	Grain flow and high density turbidity flow
B	Medium-coarse, ungraded sandstones with a v. high sand/shale ratio and often amalgamated	
B_1 Massive unlaminated sandstones	Bedding typ. 40-200 cm and broadly lenticular with minor channeling at the base and fluid escape structures developed internally	Liquefied flow and high density turbidity flow
B_2 Massive laminated sandstones	Bedding 10-80 cm and strongly lenticular with coarse parallel or inclined laminae, upper surface commonly duned or rippled and sand/shale ratio more variable than in B_1	High density turbidity flow and grain flow
C	Fine-coarse sandstones with interbedded mudstones and a high sand/shale ratio, classical proximal turbidites beginning with Bouma T_a division, bedding is typ. 50-300 cm and sole structures are common	
C_1 Immature sandstones	Coarse-tail graded, coarse-fine sandstones with rare amalgamation and Bouma T_{ae}, T_{ac} and T_{ace}	(Decreasing) High density turbidity flow ↓
C_2 Mature sandstones	Distribution graded, medium-fine sandstones with Bouma T_{abcde}, T_{abce} and T_{abde}	
D	Fine sandstones, siltstones and mudstones, classical distal/base-missing turbidites	
D_1 Rippled sandstones	Poorly graded, fine sandstone-siltstone/mudstone interbeds with a low sand/shale ratio, beds are <40 cm thick and Bouma T_{ce} and T_{cde}, sole structures rare	(Decreasing) Low density turbidity flow ↓
D_2 Laminated sandstones	Distribution graded, fine sandstone, - siltstone/mudstone interbeds with a medium sand/shale ratio, beds are 50-150 cm thick and Bouma T_{bcde}, T_{bce} and T_{bde}, sole structures common	
D_3 Laminated siltstones	Bouma T_{de} and T_e siltstones and mudstones <30 cm thick	
E Dune-bedded sandstones	Thin (<10 cm) pinch and swell, lenticular or dune-bedded coarse-fine sandstones interbedded with mudstones, beds are Bouma T_{ae}, $T_{dune/e}$, $T_{dune/ce}$ or N/A and are coarse-tail graded or ungraded, the sand/shale ratio may be low-high	High-low density turbidity flow
F Chaotic deposits	Pebble-boulder deposits/isolated blocks set in a structureless mudstone matrix; slumps, olistostromes, etc	Debris flow
G Hemipelagic deposits	Siltstones, mudstones and shales	'Fallout' from surface waters

N/A: not applicable. v.: very. typ.: typically

TABLE 3.2 - TURBIDITE FACIES OF THE RHINNS (BASED ON WALKER AND MUTTI (1973) AND MUTTI AND RICCI-LUCCHI (1975))

Red mudstones are present, though not abundant, in the Moffat Shale Group, the Grennan Point Formation, Mull of Logan Formation, Port Logan Formation and Mull of Galloway Formation and are sometimes associated with irregular green bands (see Plate 2.4(A)). These mudstones are believed to result from the erosion of a terrestrial source rock, rich in oxidised iron, during a marine transgressive phase and the subsequent rapid deposition of the sediment in a 'quiet' deep-sea environment before reduction could occur (Ziegler and McKerrow 1975). The red colour is usually due to the presence of the ferric iron oxide haematite and its diagenetic reduction produces the irregular green coloured bands.

The shales of the Mull of Galloway Formation, and throughout the Hawick Group, are a characteristic pale green colour and this is believed to result from an increase in the amount of green phyllosilicate minerals, notably chlorite, present.

3.4.1.2 Cherts

Cherts are found at only one locality, Brocks Cave (NX09303943), in the Green Saddle Member of the Port Logan Formation. They are grey in colour, glassy and occur in plane parallel beds less than 10 cm thick interbedded with laminated siltstones and mudstones. In thin section they consist of a cryptocrystalline mass of quartz with a few angular, silt grade quartz clasts and numerous flecks of colourless mica, the latter maybe accounting for as much as 10% of the rock. The origin of cherts and particularly cherts interbedded with clastic deposits is problematical with silica resulting from either the biogenetic sedimentation of radiolarians and siliceous sponges or inorganic precipitation from volcanic sources (for discussion see Pettijohn 1975, p 402-407). No organic structures have been identified in the cherts of the Green Saddle Member and they are not found in association with any volcanic rocks, although thin bentonites evidencing contemporaneous vulcanicity are present in the Port Logan Formation. The depositional history of these cherts therefore remains unresolved.

3.4.1.3 Bentonites

Bentonites have ben identified in shale and mudstone sequences in all the formations of the Rhinns apart from the Portayew Formation and Cairngarroch Formation and are most abundant in the stratigraphically condensed Moffat Shale Group (Plate 3.12). They form pale, greenish grey, clay layers up to 40 cm thick, though more typically less than 10 cm, and are sometimes interlaminated with mudstones on a mm-scale over this thickness. Occasionally sand grade grains may be present in the layer and they may show grading.

Bentonites are rocks composed of clay minerals produced *in situ* by the devitrification and chemical alteration of glasses in volcanic ash. They may in addition contain the original phenocrysts of the glass, typically feldspar and biotite. Their presence is thus indicative of vulcanicity contemporaneous with deposition. No geochemical or mineralogical examination of the Rhinns bentonites has been undertaken and their identification is based on comparison with the texture and petrography of bentonites in the Ards Penninsula and Lecale (Cameron and Anderson 1980). They demonstrate that the dominant clay has a mixed layer structure resulting from the low temperature alteration of smectite towards illite.

3.4.1.4 Winnowed turbidites

In the top 300 m of the Money Head Formation many of the turbidites are parallel laminated, amalgamated, coarse to fine sand grade and typically up to 60 cm thick. They most readily equate with Facies B_2 beds. These beds have the lowest matrix content (less than 15%) and best sorting (moderate) of any in the Rhinns and define as arenites rather than wackes (Pettijohn 1975). The coarse lamination appears related to differences in clast size. However in fine sand and silt grade material comprising some beds, thin, dark laminae less than 0.5 mm thick and spaced at between 1 and 100 mm are found. In thin section (Plate 3.3) these laminae are defined by pyrite grains possibly replacing ilmenite which is found throughout the rock. Some

Plate 3.12: Dextral imbrication of bentonite horizons in Birkhill Shales at the northern end of Drumbreddan Bay (NX07744376)

Plate 3.13: Spherulitic siderite nodules (dark) in oxidised Barren Mudstones (red) at the northern end of Clanyard Bay (NX10103809) have reduced the surrounding mudstones to form irregular pale bands

laminae define thinly bedded units displaying coarse-tail grading with sharp differences in clast size evident between adjacent units.

The low matrix content, moderate sorting and concentration of ore minerals into thin laminae together suggest that these turbidites have undergone winnowing, ie. vigorous tractional reworking, subsequent to their deposition. This could be effected by either canyon currents of variable origin, eg. surface currents, storms, etc., or contour currents of thermohaline origin, dependent on the site of deposition, ie. submarine canyon for the former and continental slope for the latter (Stow 1986). Ziegler *et al* (1977) proposed that the Southern Uplands were positioned on the NW side of the Iapetus Ocean during Silurian times. This palaeogeography would support depositon by contour currents as these are at their most vigorous on the western side of the oceans (see Stow and Lovell 1981).

3.4.2 Facies analysis and interpretation

In this section each of the major tectonic blocks will be discussed independently from oldest to youngest before an attempt is made to relate and integrate their depositional histories. Their relationship to the rest of the Southern Uplands will also be briefly examined. The distribution of the facies is described in Chapter 2 and Table 2.1, the aim here is to provide a clear and succinct interpretation of the facies associations and sequence trends, plus any other factors relevant to their depositon.

Portayew Block (extreme southern edge) - a progradational sequence exists at the base of this block with the deposition of pelagic Moffat Shales in a basin plain environment under anaerobic and then aerobic bottom conditions. These are overlain by a thin outer fan sequence (Facies D_3 and G) before the arrival of the suprafan as indicated by the appearance of C_1 turbidites in the succession.

Cairngarroch Block - metamorphism has masked much of the lithological variation in this block with the result that the rather glassy, hornfelsed turbidites have the uniform appearance of Facies D_1, D_2 and C_2 deposits (see Fig 2.5). This association typifies middle fan lobes and the distal portions of middle fan channels. The absence of identifiable vertical variation and true channelized deposits in the 650 m thick succession is due to the homogenising effects of metamorphism and the deposits can therefore only be loosely described as middle fan.

Money Head Block - the black pelagic and hemipelagic Moffat Shales were deposited in a basin plain environment under anaerobic bottom conditions and were immediately overlain with middle fan channel deposits, succeeded by inner fan channel deposits, in what was a major and very rapid (catastrophic?) progradational event (see Fig 2.6). There then followed a 600 m thick retrogradational megasequence (Ricci-Lucchi 1975) in which massive, inner fan channel deposits (Facies A_3) developed into bedded middle fan channel deposits(Facies A_4, B_2, C_1 and A_3 (see Plates 2.2(A) and (B)) and thinned upwards into interchannel depositis (Facies B_2, E and D_1) (see Figs 2.6 and 3.19). The latter occurred in five separate cycles, each progressively more distal than the last. This retrogressive trend continued with the deposition of a very uniform 150 m thick sequence of tractional B_2 deposits characteristic of channel-mouth bar deposition at the distal end of middle fan channels (Mutti and Ricci-Lucchi 1975). These deposits were subsequently winnowed by probable contour currents (see Section3.4.1.4). There then followed a major progradational event in the upper 150 m of the Money Head Formation with facies associations, though disturbed by faulting, indicative of proximal middle fan channel and channel levee deposition (Fig 2.6).

Float Bay Block - the basal 120 m of the Float Bay Formation was deposited at the fringe of a middle fan lobe and outer fan followed by a rapid progradation into the middle fan channel. The rest of the formation consists of a major retrogradational megasequence from the middle fan channel into the outer fan and possibly basin plain. Initially a thick sequence of C_1 and B_2 beds was deposited before developing gradually into a series of thinning upward sequences as individual channels filled and were succeeded by interchannel deposition. Ultimately middle fan lobe deposition,

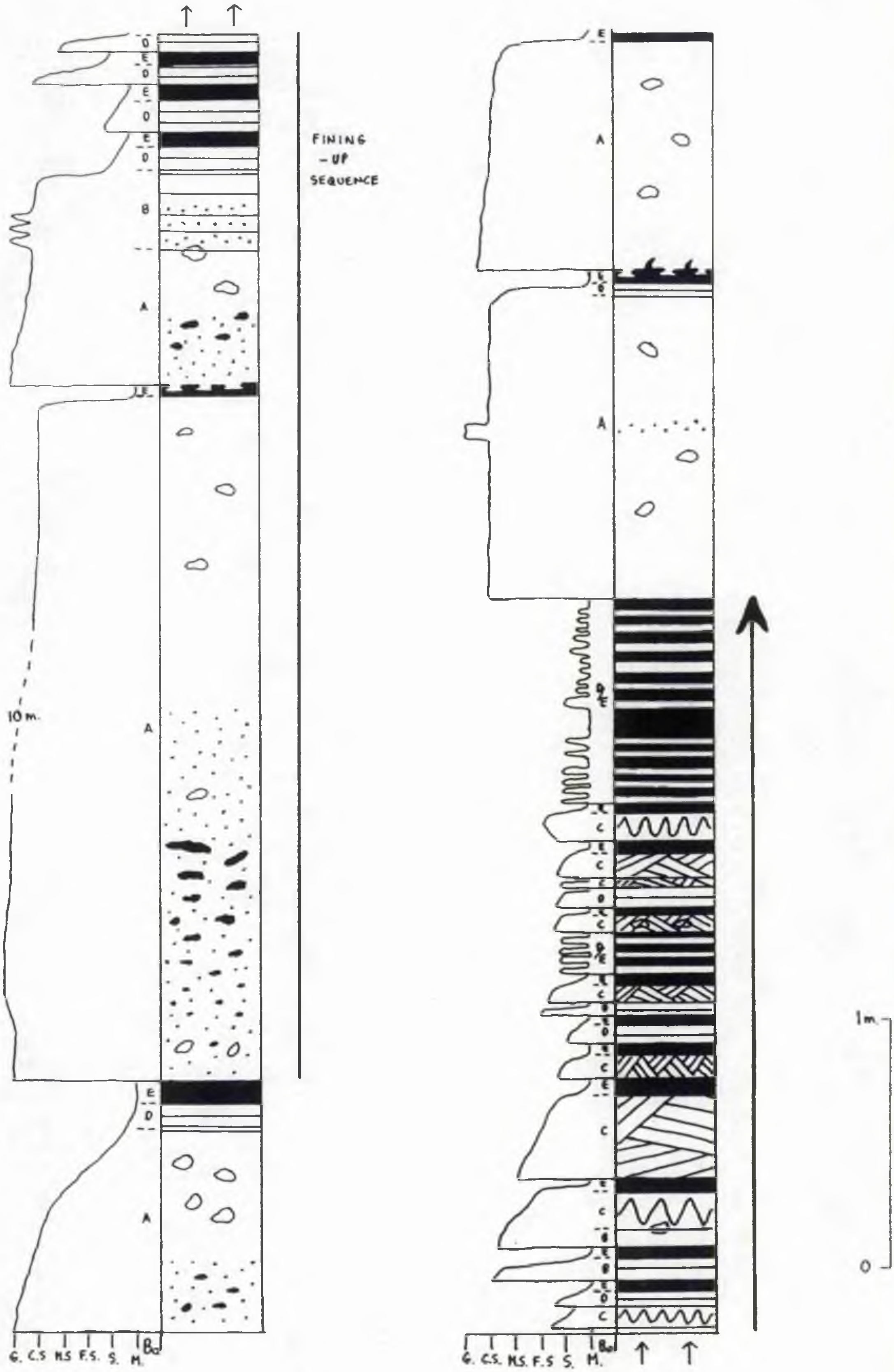


Fig 3.19: One of a series of thinning- and fining-up sequences characteristic of the Money Head Formation at Scarty Head (NX04494845). This sequence shows the infilling of a middle fan channel and switch to interchannel deposition.

characterised by regular interbedding of C_1 turbidites and mudstones (Facies G) with a low sand/shale ratio, becomes dominant. Within this 300 m sequence bands of Facies G mustones and rare thin D_1 turbidites are indicative of abrupt switching of active deposition between lobes and subsequent intermittent outer fan deposition. The spacing between these bands decreases from 100 m at the base of the sequence to 12 m at the top. Eventually middle fan deposition is replaced altogether by deposition of the 200 m thick, G and D_3 mudstones and siltstones of the Strandfoot Member in the outer fan and/or basin plain.

Stinking Bight Block - the lower 60 m of these beds consist of a progradation from the outer fan into a middle fan lobe followed by a return to the outer fan. The presence of a 4 m thick A_4 greywacke within the lower outer fan sequence (typically Facies G and D_3) is anomalous, as is the rather frequent occurrence of Facies E turbidites within such a sequence. This is not an association recognised by Mutti and Ricci-Lucchi and its significance is discussed later. Above this there was a rapid, thickening upward progradation into the middle fan channel, whose sandy C_1 and A_4 deposits have a high sand/shale ratio and dominate the overlying 200 m succeession. After this the depositional sequence is unclear due to tectonic disturbance, but consists exclusively of middle fan channel deposits, some of which are very proximal, and middle fan lobe deposits, the former being the more dominant.

Grennan Point Block - this block, consisting of the Moffat Shale Group overlain by the Grennan Point Formation, contains a major progradational magasequence. At the base the pelagic and hemipelagic shales of the Moffat Shale Group were deposited in a basin plain environment in predominatly anaerobic bottom conditions, except during the Ashgill when aerobic conditions prevailed. These are overlain by a 6 m sequence of D_1, D_3 and G laminated siltstones and mudstones in an outer fan facies association that progrades very rapidly into C_2 and occasional C_1 turbidites of the middle fan lobe (Fig 2.7 and 2.9). 80 m above the base of the succession a 5 m band of Facies G and D_1

red and green mudstones was deposited indicating a brief return to an outer fan environment during what was possibly a period of minor marine transgression (see Section 3.4.1.1). The Moffat Shale Group and basal sequences of the Grennan Point Formation including the red mudstones have been tectonically imbricated and are exposed at three localities. Interestingly the red mudstones apparently occur at different heights above the Moffat Shale Group at each of the localities, however this may be due to tectonic faulting or folding and only the 80 m height is unequivocal. Thickening upward sequences of between 5 and 25 m have been detected at each of these localities which show no evidence of rapid lateral changes in the sedimentation pattern. Throughout the rest of the Grennan Point Formation there is little change in the character of deposition (Fig 2.9) apart from the gradual predominance of C_1 turbidites over C_2 turbidites and an increase in the sand/shale ratio indicating progressive movement into the middle fan channel.

Mull of Logan Block - the Cairnie Finnart Member is composed of middle fan lobe deposits with occasional phases of outer fan deposition, however at Cairnie Finnart itself there is a progradation into the middle fan channel with the deposition of a 70 m sequence of C_1 turbidites with a high sand/shale ratio (Fig 2.10). Mudstone interbeds often contain red or purple layers indicating deposition of oxidised sediments. These middle fan lobe deposits are overlain catastrophically though conformably by the massive, disorganised pebbly sandstone deposits (Facies A_3) of the Daw Point Member (Fig 2.10) which are characteristic of deposition in the inner fan channel. The presence of interbedded Facies E and G deposits towards the top of the succession are indicative of channel levee deposition, while the rare occurrence of thin sequences of more organised pebbly sandstones (Facies A_4) suggest occasional downchannel retrograde movement. Overall though progradation continued into and throughout the Duniehinnie Member with initial deposition of A_2 organised conglomerates succeeded by A_1 disorganised conglomerates and finally slump formation of an olistostrome (Facies F)

(Fig 2.10). This facies sequence indicates progradation from an inner fan channel into a slope channel. At the faulted boundary between the A_2 and A_1 conglomerates is an anomalous 100 m thick progradational sequence from an outer fan association (Facies D_1, D_2 and G), through middle and inner fan associations (Facies C_1, A_4 and A_2) into a slope channel association (Facies $A_1$and F) (Fig 3.20). The abrupt though conformable transiton from the conglomeratic and slumped deposits at the top of the Duniehinnie Member into the C_1 turbidites at the base of the Chair Member marks a retrogradational step into a proximal middle fan channel. There is no gradational sequence development in this member, only rather rapid changes from middle fan channel deposition (Facies A_4, C_1 and rare A_2 and A_3) to interchannel deposition (Facies D_1, D_3, G and E) (Fig 2.10).

The most striking lateral facies change is the complete absence of the A_1, A_2 and F deposits of the Duniehinnie Member 4.5 km to the NE along-strike, though this is perhaps not surprising of deposition confined to a large, localised inner fan or slope channel. The other major change is the northeastwards development of the Daw Point Member from a disorganised, massive sand body (Facies A_3) into a bedded succession of organised pebbly sandstones (Facies A_4), suggesting retrograde, downchannel movement northeastwards.

Port Logan Block - the Port Logan Formation consists of a series of prograde and retrograde megasequences that show no overall trend. Deposition took place mainly in middle fan lobes characterised by C_1 and C_2 turbidites with a low sand/shale ratio (Fig 3.21 and Plate 2.4 (A)). Thickening upward sequences of up to 10 m are common and represent progradations into middle fan channels dominated by C_1 turbidites with a high sand/shale ratio (Fig 3.21 and Plates 2.4 (B) and 3.8). The three 100 m thick, hemipelagic members within this formation represent significant periods of deposition in an outer fan or possibly basin plain environment. They are composed of Facies G, D_3, D_1 and in the case of the Strones Bay Member, D_2 deposits, though the Green

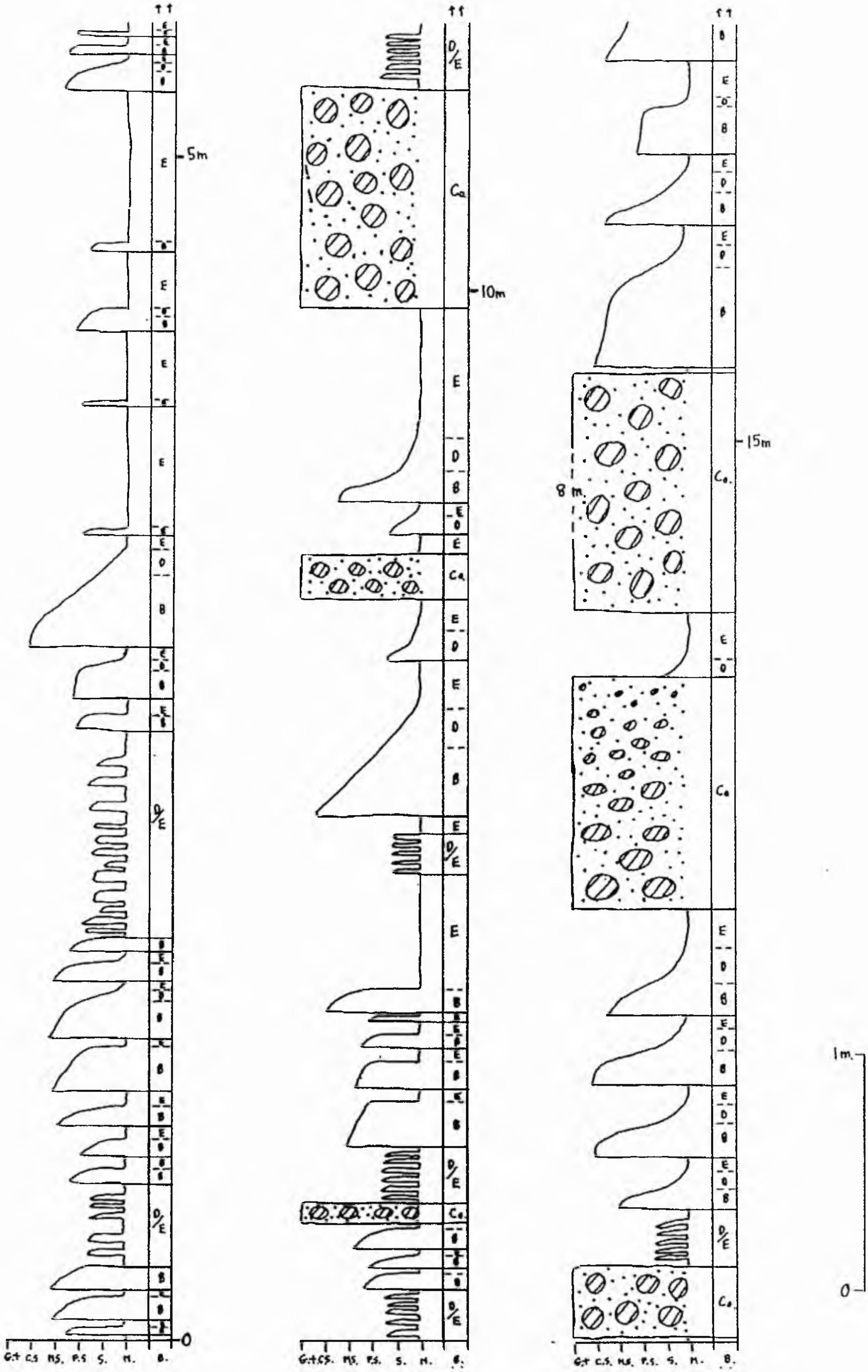


Fig 3.20: Juxtaposition of outer fan and slope channel deposition in a progradational megasequence from the Duniehinnie Member at Peters Paps (NX07604228).

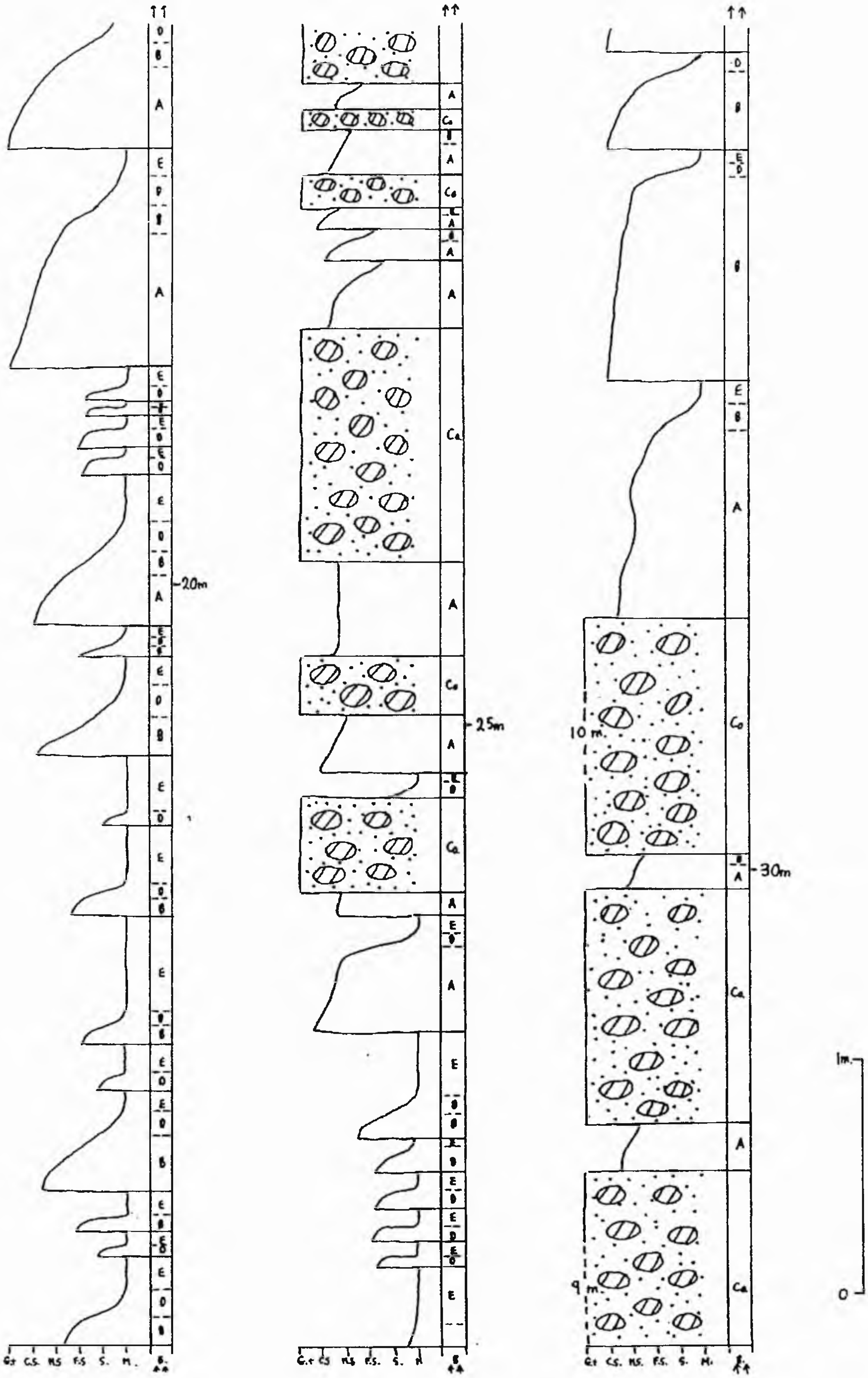
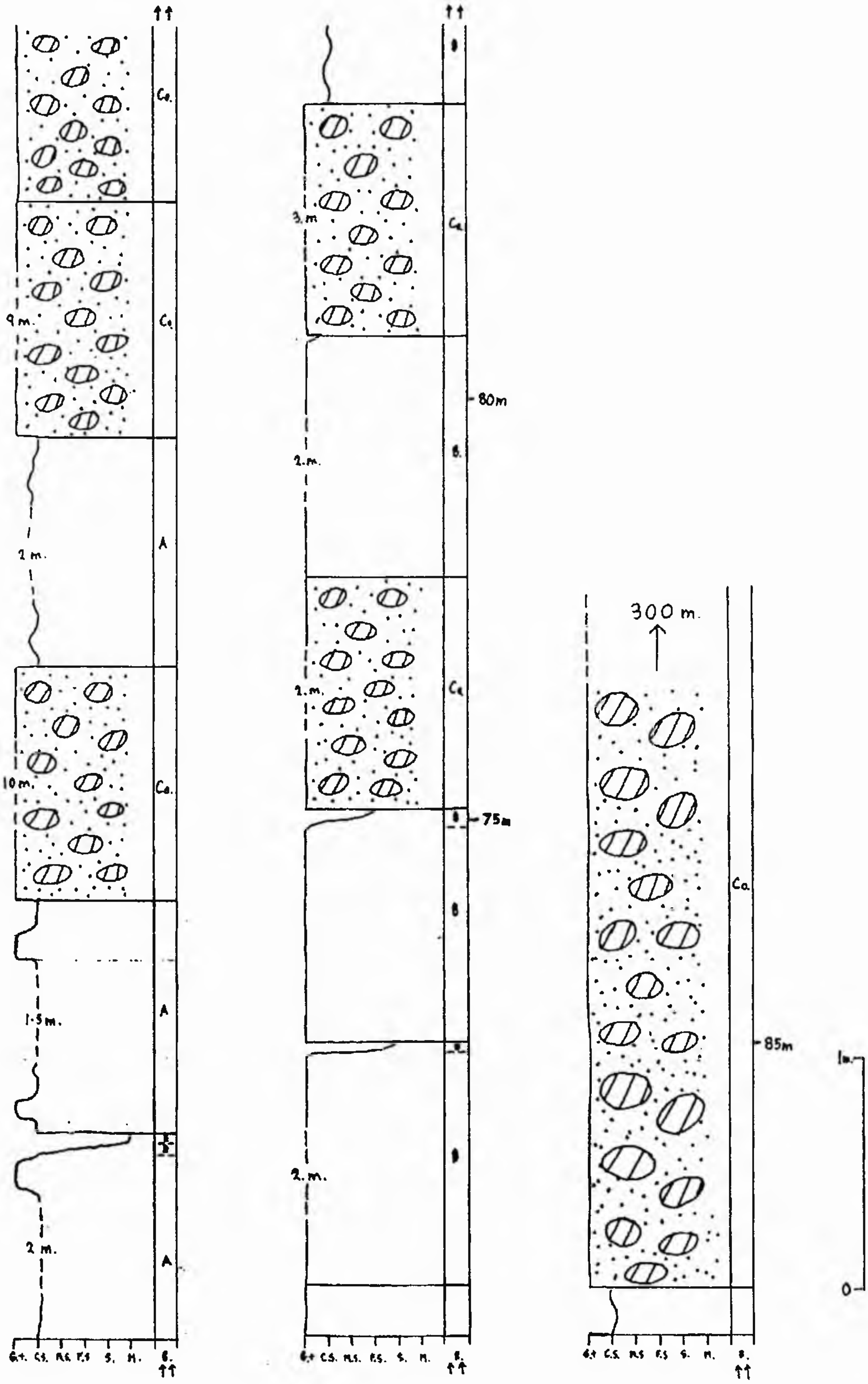


Fig 3.20: continued



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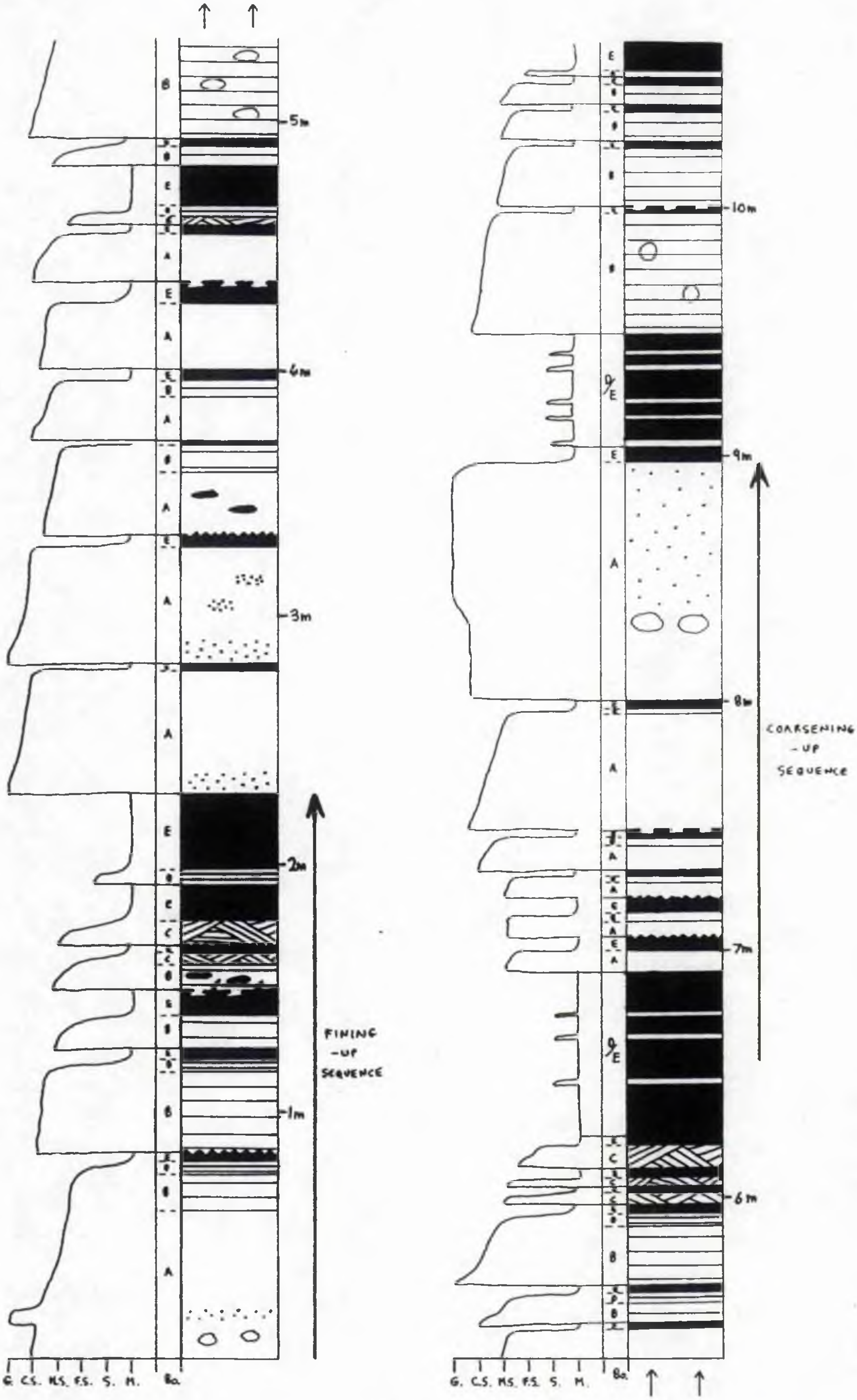


Fig 3.21: Composite sequencing in the Port Logan Formation at Needles and Pins (NX09164021).

Saddle Member contains bedded cherts in addition (Fig 2.11). The transition between middle fan lobe and outer fan deposition is sometimes gradational with thinning or thickening-upward sequences of up to 20 m while in some places it is abrupt over 1 or 2 metres. A few much thinner (less than 10 m) sequences of outer fan deposits are intercalated in the succession and in places contain oxidised red mudstones and dark, carbonaceous, fissile shales indicating periods of anaerobic bottom conditions possibly related to minor marine transgressions. There is no significant lateral facies variation over the 3.5 km the beds are exposed along-strike. The marked uniformity and cyclicity of deposition in the Port Logan Formation is characteristic of middle fan and outer fan deposition in a 'classical' submarine fan of Mutti and Ricci-Lucchi (1972, 1975). Active deposition switches between different lobes in relation to the sudden plugging of channels in the middle fan, with intervening deposition in an outer fan environment.

Clanyard Bay Block - pelagic and hemipelagic Moffat Shales were deposited in a basin plain environment with a progradational increase in clastic input during the Llandovery. The dominant anaerobic bottom conditions were temporarily replaced in the Ashgill by aerobic condtions caused by a major marine regression resulting from glacial advance (Leggett 1978). During this period oxidised red mudstones were deposited and spherulitic siderite nodules formed diagenetically causing reduction of the iron oxide and a green colouration in the surrounding red mustone (Plate 3.13). As before, deposition of the Moffat Shale Group was followed by rapid progradation into the middle fan with the lower 250 m of the Clanyard Bay Formation characterised by interchanging outer fan, middle fan lobe and rare middle fan channel deposition, in an overall progradational megasequence. Thin, pelagic, black shale units intercalated in this succession are thought to relate to minor fluctuations in oxygen content related to differences in current density and/or an increase in the density of carbonaceous material (Williams and Rickards 1984). By contrast the overlying Port Mona Member consists of a major retrogradational megasequence, with initial deposition in a channel mouth bar characterised by thick to massive B_2 and C_1 deposits with little shale (see Plate 2.7), and subsequent deposition of C_1 and C_2 turbidites in a middle fan lobe with the shale content increasing inversely with age. Towards the top of this megasequence intercalated bands of interbedded shales (Facies G) and thin turbidites (Facies E) are suggestive of channel levee or out of channel deposition in a proximal environment. Their association with middle fan lobe deposits in anomalous.

<u>Cardrain and Mull of Galloway Blocks</u> - the Mull of Galloway Formation is, like all of the Hawick Group, remarkably uniform lithologically. The vast bulk of the sediment, consisting of C_1, C_2 and E turbidites is characteristic of middle fan lobe deposition (Fig 3.22(A)), though a few thin sequences of D_1, D_3, G and rare D_2 deposits are indicative of an outer fan environment. The Leucarron Member contains in addition middle fan channel sequences up to 12 m thick that may display composite cycling but overall thin upwards (see Fig 3.22 (B)). These sequences have a B_2, C_1, C_2 and E association at their base and a G, D and D_3 association at their top indicating retrograde movement into outer fan deposition as the channel fills, before a return to middle fan lobe deposition. These channelised sequences are typically amalgamated, lenticular bedded and contain prolapse structures in contrast to the laterally extensive regular bedding of the middle fan lobe. Sand volcanoes are common throughout the formation indicating rapid deposition, in addition the marked decrease in greywacke grain size and paucity of tool formed sole markings, relative to the formations to the N, are noteworthy features. The high detrital carbonate content of the formation suggests deposition above the carbonate compensation depth which in turn implies a shallower depth of sedimentation than in the formation to the N. There is no evidence of a major marine regression at this time to account for this. The origin of the thin, oxidised red mudstone layers developed sporadically throughout the formation is unknown.

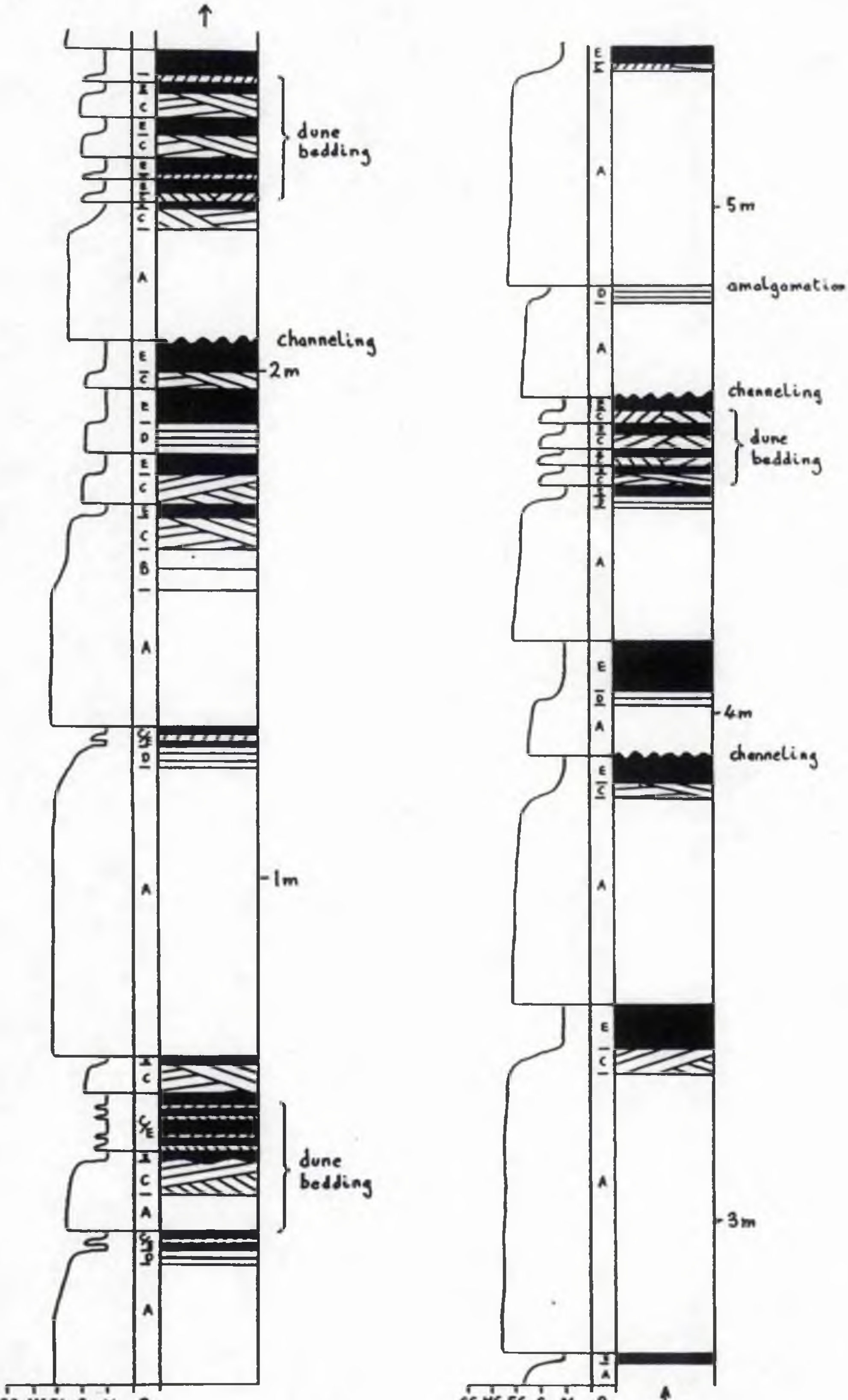
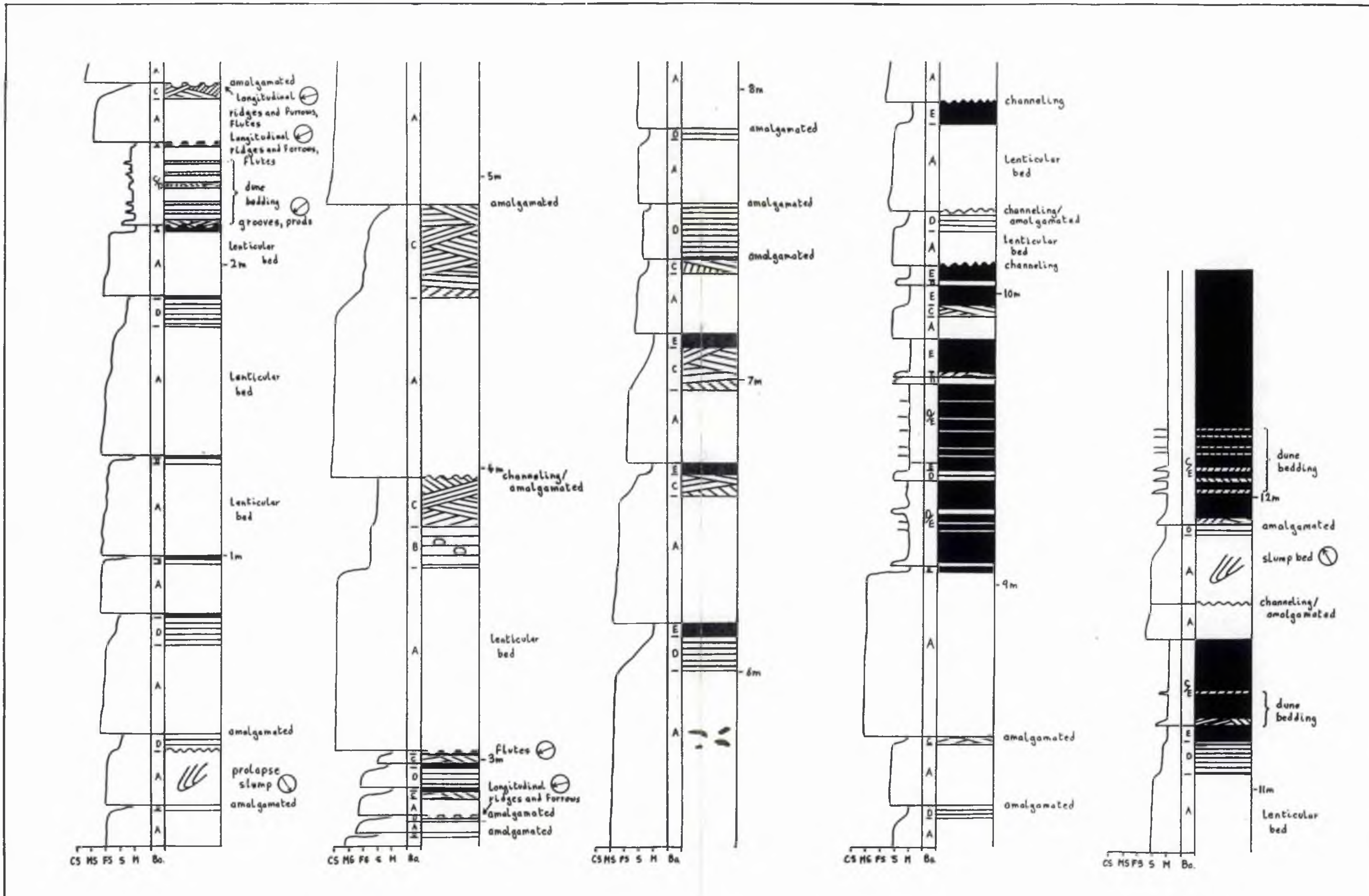
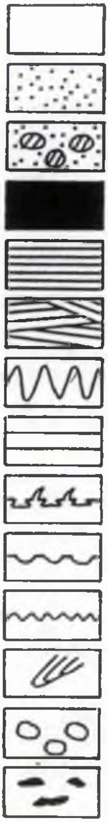


Fig 3.22 (A): 5 m section from the Mull of Galloway Formation at Carrickamickie Bay (NX12133151) showing characteristic middle fan deposition.


amalgamated
Longitudinal ridges and furrows, flutes
Longitudinal ridges and furrows, flutes
dune bedding
grooves, prods
Lenticular bed
2m
Lenticular bed
Lenticular bed
1m
amalgamated
prolapse slump
amalgamated
CS MS FS S M Ba.
5m
amalgamated
4m
channeling/ amalgamated
Lenticular bed
Flutes
3m
Longitudinal ridges and furrows
amalgamated
amalgamated
CS MS FS S M Ba.
8m
amalgamated
amalgamated
amalgamated
7m
6m
CS MS FS S M Ba.
channeling
Lenticular bed
channeling/ amalgamated
Lenticular bed
channeling
10m
9m
amalgamated
amalgamated
CS MS FS S M Ba.
dune bedding
12m
amalgamated
slump bed
channeling/ amalgamated
dune bedding
11m
Lenticular bed
CS MS FS S M Ba.



Sand and silt grade clasts

Granule grade clasts

Conglomerate (Co.)

Bouma Te - mudstone

Bouma Td - parallel lamination (silt grade)

Bouma Tc - cross lamination

Bouma Tc - convolute lamination

Bouma Tb - parallel lamination (sand grade)

Load and flame structures

Sole structures

Erosion surface (channeling)

Slump structure

Carbonate concretions

Mudstone rip-up clasts

Grain size grades — UDDEN-WENTWORTH SCALE:

(width of column indicates <u>maximum</u> grain size)

G	granule (+larger)	2mm+
CS	coarse sand	0·5 - 2mm
MS	medium sand	0·25 - 0·5mm
FS	fine sand	0·0625 - 0·25mm
S	silt	0·0039 - 0·0625mm
M	mud	< 0·0039mm
Bo.	Bouma divisions (A, B, C, D, E)	

Discussion - although the Mutti and Ricci-Lucchi (1972, 1975) and Mutti and Walker (1973) facies analysis schemes have proved of great value in interpreting the sediments and their distribution and associations in the Rhinns, it is clear that the depositional environment of the Rhinns sediments is more complex than the simple submarine fan systems on which the facies schemes are based. Three main points emerge from the analysis above concerning the sedimentation history of the Rhinns:-

(1) Two fundamentally different environments of deposition are represented in the sediments of the Rhinns. The older of these is dominated by pelagic, black shales deposited in a basin plain environment. Deposition continued uninterrupted for up to 35 million years from Llandeilo to mid Llandovery without any substantial clastic input. Such extended remoteness from a clastic source is only possible in an oceanic basin. Throughout the period of time represented by clastic deposition in the Rhinns, some 12-14 million years from Ashgill to late Llandovery, a clastic apron, representing the second major depositional event, prograded across the oceanic basin.

Attempts to laterally relate facies associations in different tectonic blocks of the same age have proved too subjective and of little value apart from showing the progradational diachronous onset of turbidite deposition above the Moffat Shale Group and its related effects.

(2) The progradational transition from pelagic, oceanic basin deposition to proximal clastic deposition is extremely rapid occurring in just a few metres, rather than a gradual change with extensive deposition of basin plain and outer fan deposits as would be expected. The catastrophic nature of the transition is best displayed in the Money Head Block where pelagic, black shales interbed with C_1 turbidites at the top of the Moffat Shale Group (Fig 2.6). It is less pronounced in the Grennan Point Block (Fig 2.7) and even less so in the Clanyard Bay Block where hemipelagic mudstones intercalate with the pelagic, black shales for a few metres prior to the deposition of proximal Facies C turbidites, though even here the transition is still rapid. For such rapid progradation to

occur continually over such a long period of time special conditions needed to exist and argues against deposition in a submarine fan system as described by Mutti and Ricci-Lucchi (1972). This is further supported by the absence of extensive tracts of clastic outer fan and basin plain deposits which normally characterise submarine fans. Instead clastic deposition is dominated by proximal high density flows with 'distal style' sedimentation generally confined to thin sediment starved sequences deposited in what was essentially a proximal environment.

(3) The distribution and vertical and horizontal sequencing of facies associations in the clastic deposits is much more irregular and complex than those described by Mutti and Ricci-Lucchi (1972, 1975) and Mutti and Walker (1973). Often seemingly incongrous environments are juxtaposed together in the succession, eg. the outer fan and inner fan channel in the 'Stinking Bight beds' and middle fan lobe and inner fan channel in the Mull of Logan Formation. No clear sequence trends or patterns emerge to the sedimentation beyond an initial progradational jump at the base of the blocks. Transitions between different environments are typically abrupt and rapid rather than gradational and cyclicity is poorly developed in all but a couple of the formations. These features suggest clastic deposition took place in a tectonically unstable, confined, high energy basin. In addition facies associations have been identified that are not described by Mutti and Ricci-Lucchi. The most widespread of these is the association of Facies E turbidites, that are lag deposits from large bypassing sediment gravity flows and typically occur as overbank deposits in the inner fan, with Facies D and G deposits, that only occur together in the outer fan or basin plain. Such an association has been identified by Underwood and Bachman (1982) as common in subduction zone trenches containing large channels, eg. eastern Aleutian Trench, southern Chile trench, etc., in which 'facies associations are similar to those of inner to middle fan facies, but more distal fan facies assocations are notably lacking'.

Two of the formations do not conform to this pattern. The remarkable uniformity and well developed cyclicity of the Port Logan Formation and Mull of Galloway Formation are more indicative of rapid deposition in a large, relatively unconfined submarine fan.

Southern Uplands - along-strike in the Southern Uplands the overall pattern of sedimentation remains very much the same although varying in detail. The progradation of a proximal clastic apron across a thick sequence of pelagic, basin floor deposits throughout the Llandovery occurs regionally, as does the change from mostly disorganised, proximal deposition in the Gala Group to organised, uniform, cyclic deposition in the Hawick Group. The first appearance of red mudstones (*M.convolutus* Zone), black shales (*M. turriculatus* and *M. crispus* Zones) and substantial amounts of carbonate detritus (Hawick Group - *M. griestoniensis* and *M. crenulata* Zones) in the clastic succession can all be correlated regionally indicating they are related to major environmental changes, such as sea level fluctuations, rather than local conditions. A more detailed attempt at correlation with areas immediately along-strike in the Ards Peninsula to the SW and Wigton Peninsula to the NE is recorded in Barnes, Anderson and McCurry (1987) - (Appendix 2). The inner fan channel and slope channel conglomerates and slumps in the Mull of Logan Block can be correlated with similar deposits of equivalent age in the Corwall Block of the Wigton Peninsula. Although it is unlikely they belonged to the same depositional system, they do perhaps suggest that a major progradational event took place at this time. The conformable succession from the Moffat Shale Group to the Gala Group to the Hawick Group, exposed along-strike from Millan Bay to Coniamstown in the Ards Peninsula and Lecale and described in Chapter 2 (Section 2.4 and Fig 2.13), is of major importance as it is indicative of progradation from an ocean basin to subduction zone to submarine fan environment and means the Hawick Group could not have been deposited in a short lived foreland basin (see Stone *et al* 1987) or successor basin (see Murphy and Hutton 1986) as it is underlain by long-lived, pelagic, ocean basin deposits. This succession is also important as it shows the conformable transition from carbonate poor deposition (Gala Group) to carbonate rich deposition (Hawick Group) probably caused by the depositional depth decreasing to above the carbonate compensation depth. The width of the Central Belt varies from a minimum of less than 30 km in SW Scotland to over 45 km in the Ards Peninsula and Lecale and is related to sediment supply rate. The much greater thickness of sediment deposited at the latter locality is possibly indicative of deposition adjacent to a submarine canyon or large slope channel.

3.5 PALAEOCURRENT ANALYSIS

A total of 242 bedding surface current indicators were analysed to provide information on palaeoflow during deposition of the eight Silurian formations. Too few sole markings were identified in the two Ordovician formations to make their analysis of statistical value. The results of the anlayses are shown in Fig 3.23.

The current markings were unfolded about F_1 folds using Ramsay's (1961) flexural slip technique. Both flexural slip and similar fold mechanisms operated during F_1 folding in the Rhinns, however the latter was dominant only in the incompetent shale and mudstone beds and was of much less importance in the competent greywacke beds as indicated by their lack of appreciable hinge thickening. Unfolding by the flexural slip technique produces a wider scatter of deduced primary orientations than with the similar technique (see Craig and Walton 1962) and is used in preference to reduce possible error. Error was further reduced by discounting data not obtained in the vicinity of a fold hinge or where the fold plunge is steep and the strata disrupted. Most of the fold hinges used had a plunge of less than 25°, although two small data groups were obtained from coherently bedded strata in hinges plunging at 40°. Similarly where the strike of the beds is clearly anomalous, ie does not conform to a general ENE-WSW pattern, the data has been discounted. No attempt has been made to rotate the beds into an 'idealised' strike prior to unfolding (see Cameron 1977) as this is regarded as too subjective. Clearly any current directions derived from attempts to rotate current markings back into their original orientations in such a structurally complex zone as the Southern Uplands can only be approximate and it is therefore statistically important to carry out as many analyses as possible. As the current directions obtained from each formation are relatively clear and unambiguous and contain few anomalies (see Fig 3.23) it suggests the rotation methods used are reasonably accurate.

As stated in Section 3.3.1, flow direction is not a fixed entity during each flow event. Groove marks on the sole of a single bed may be divergent by up to 30°, while at Robertson's Bay (NX08324167) in the Port Logan Formation ripple marks on a bedding surface indicate a flow direction at 90° to that shown by goove marks on the sole of the same bed. This divergence in flow direction shown by ripple marks relative to sole marks is ubiquitous throughout the Rhinns and may be due to flow divergence in turbidite tails as they become less gravity constrained, or may be caused by the reworking of turbidite tops by bottom 'contour' currents, though no winnowing effects have been found in association with the ripple to indicate this. Scott (1967) lists four possible causes of intra-bed variation in palaeocurrent direction in Southern Uplands turbidites:

(1) the changing resolution of gravitational forces and fluid energy forces where the current flow is not directly downslope at a given point in time; (2) turbulence within the current, particularly resulting from irregularities in the bottom topography; (3) deflection by normal ocean currents (ie. 'contour' currents); and (4) multiple sources of turbidity currents depositing a single composite bed.

The dominant flow within the Rhinns was axial and from the NE (Fig 3.23). Exceptions to this are the 'Stinking Bight beds' where flow was from the NW and more surprisingly the Clanyard Bay Formation and Mull of Galloway Formation where flow

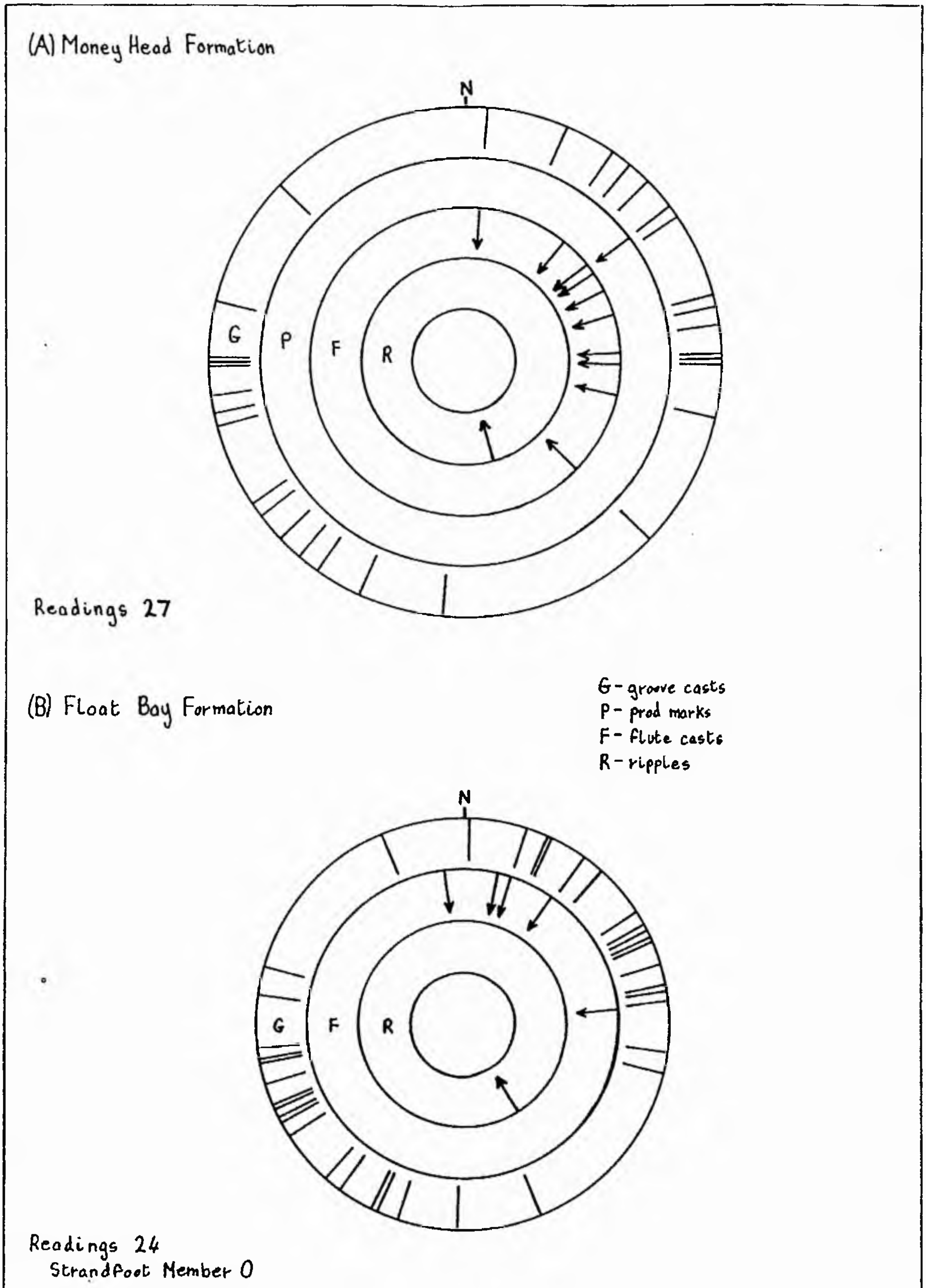
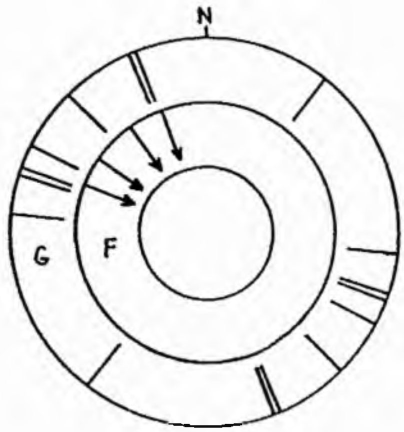


Fig 3.23: Palaeocurrent directions for each formation (A-H).

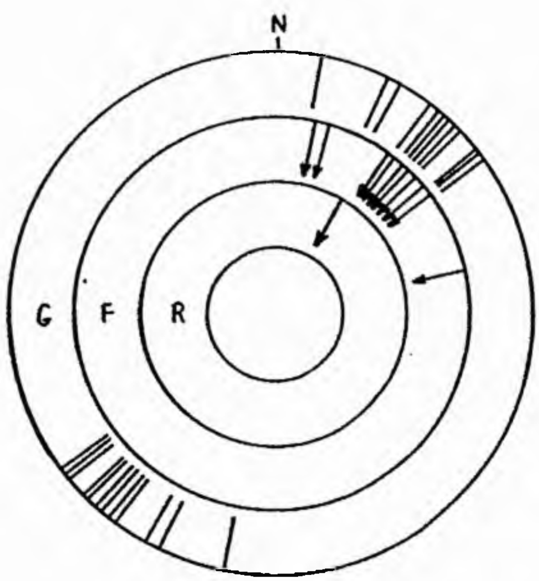
(C) 'Stinking Bight beds'



Readings 12

G- groove casts
F- flute casts
R- ripples

(D) Grennan Point Formation



Readings 23

Fig 3.23: continued

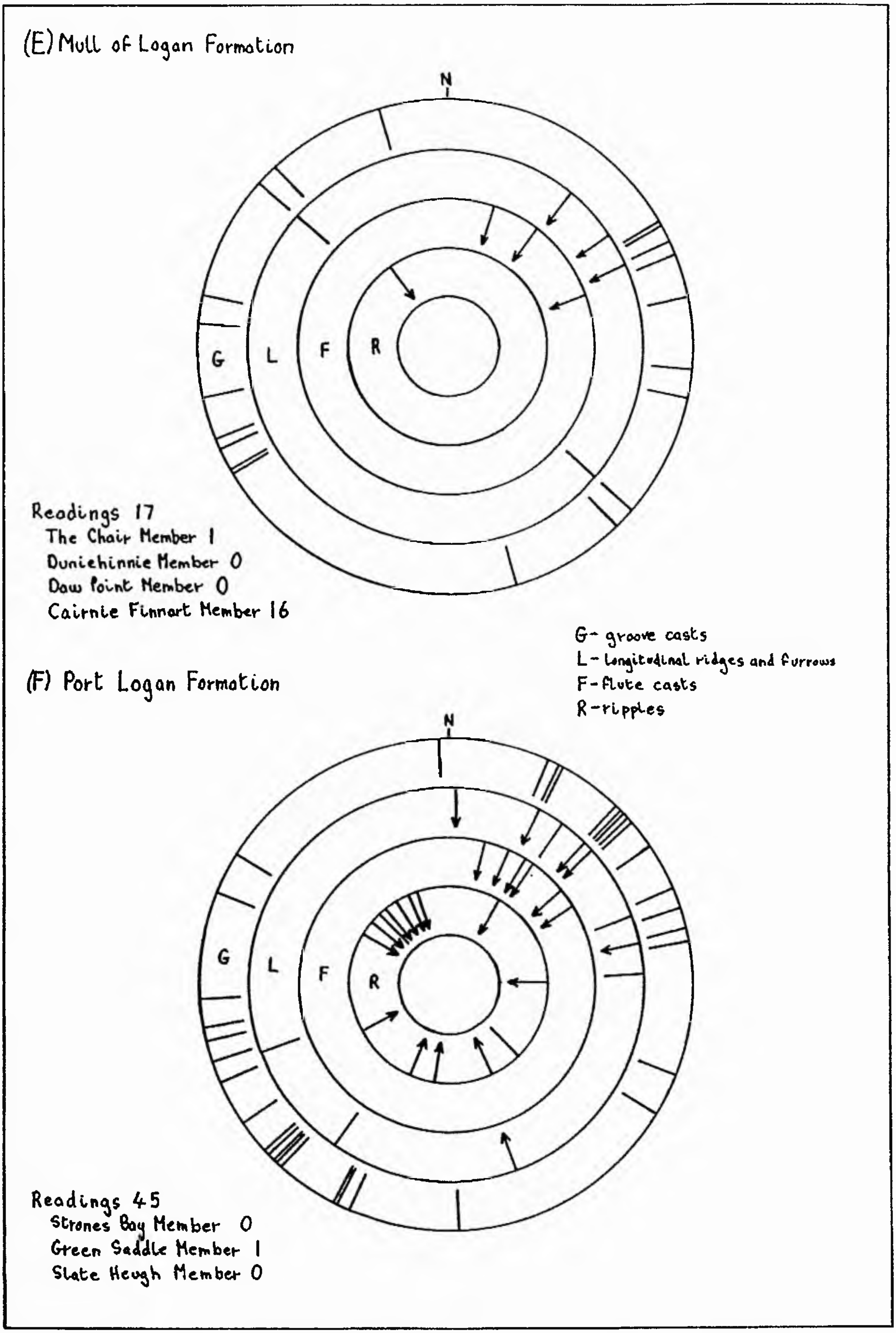


Fig 3.23: continued

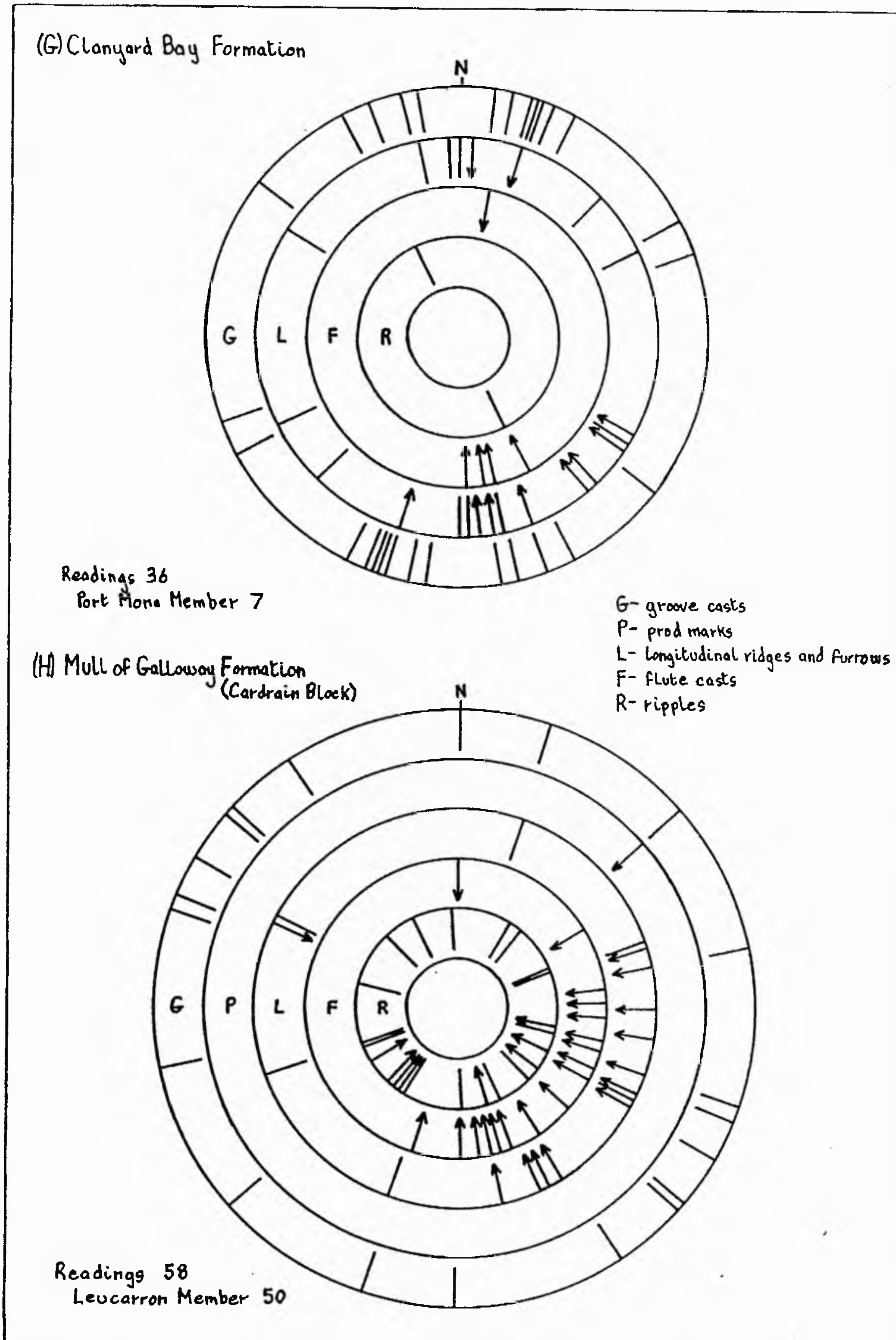


Fig 3.23: continued

was from the SE. These are the only formations in the Central and Southern Belts with a southeasterly derivation through a few sole markings indicating flow from the SE have been found in the Northern Belt (see Walton 1983 - Table 6.2, Stone *et al* 1987). Flow throughout the Southern Uplands was predominantly from either the NW or NE, though on occasions from the SW. Apart from in the Rhinns, the Hawick Group was dominated by axial flow mainly from the NE though Rust (1965b) provides some additional evidence of southeasterly derivation, while by contrast Warren (1963) indicates northwesterly derived flow. In relation to the rest of the Southern Uplands flow from the SE is clearly anomalous and needs explanation (see later - Section 3.7 and Chapter 5).

3.6 DERIVED CORALS

During the course of this study two derived specimens of coral were found. One of these, the colonial rugose coral *Ceriaster* sp., was found 150 mm above the base of a 1 m thick, granule grade turbidite in the 'Stinking Bight beds' 250 N of Ardwell Bay (NX07144551). The other, the hemispherical tabulate corallum *Propora exigua* was found upside-down in a small shear-bounded mudstone lens in the Chair Member of the Mull of Logan Formation at Back Port (NX07724285). Previous records of the genus *Ceriaster* were confined to Asiatic Russia (Tadzhikstan) and China and no record of it or its close relative *Stauria*, are known from the North American side of the Iapetus Ocean. The specimen found does not belong to any existing species, however it is considered inappropriate to erect a new species on a single, derived specimen. The specimen of *Propora exigua* and a contemporaneous *in situ* find of the same species by Dr C T Scrutton in the late Llandovery Hughley Shales of the Welsh Borderland represent the first unequivocal European records of this species, though on opposing margins of the Iapetus Ocean. The Rhinns specimen is believed to be derived from the North American side of Iapetus from where it has been moderately widely reported.

Both the specimens of *Ceriaster* sp. and *Propora exigua,* along with a third coral examined, *Propora edwardsi* found by Rust (1965b) in the Hawick Group of the Wigton Peninsula, are believed to have been derived from contemporaneous shelf environments and transported by floatation and sinking to their points of interment, excepting *Ceriaster* sp. which underwent a further stage of transportation as part of a turbidite bedload before reaching its final locus of deposition. A full account of the field relations, derivation, biostratigraphy and palaeobiogeographic significance of these corals is given in Scrutton and McCurry (1987) - (Appendix 5).

3.7 SUMMARY

The most important findings with regard to the tectonic setting of deposition come, not from petrographic or palaeocurrent analyses, but from facies analysis. It is apparent that while clastic deposition was taking place in a confined, high energy basin inboard, pelagic deposition was taking place in a large ocean basin outboard to the SE. At the same time the clastic deposits were catastrophically prograding over the pelagic deposits. Such a paradoxical situation is best explained by trench sedimentation in an active subduction zone. In particular the significant occurrence of Facies D, G and anomalous E in common association and absence of clastic outer fan and basin plain deposits are telling factors in support of this conclusion. The Port Logan Formation and Mull of Galloway Formation were by contrast deposited in large, relatively unconfined submarine fans which could only occur if the trench were overtopped or if they originated from a different margin.

The sedimentation pattern described could not have formed in the successor basin modelled by Hutton and Murphy (1987), as any inboard trough would have quickly infilled with clastic deposition once subduction ceased giving rise to large, unconfined, submarine fan sedimentation. The progradation of these fans across an ocean floor would have resulted in extensive outer fan deposition overlying the pelagic Moffat Shales, a progradational sequence not found in the Southern Uplands. The same problem applies to the back-arc basin model of Stone *et al* (1987). Even more problematical is the failure of the back-arc basin model to satisfactorily account for the presence of outboard pelagic deposition, requiring sediment bypass on one margin of the basin and not the other. Southeasterly derived palaeocurrents in the Gala Group are predicted by the model but the Clanyard Bay Formation in the Rhinns is the only known example of this. Both the successor basin and back-arc basin models have problems in accommodating the extreme duration of pelagic sedimentation (35 million years in the Central Belt of the Rhinns) which could only occur in a large oceanic basin remote from a clastic source. The subsequent foreland basin model of Stone *et al* (1987), explaining Hawick Group and Wenlock deposition, is simply disproved by the presence of these pelagic deposits conformably beneath the Hawick Group in the Ards Peninsula and Lecale (see Sections 2.4 and 3.4.2).

The occurrence of southeasterly derived palaeocurrents is of great interest and needs explanation, however their importance is somewhat negated by their uniqueness. Before they could be used as evidence of a major landmass to the SE, it needs to be demonstrated that they are more than just a local anomaly in a terrane otherwise dominated by flow from the NE and NW. Their significance is discussed more fully in Chapter 5.

The petrographic analysis demonstrates a subduction complex source for the detritus with additional input from a magmatic arc in the Portayew Formation (base only), Money Head Formation and Mull of Logan Formation. The latter two interestingly are also composed of the most proximal deposits in the Rhinns. The other formations may have had a slight subsidiary input from a foreland uplift or collision orogen source. These sources lend support to all three tectonic interpretations of the terrane. No major compositional change is evidenced in the SE-derived formations though the three southernmost formations, two of which derive from the SE, are also the most mature. The high carbonate content of the Mull of Galloway Formation suggests it was deposited above the carbonate compensation depth and thus at a shallower depth than the other formations.

CHAPTER FOUR : STRUCTURAL GEOLOGY

4.1 INTRODUCTION

Early structural interpretations of the Southern Uplands evolved a fold dominated scenario in which intense isoclinal folding culminated in a major anticlinorium in the NW and synclinorium in the SE (Lapworth 1889). Subsequent re-interpretation as a series of N-facing monoclines with alternate intensely folded sub-horizontal limbs and unfolded sub-vertical limbs, the latter cut by major reverse faults (Craig and Walton 1959), led to its present definition as a thrust dominated terrane (Mitchell and McKerrow 1975, McKerrow *et al* 1977). Further to this modern interpretation, uncertainty remains as to the tectonic setting with discussion majoring on the precise timing of deformation, whether diachronous (Leggett *et al* 1979), climactic (Murphy and Hutton 1986, Stone *et al* 1987) or even pre-tectonic, i.e. soft sediment deformation (see Knipe and Needham 1986).

The cliffs along the W coast of the Rhinns provide one of the best exposed dip sections in the Southern Uplands. The aim of this chapter is to give a detailed account of the major and minor structure throughout the Rhinns. Emphasis is placed on describing the three-dimensional structure of the area and on how the structures formed and relate to one another in time and space, rather than on describing individual structures and their orientation changes throughout the Rhinns. The structure of the Rhinns is shown on Maps A-D on which most folds and all but the most minor faults are indicated along with the fold plunge, axial plane dip, fault displacement, bedding, younging and cleavage. A cross-section through the area has been drawn and orientation data for each tectonic block has been plotted stereographically.

The chapter begins with an overview of the structure of the Rhinns followed by a detailed account of the structure of each tectonic block. This descriptive section is a necessary aid in the understanding of the structure of the Rhinns as displayed on

Maps A-D. F_1 folding, F_2 folding and the post-F_2 fold types are each then examined followed by an examination of the three types of faulting present: strike faults, wrench faults, and late minor (thrust and normal) faults. The igneous intrusions and resultant contact metamorphism are discussed in addition to an examination of the regional metamorphism. The history of deformation in the Rhinns is stated and is placed in the context of the Southern Uplands as a whole.

All strike and azimuthal directions are given as three-figure bearings, corrected to true N. Stereographic analyses of structural data are on Lambert, equal-area, lower hemisphere projections. Folds are described using the nomenclature of Fleuty (1964) and Hobbs *et al* (1976).

4.2 DETAILED STRUCTURE OF THE RHINNS

4.2.1 Structural overview

The repetition of the stratigraphy, identification of a distinct décollement horizon (the Moffat Shale Group), sub-parallel orientation of faulting and bedding, and the common occurrence of hanging wall anticlines and footwall synclines suggest the Rhinns outcrop constitutes an imbricate thrust stack. Marked changes in lithostratigraphy or biostratigraphy often occur at the major thrust boundaries with further imbrication developed between these at lesser scales. These faults merge both laterally and at depth to produce a complex system of anastomosing thrusts defining tectonic lenses. In the Rhinns these tectonic lenses resolve into the eleven major tectonic blocks shown in Maps A-D and Fig. 2.2

A detailed account of the deformation phases affecting the Rhinns is presented in Section 4.3 and 4.4, however a summary of the major features is provided here to aid understanding of the structural account given later in this section and in Maps A-D. A system of major to minor, isoclinal to close, F_1 folds developed synchronous with thrusting and is associated with a contemporaneous regionally developed slaty cleavage (S_1). The sense of vergence of F_1 folding and thrusting is opposite across the Port Logan Bay Fault, being to the SE north of the fault and to the NW south of it. Intermediate to minor, tight to open, SE-verging F_2 folds relate to a second phase of thrust development and are associated with a sporadically developed S_2 crenulation cleavage. Four systems of mostly post-F_2 minor folds are developed. Most significant of these are NW-verging recumbent folds closely associated with minor sub-horizontal thrusts and a weak crenulation cleavage. A system of steeply plunging fold pairs both sinistrally and dextrally verging are found in association with some of the strike faults and are referred to as Tarbet folds (West Tarbet (NX13953095) being the locality where they are most intensely developed and best exposed). These are tight to open, cleavageless folds, often possessing a chevron like geometry and displaying a consistent vergence at any one locality. Rare kink banks are predominantly steeply plunging, dextral and represent the last fold deformation.

Bedding within the fault zones of the major thrusts is often very brecciated having undergone extensive brittle as well as ductile deformation. Much of this deformation took place in a sinistrally transpressive regime resulting in the common clockwise transection of F_1 fold axial planes by the S_1 cleavage (Murphy 1985, Anderson 1987). Sinistral movement is also indicated by the mylonitic fabric of the Cairngarroch Fault and its splay with a postulated displacement in excess of 400 km (Anderson and Oliver 1986). Late N-S trending wrench faults effected major sinistral, brittle dislocation of the area.

In the following section the structure in each of the eleven major tectonic (thrust) blocks is described and a picture of the overall structural configuration of the Rhinns is built up. The blocks are described in order from the oldest in the N to the youngest in the S and internally from N to S. The major structure of the Rhinns was determined early during D_1 deformation and, apart from major strike-slip movements, underwent only minor modification later. As a result this description is primarily of the D_1 structure, but draws attention where appropriate to post-D_1 features. This section is purely descriptive and does not attempt interpretation. The structure described is shown in detail on Maps A-D and the attendant dip sections and stereographic plots.

4.2.2 Tectonic blocks

4.2.2.1 Portayew Block - the brecciated northwestern limb of a large faulted syncline immediately NW of Portayew (NX03755040) contains steeply plunging minor folds in which the S_1 cleavage is clearly clockwise transecting. To the SE the 420 m wide Portayew Fault Zone consists of at least three major strike faults causing imbricate repetition of Moffat Shales and the overlying Portayew Formation turbidites. The beds young consistently to the NW necessitating southeasterly downthrow on the faults. The greywackes of the Portayew Formation are intensely brecciated within this zone and contain rare, minor, SE-verging fold pairs. The strike fault forming the southeastern limit of the fault zone (and block) is located 150 m NW of Cove Hip (NX04025001) and has small slivers of sheared Moffat Shale incorporated along it. The S_1 cleavage shows ubiquitous downward facing relations throughout the block.

Post-F_1 - post-F_1 folding is very common in the Portayew area where a series of minor, predominantly N-verging and possibly conjugate S-verging, recumbent, kink like fold pairs bend the S_1 cleavage. A much larger intermediate scale, N-verging recumbent fold affects the Moffat Shale succession in the Portayew Fault Zone at Portayew and is believed later than a similarly intermediate scale, S-verging, close to open, fold pair immediately S of it and ascribed to F_2.

4.2.2.2 Cairngarroch Block - no F_1 fold hinges are present within this block. The bedding both youngs and dips steeply NW except at the block boundaries where it remains NW-younging, but is slightly overturned. Bedding is intensely brecciated for 50 m SE of the northwestern fault boundary (described above) and similarly adjacent to the Cairngarroch Fault forming the southeastern boundary where the greywackes have deformed into distinct shear lozenges. This fault has a postulated sinistral movement in excess of 400 km (Anderson and Oliver 1986) and in a 2 m x 1 m outcrop at Calves Hole (NX04644905) attains a phyllonitic texture with a well developed sinistral S-C fabric. S_1 cleavage is only sporadically observable within the block due to the hornfelsed nature of the lithology, but is invariably downward facing. Post-F_1 - intermediate to minor, NW-verging recumbent folds are common throughout the block, with the rare development of intermediate, SE-verging, possible F_2 folds. The NW-verging folds typically have very angular hinges and are open to close, while the SE-verging folds have rounded hinges and are open.

4.2.2.3 Money Head Block - no F_1 fold hinges are present within this block and bedding consistently youngs and dips at a moderate to steep angle northwestwards. The Strandfoot Fault Zone marks the southeastern boundary of the block and consists of three strike faults each within a southeasterly downthrow causing tectonic repetition of the Moffat Shales and overlying Money Head Formation greywackes. All three imbricate slices are exposed in the Cairnweil Burn (NX08654936), however only the two northernmost are exposed at Strandfoot (NX05204814) due to the displacement of the fault zone by an E-W trending dextral wrench with a slip in excess of 200 m (Map A). The Cairnweil Burn section is similarly displaced at least 250 m by a NW-SE trending wrench that also displaces a splay of the Cairngarroch Fault. This splay migrated 1 km S from the main fault and developed preferentially along a 50 m thick sequence of Moffat Shales which deformed into an anastomosing sequence of sheared microlithons with a rare phyllonitic fabric (for full discussion see Chapter 2 - Section 2.2). An S_1 slaty cleavage is well formed throughout the block and is upward facing.

Post-F_1 - a conjugate series of minor, NW- and SE-verging, open to gentle folds are sporadically developed, and a steeply plunging, intermediate, sinistrally-verging fold pair is present immediately SE of the Cairngarroch Fault at Anns Cave (NX04574900).

4.2.2.4 Float Bay Block - the Strandfoot Fault Zone extends for 300 m SE of the Money Head Block at Strandfoot and contains five tectonically emplaced lenses of Moffat Shale up to 20 m thick. The synclinal hinge of a major SE-verging fold pair within the fault zone has been removed by faulting and a brecciation zone formed. The northern limb of the anticline contains numerous, minor, SE-verging, isoclinal to open fold pairs. For 900 m SE of the fault zone the sequence is intensely brecciated and contains five major folds, all overturned to the N. Four of these have strike faults developed in their hinge zones. The first fold encountered occurs 130 m SE of Goodwifes Cave (NX05354788) and is a syncline with a clockwise transecting S_1 slaty cleavage. 140 m SE of this at Horney (NX05454779) is a faulted anticline. An 80 m zone of neutrally-verging, steeply plunging, minor folds and associated strike faulting represent a major synclinal hinge zone immediately NW of Clow Caves (NX05504770). 140 m to the SE of this (Grid Reference NX05684760) a major SE-verging fold pair is developed in the otherwise NW-younging succession. Both hinges are faulted and the 100 m wide SE-younging short limb is intensely brecciated and folded by minor NW-verging fold pairs. SE of this point the beds young consistently to the NW dipping variously both to the NW and SE and are affected only by minor SE-verging fold pairs and one intermediate isoclinal fold pair 150 m SE of Float Bay (NX06354700). Fold plunge is predominantly to the NE, but commonly to the SW also and varies from steep to gentle. S_1 slaty cleavage is commonly downward facing on NW-younging fold limbs indicating non-axial planar cleavage relations. Major strike faults occurring at Arthurs Slunk (NX0654689), Island Buoy (NX06484690) and Float Bay (NX06354725) indicate that the Float Bay Block is an amalgam of a number of tectonic blocks currently unresolvable stratigraphically. The southeastern boundary of the block is a poorly exposed strike fault displaced on the coast at Salt Pans Bay (NX06934616) by a sinistral wrench. The bedding is intensely brecciated for 300 m NW of this fault.

Post-F_1 - apart from a well developed system of conjugate, though predominantly dextral, kink bands present in the Salt Pans Bay area, post-F_1 folding is rare. Minor, sub-horizontal, NW-directed thrusting is locally common.

4.2.2.5 Stinking Bight Block - intense neutral to NW-vergent minor folding is present immediately SE of the Float Bay Block at Salt Pans Bay and is succeeded to the S for 150 m by a SE-younging succession suggesting the folding represents a major faulted anticlinal hinge. The SE-younging succession ends at a NNE-SSW trending fault, to the S of which various faults of mostly unknown displacement are present. Nevertheless the bedding remains consistently NW-younging and is dominantly overturned. Across one of these faults immediately to the N of Ardwell Bay (NX07124527), a series of minor, neutrally verging folds with clockwise transecting S_1 cleavage are succeeded to the S by a SE-younging succession suggesting once again the presence of a major anticlinal hinge. SE of the bay bedding youngs to the NW and dips SE at approximately 10^o-40^o. Approaching The Hooies (NX06704470) the bedding develops a N-S strike and is cut at a high angle by the S_1 slaty cleavage which maintains its NE-SW trend. At The Hooies (NX06804460) major strike faulting has intensely brecciated the succession. Minor to intermediate folds, some with well developed axial planar cleavage, are present. The folds are steeply plunging and in some places downward facing. Folds within the block have gentle to steep plunges both to the NE and SW.

Post-F_1 - NW of The Hooies (NX06704470) a number of minor, open, sinistrally-verging fold pairs are present and plunge moderately eastwards.

4.2.2.6 Grennan Point Block - within this block the bedding youngs to the NW and is inverted, apart from two 100 m and 300 m thick sequences younging and dipping to the SE. The former of these forms the northwestern limb of a major syncline at Step Craig (NX07034397) and the latter is juxtaposed between two N-S trending wrench faults at Iron Slunk (NX06884403). Rare, minor, SE-verging fold pairs are present within the NW-younging successions. Threefold imbricate repetition of Moffat Shales overlain by Grennan Point Formation greywackes is superbly displayed along the southeastern edge of the block. The northwesternmost Moffat Shale inlier has a width of 100 m across-strike. It is both intensely folded by neutrally-verging, isoclinal to close folds and faulted by strike faults with a southeasterly downthrow. A major synclinal hinge exists in the greywackes immediately SE of the inlier. Anomalous NW-verging, downward facing, minor folds with a clearly developed axial planar S_1 cleavage are found NW of the next inlier to the S at Drumbreddan Bay (NX7734376). The greywackes juxtaposed between the Moffat Shale inliers are coherently bedded, however NW of the northwesternmost inlier they are brecciated for over 130 m across-strike. Despite the apparent axial planar relations of the well developed S_1 slaty cleavage to some upward facing F_1 folds, the cleavage is downward facing over most of the block. Folds typically plunge at gentle or moderate angles to the NE.

<u>Post-F_1</u> - minor to intermediate, open, SE-vergent F_2 folds and NW-vergent later folds are commonly developed NW of Step Craig. A minor, steeply plunging, dextral fold pair is present in the Moffat Shale inlier at the northwestern end of Drumbreddan Bay.

4.2.2.7 Mull of Logan Block - apart from a pair of intermediate, open folds at Crubben Point (NX07704310) and a 50 m fault bounded zone of southeasterly younging at Back Port (NX07734287), the whole succession is northwesterly younging and dips steeply to the SE for over 2 km to Bonny Well Bay (NX08444163). Immediately SE of the Grennan Point Block the bedding is intensely brecciated for 160 m. For a further 450 m a series of major strike faults are developed, one of which, at Port Gill (NX07804298), exposes a 10 m thick tectonic lens of sheared Moffat Shales. This 1 km zone of intense shearing spanning the boundary of both the Grennan Point Block and Mull of Logan Block is referred to as the Drumbreddan Bay Fault Zone. At Bonny Well Bay the first of three major, SE-verging fold pairs affecting the succession SE to the Portavaddie Fault (NX09154135) occurs. The SE-younging short limbs of the two northwesternmost fold pairs have an outcrop width of over 100 m and are intensely folded by minor, NW-younging, F_1 fold pairs. The Portavaddie Fault is a late wrench of unknown displacement and the succession to the SE is extremely brecciated, SE-younging and folded by minor, NW-verging fold pairs with isolated steep plunging hinges. Within the block folds plunge gently to steeply both to the NE and SW. The S_1 slaty cleavage is variably axial planar and clockwise transecting in relation to the F_1 folding.

The southeastern boundary of the block (NX09654085) is the Port Logan Bay Fault which is topographically expressed as a zone of no exposure with an across-strike width of 700 m. This zone traverses the Rhinns at its narrowest and lowest point from Port Logan Bay on the W coast to Terally Bay (NX12404110) on the E coast. At Terally Bay the steeply shelving nature of the beach relative to the rest of the E coast indicates a marked increase in the water depth offshore. This fault marks a fundamental change in the geometry of D_1 deformation as the sense of vergence and younging direction are opposing across it.

<u>Post-F_1</u> - minor, gentle folding, attributable to F_2 is present in the Cairnie Finnart Member and a weak SE-verging crenulation cleavage occurs immediately NW of Portavaddie (NX09004140). Kink bands with a predominant dextral vergence are present in a thick siltstone/mudstone sequence at Parkers Point (NX07764338).

4.2.2.8 Port Logan Block - immediately S of Port Logan Bay a 50 m thick NW-younging succession ends abruptly at a strike fault. Across this fault a major syncline is exposed at Quarry Bay (NX09204033), to the SE of which bedding youngs and dips moderately NW. In places the succession is intensely folded by intermediate to minor, isoclinal to rare open, SE-verging fold pairs. This NW-younging short limb ends at a major periclinal anticline at Cairnywellan Head (NX09053980) over which bedding is steeply N-dipping and S-younging for 550 m. A short 40 m fault bounded tract of neutrally-verging folds occurs 100 m SE of the Cave of Carlin Bed (NX09143967). The southerly younging ends at Green Saddle where a major syncline, overturned to the SE, is succeeded to the SE by a major strike fault which effectively splits the tectonic block into two. SE of this fault an intermediate scale anticline and syncline are overturned to the SE and are succeeded by a major, upright anticline N of the Caves of Lennans (NX09403902). Bedding on the southeastern limb of this anticline dips and youngs to the SE for 350 m to a major, upright syncline at Strones Bay (NX09503865). The southern boundary of the block is defined by a major strike fault immediately SE of Strones Bay. The major structural components on the W coast remain broadly intact for 3.5 km along-strike to the less well exposed E coast, apart from changes due to fold plunge and late sinistral and dextral wrenching. Throughout the block folds plunge predominantly to the NE at gentle to steep angles and the well developed S_1 slaty cleavage is clearly seen to be non-axial planar in a number of exposed hinges.

Post-F_1 - a SE-vergent S_2 crenulation cleavage is developed locally, particularly within the hemipelagic members where it is sometimes associated with minor, SE-vergent, open folding. Dextral kink bands are also found within the hemipelagic members.

4.2.2.9 Clanyard Bay Block - the Clanyard Bay Fault Zone extends for 1.6 km S from the Port Logan Block and consists of four tectonically imbricated Moffat Shale inliers and overlying Clanyard Bay Formation turbidites. The succession is severely disrupted by strike faulting, brecciation and major, intermediate and minor folding. Between the Port Logan Block boundary and Clanyard Bay (NX10103790) bedding is predominantly SE-younging, NW-dipping and intensely folded by intermediate and minor, NW-verging chevron folds. This succession is separated from NW-younging

Moffat Shales at the northern end of Clanyard Bay by a major faulted syncline with a clear northwesterly downthrow. The Moffat Shale inliers at the southern edge of Clanyard Bay and Breddock Bay (NX09163720) both young to the NW. The succession between them is similarly predominantly NW-younging, though is intensely folded by intermediate, neutral to SE-vergent folds. A set of late, sinistral, NW-SE trending wrenches causes the Moffat Shale inlier at Breddock Bay to crop out on the coast a second time, 750 m to the SW at Cave of the Saddle (NX08553675). Across a strike-fault to the NW of the inlier at Cave of the Saddle an 80 m thick SE-younging succession is present. The Breddock Bay inlier can be traced inland where it imbricates further forming outliers of Clanyard Bay Formation greywackes tectonically enclosed within Moffat Shales. The southeasternmost Moffat Shale inlier is not exposed on the coast and is only poorly exposed inland. A major anticline occurs immediately SE of the major strike fault forming the southeastern boundary of the Cave of the Saddle Moffat Shale inlier. SE of this anticline bedding both youngs and dips to the SE and is folded by intermediate, neutral and NW-verging folds.

SE of the Portencorkrie granite-diorite intrusion a major, upright anticline at Slouchavaddie (NX09543362) has numerous, minor, SE-verging fold pairs on its northwestern limb. The anticline is succeeded to the SE by over 600 m of sub-vertical SE-younging beds. These beds are virtually unfolded and extend to a major syncline at Portdown Bay (NX09703313) over which six intermediate, neutrally verging, open F_2 folds occur. To the SE of these folds a major SE-verging fold pair, overturned to the SE, is formed on what is the 500 m wide NW-younging short limb of a large-scale NW-verging fold pair. This short limb is cut by a strike fault at Scart Craig (NX10253280), to the SE of which the bedding youngs consistently southeastwards for 1 km to the Nick of Kindram Fault. Bedding dips at a moderate to steep angle northwestwards and, excepting a few minor NW-vergent fold pairs at Inchlithery (NX10783215), contains no F_1 fold hinges. The Nick of Kindram Fault is a major, late, sinistral wrench with a slip in excess of 2.1 km. The southeastern boundary of the block is displaced inland by the fault and is not exposed. Fold plunge within the block is predominantly gentle to moderate to the ENE or W. The S_1 slaty cleavage appears axial planar in most F_1 fold hinges though downward facing bedding/cleavage relations occur.

Post-F_1 - a crenulation cleavage is developed in the hinges of the six open F_2 folds described from SE of Portdown Bay. Apart from this locality F_2 features are rare and minor, as are NW-vergent post-F_1 folds. By contrast Tarbet folds make their most northwestern appearance in the Rhinns in this block and steep plunging, fault related folds are also common. The Tarbet folds are concentrated at Dunbuck (NX09603851), though they extend as far S as Clanyard Bay and have a dextral vergence. A second cluster with a similar sense of vergence is found in the vicinity of Inchlithery (NX10783215). Steeply plunging folds occur sporadically throughout the Clanyard Bay Fault Zone and have a dominant sinistral vergence. Unlike the Tarbet folds these usually have an associated pressure solution or crenulation cleavage developed in their hinges. Many NW-dipping strike faults cross-cut earlier sub-vertically orientated strike faults at moderate to steep angles and have a southeasterly downthrow. Numerous dextral and more commonly sinistral wrench faults effect both minor and major displacements within the block.

4.2.2.10 Cardrain Block - SE of the Nick of Kindram Fault, bedding remains steep, overturned and SE-younging for 500 m to a major strike fault at Wallace Hole (NX11323177). Across this bedding dips moderately NW for 600 m and is intensely folded by numerous, minor, SE-verging fold pairs defining a shallow NW-dipping fold envelope. The bedding continues to young and dip northwestwards for a further 100 m to a major, NW-dipping strike fault at Carrickamickie (NX12153145). Across this the bedding is consistently SE-younging and inverted for 1.3 km across strike to the Mull Glen Fault (NX13883100), except in four approximately 100 m wide zones.

In these zones moderate, NW-younging and dipping beds are typically folded by minor, SE-verging fold pairs, defining shallow, NW-dipping fold envelopes. The zones are located at Port Kemin (NX12403145), Mid-Point (NX12873105), Belloue (NX13203095) and Carrickgill (NX13453092) and represent the short limbs of major NW-verging fold pairs. The hinges of some of these folds are faulted. The major, NW-dipping strike faults at Cave of the Biawn (NX12603129), Belloue and Carrickgill all have a northwesterly downthrow, whereas that at Carrickamickie has a post-S_1 southeasterly downthrow.

The Mull Glen Fault is a major, late, N-S trending sinistral wrench with a slip in excess of 1.6 km. The succession to the E of it and exposed on the E coast consists of a series of major, neutral and NW-vergent folds with parasitic, intermediate and minor folds developed on some limbs. Major strike faulting has taken place at Portankill (NX14103250) where the presence of an isolated 1.5 m thick outcrop of intensely sheared and quartz veined, fissile, black shale suggests the presence of the Moffat Shale Group underlying the Mull of Galloway Formation. In the Ards Peninsula the Moffat Shale Group has been shown to stratigrapically underlie the Hawick Group (see Anderson in Barnes *et al* 1987 - (Appendix 2)).

The Cardrain Block is clearly an amalgam of a number of tectonic blocks currently unresolvable stratigraphically. Fold plunge is gentle to steep and predominantly to the NE. The well developed S_1 cleavage is often downward facing and commonly clockwise transects F_1 hinges.

<u>Post-F_1</u> - NW and SE-vergent crenulation and rare pressure solution cleavages of at least two generations are commonly developed throughout the block. Minor to intermediate, SE-verging, close to open F_2 folds plunge gently both to the NE and SW and are common locally. Steeply plunging Tarbet folds are also found locally and abound at West and East Tarbet (NX13953095 and NX14453020 respectively), as well as at Half Ebb Stone (NX12473145), Old Mill Bay (NX12653122),

Carrickacamrie (NX13003105) and many E coast localities. At each locality one sense of vergence tends to be dominant, either sinistral or dextral. Minor to intermediate, NW-vergent, recumbent folds and associated NW-directed, sub-horizontal thrusts occur commonly NW of Wallace Hole. Isolated, minor to intermediate, steeply plunging fold pairs of both dextral and sinistral vergence are sporadically developed throughout the block.

4.2.2.11 Mull of Galloway Block - (the section shown in Map D is of the more accessible northern coast). Over much of this block the bedding is intensely brecciated and correspondingly fold plunges tend to be steep to the degree that in some places the F_1 folds face obliquely downward. Three major changes in younging direction are recorded, the first of these is at a major synclinal hinge at Black Rock (NX14673085). The second and third are at NNE-SSW trending faults of unknown displacement and are exposed 50 m SE of Man of War Craig (NX14983075) and at Broad Stone (NX15423078). Bedding within the block dips steeply to the SE and the younging where recorded is also predominantly to the SE. Minor folding is developed locally within the succession and in places the S_1 cleavage is observed to be downward facing.

<u>Post-F_1</u> - a SE-verging S_2 crenulation cleavage is well developed locally and is associated with rare, minor, SE-verging F_2 folds.

4.3 FOLDING: Geometry, Mechanisms and Associated Cleavage Development

4.3.1 F_1 folding

Major to minor F_1 folds dominate the structure and are typically isoclinal to close with angular hinges which plunge gently to the NE or SE where unaffected by faulting (Plate 4.1) Although upright, inclined and rare recumbent folds occur, overturned folds are dominant, though the direction of overturning, like the sense of vergence, changes across the Port Logan Bay Fault (see Maps, Dip Sections and

Stereographic Plots A-D).

Within each of the seven tectonic blocks N of the Port Logan Bay Fault over 80% of the outcrop is of beds younging NW so that the fold envelope (Ramsay 1967) inclines steeply in the same direction and the F_1 folds verge southeastwards. The extensive belts of NW-younging are interrupted by major SE-verging fold pairs with a typical short limb width of less than 100 m, but reaching a maximum of 300 m. A number of SE-younging limbs contain numerous NW-verging parasitic folds, although typically these limbs contain no parasitic folds and the fold envelope descends at a steep to moderate angle to the SE. At the northern edge of the Float Bay Block the fold envelope in the 800 m zone containing six major fold closures, descends gently NW. The intensity of folding also increases in the southernmost 800 m of the Port Logan Block giving a flatter envelope approaching the Port Logan Bay Fault.

In each of the four tectonic blocks S of this fault the fold envelope is inclined at a steep to moderate angle to the SE with over 65% of the beds present younging SE. Folding is much more regular and intense than N of the Port Logan Bay Fault producing a series of NW-verging fold pairs, overturned to the SE and possessing a distinct chevron geometry in which the very angular hinges separate otherwise planar limbs (Plate 4.2). This pattern of folding has given a distinctive 'steep belt' - 'flat belt' character to the fold envelope in the section (see Craig and Walton 1959). 'Flat belts' are intensely folded by numerous minor to intermediate, SE-verging fold pairs and have a fold envelope inclined gently to moderately NW (Plate 4.3 (A)). In contrast the 'steep belts' are up to 1.1 km wide and consist of overturned SE-younging beds inclined steeply to the NW and containing either no, or very rare, F_1 folds (Plate 4.3(B)). The maximum 'flat belt' width is 670 m. The scale of the folding increases dramatically away from the major fault zones at Clanyard Bay (NX10133800) and Tarbet (NX14053087). Thus bedding is predominantly overturned in the Rhinns and

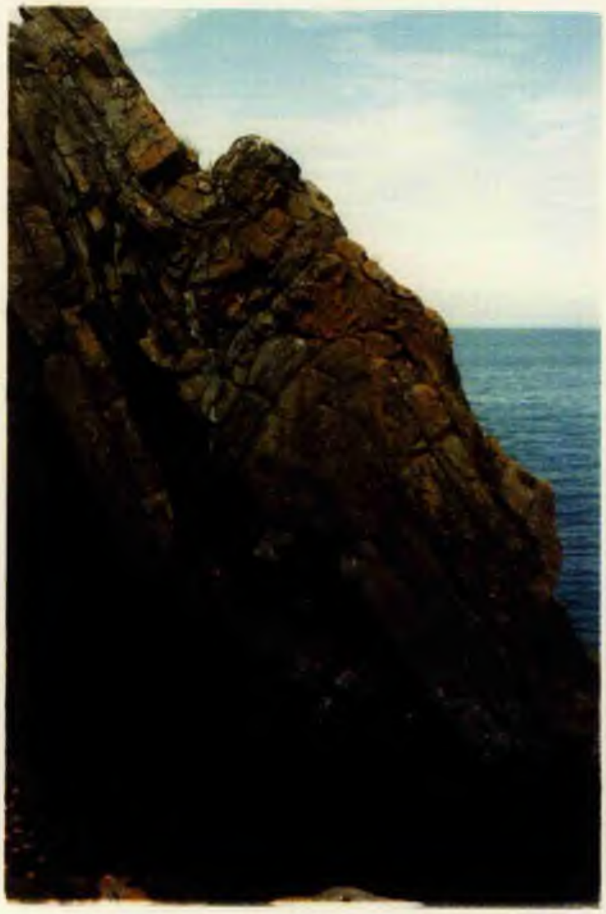


Plate 4.1: SE-vergent F_1 fold pair at Slouchgarie (NX09433732)

Plate 4.2: Overturned, NW-vergent, F_1 chevron fold pair at Carlin House Bay (NX09823922) displaying characteristic F_1 geometry S of the Port Logan Bay Fault

Plate 4.3(A): 'Flat belt' geometry S of the Port Logan Bay Fault - minor to intermediate, SE-verging, F_1 fold pairs define a fold envelope inclined gently to moderately NW. Bullet (NW11563155)

Plate 4.3(B): 'Steep belt' geometry S of the Port Logan Bay Fault - overturned bedding inclined steeply NW contains either no or rare F_1 folds. Cave of Carlin Bed (NX09143978)

the F_1 structure broadly conforms to a major anticlinorium with its axial region centred on the Port Logan Bay Fault.

The modal F_1 fold plunge of the Rhinns is 25→076, although this typical Southern Uplands value is accompanied by a much higher degree of variability than has been described elsewhere. This variability is amply displayed in the stereographic plots of each block in Maps A-D and in the modal fold plunge values given for each block in Table 4.1. Steeply plunging folds are abundant and are not confined to particular belts, although they are obviously associated with (some) fault zones (Plate 4.4)(*cf* Stringer and Treagus 1980). Fold plunge in most blocks is predominantly, though far from exclusively, to the NE and is gentle to steep. Only in the Grennan Point Block and Port Logan Block, both relatively unaffected by brecciation due to strike faulting, is there clustering of data, with modal plunges of 32→070 and 33→061 respectively. F_1 folds appear to have commonly been rotated in brittle deformation related to post-F_1 strike faulting, as exemplified in the intensely brecciated Mull of Galloway Block where modal plunges of 86→260 and obliquely downward facing folds are common. Both axial surfaces and bedding are generally steep to moderate dipping and overturned, as described above. They have a predominant ENE-WSW strike, though are more E-W trending in the 1 km wide Clanyard Bay Fault Zone and NE-SW trending in the Cardrain Block and Mull of Galloway Block.

Fold profiles are essentially cylindroidal at outcrop scale. However fundamental differences exist in fold style and geometry either side of the Port Logan Bay Fault. N of the fault folding is disharmonic. Angular hinges developed in the cores of anticlines and synclines become more rounded and increase their wavelength away from the cores. Angular hinges predominate, though commonly fold pairs are found in which one hinge is very angular and the other very rounded. Well exposed examples of this occur at Strandfoot (NX05264806), Castle Naught (NX06054728), Ardwell Bay (NX07124529), Grennan Bay (NX07504380) and Crubben Point

	MODAL ORIENTATION OF F_1 HINGES	STRENGTH OF MODE	DEGREE OF VARIABILITY
FLOAT BAY BLOCK	66→063	WEAK	HIGH
STINKING BIGHT BLOCK	77→068	MODERATE	INTERMEDIATE
GRENNAN POINT BLOCK	32→070	STRONG	LOW
MULL OF LOGAN BLOCK	29→240	WEAK	HIGH
PORT LOGAN BLOCK	33→061	MODERATE	INTERMEDIATE
CLANYARD BAY BLOCK	22→076	MODERATE	HIGH
CARDRAIN BLOCK	30→042	WEAK	HIGH
MULL OF GALLOWAY BLOCK	86→260	WEAK	HIGH

TABLE 4.1 MODAL F_1 HINGE ORIENTATION OF EACH BLOCK

(NX07754310), and are illustrated in Fig. 4.1 and Plate 4.5. Fold development is sporadic throughout the area and only in the 800 m immediately N of the Port Logan Bay Fault do more regular, chevron like folds appear.

By contrast S of the fault folding is extensive, regular and ordered consisting of harmonic, chevron folds with pronounced angular hinges and straight limbs (Fig. 4.2 and Plates 4.6 (A) and (B)). Features typically associated with chevron fold development and described by Ramsay (1974) such as bulbous hinges, limb thrusts and saddle reef structure are abundant and result from geometric modifications accommodating changes in the competent (sandstone) bed thickness. Rounded hinges are rare to absent in these SE-younging blocks (Plate 4.7, see also Plate 4.13 (B)).

Hinge thickening over the whole of the Rhinns is locally variable, but is generally low (less than 1.2) in the sandstones and high (more than 2) in the mudstones. Geometric analysis of an F_1 fold in a sandstone bed and a mudstone bed using Ramsays (1967) dip isogon classification scheme indicated Class 1C and Class 3 folding respectively (Fig. 4.3 (A) and (B)). The flattening present in the Class 1C fold was somewhat variable when determined using the method described by Ramsay (1962), but approximated to 35% (Fig. 4.4). In general most F_1 folds, whether rounded or chevron like, in sandstone beds are flattened parallel, though the degree of flattening is often small. In mudstone beds F_1 folds are typically Class 3. Quartz and calcite slickenfibres are commonly present on bedding surfaces at high angles to fold axes indicating flexural-slip was an important mechanism in fold development.

Unlike the rounded, sinusoidal forms often depicted in textbooks, folds within thrust belts are now regarded as dominantly possessing a chevron like geometry (see Davis 1984). Little is known about the origin of these folds, though theoretical and experimental modelling by Johnson (1977) provides a basis for interpreting the different geometries encountered N and S of the Port Logan Bay Fault. In a thick, horizontal, multilayer sequence consisting of alternating hard and soft layers, layer

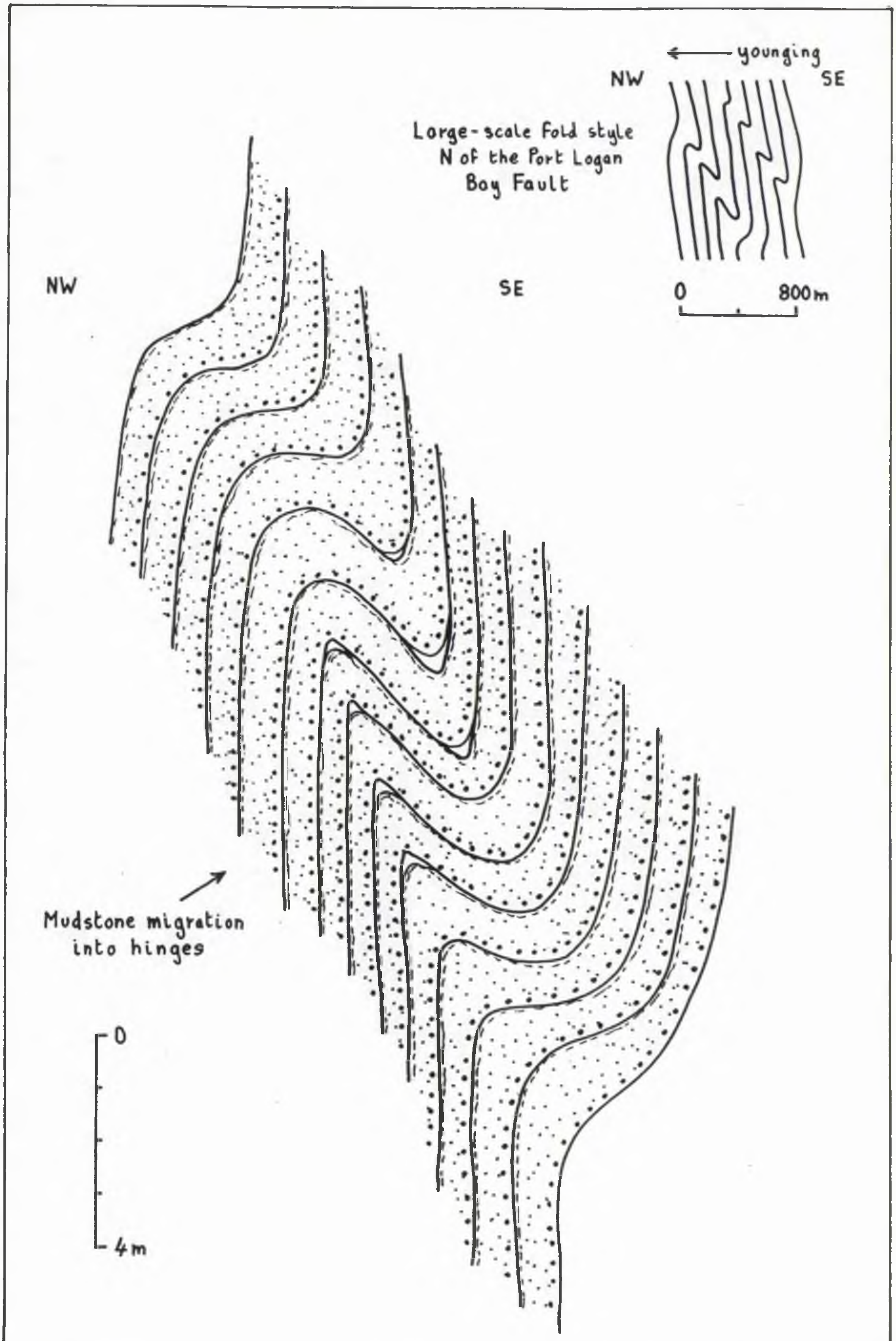


Fig 4.1: Sketch of a disharmonic F_1 fold pair in a proximal turbidite succession at Castle Naught (NX06054728). Most exposed F_1 fold profiles N of the Port Logan Bay Fault are recognisable in this sketch.

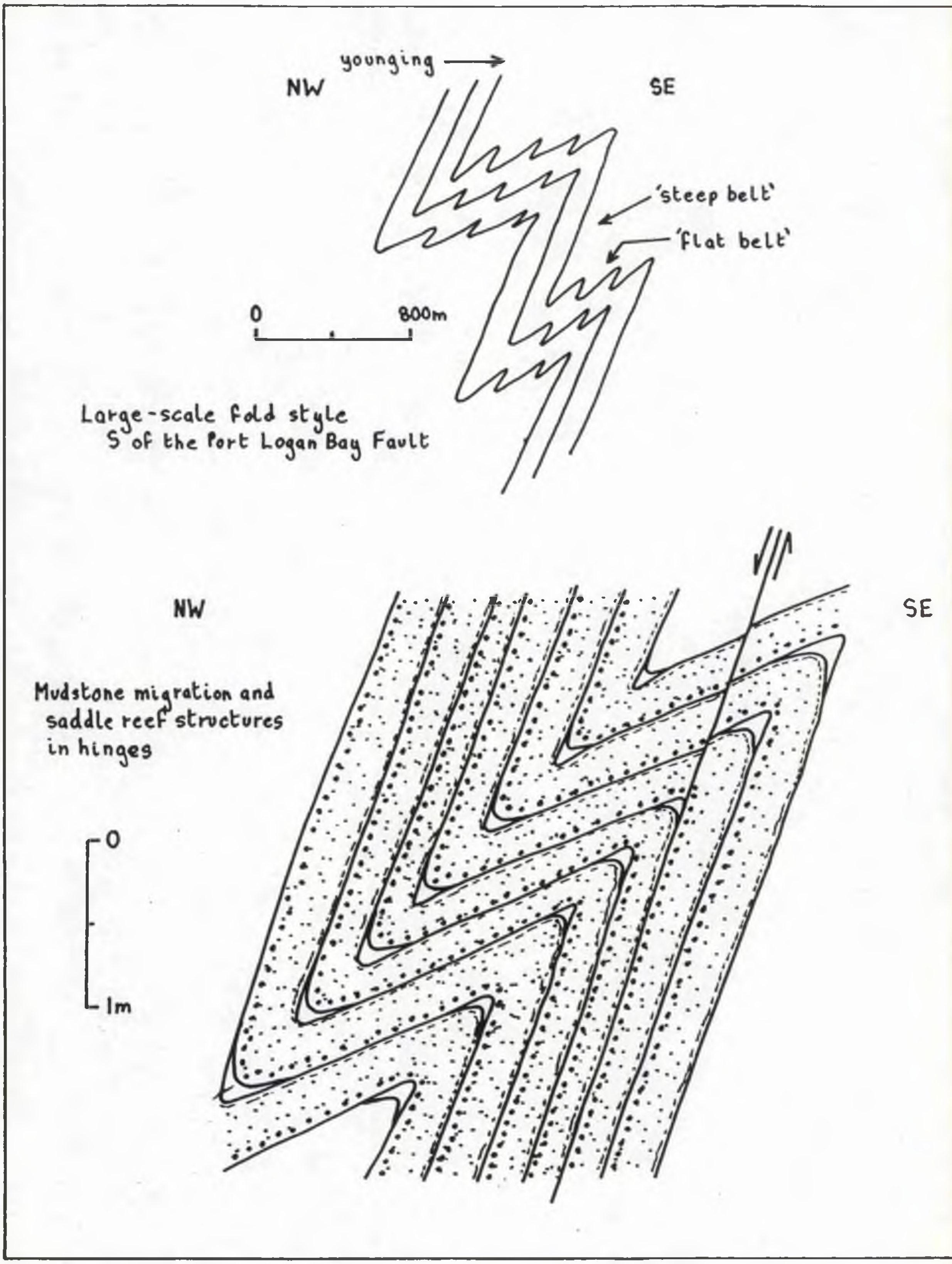


Fig 4.2: Sketch of an F_1 chevron fold pair in a proximal turbidite succession S of Port Logan Bay Fault at Calliedown (NX09653843). Bedding parallel F_1 thrusts are commonly developed along the long limbs of the folds.

Plate 4.4: Steeply plunging and gently plunging F_1 folds occurring in close proximity in a brecciated zone at Slunkrainy (NX05514771)

Plate 4.5: Disharmonic F_1 folds at Ardwell Bay (NX07124529)

Plate 4.6(A): NW-vergent, F_1 chevron fold pair at Carlin House Bay (NX09823922) with an F_1 thrust developed along the synclinal hinge. Note extreme angularity of hinges and planar limbs

Plate 4.6(B): NW-vergent F_1 chevron fold pair at Carlin House Bay (NX09823922). Note extreme angularity of hinges and planar short ('flat') limb

Plate 4.7: Major F_1 anticlinal hinge at Caves of the Lennans (NX09393903). Note angularity of hinge

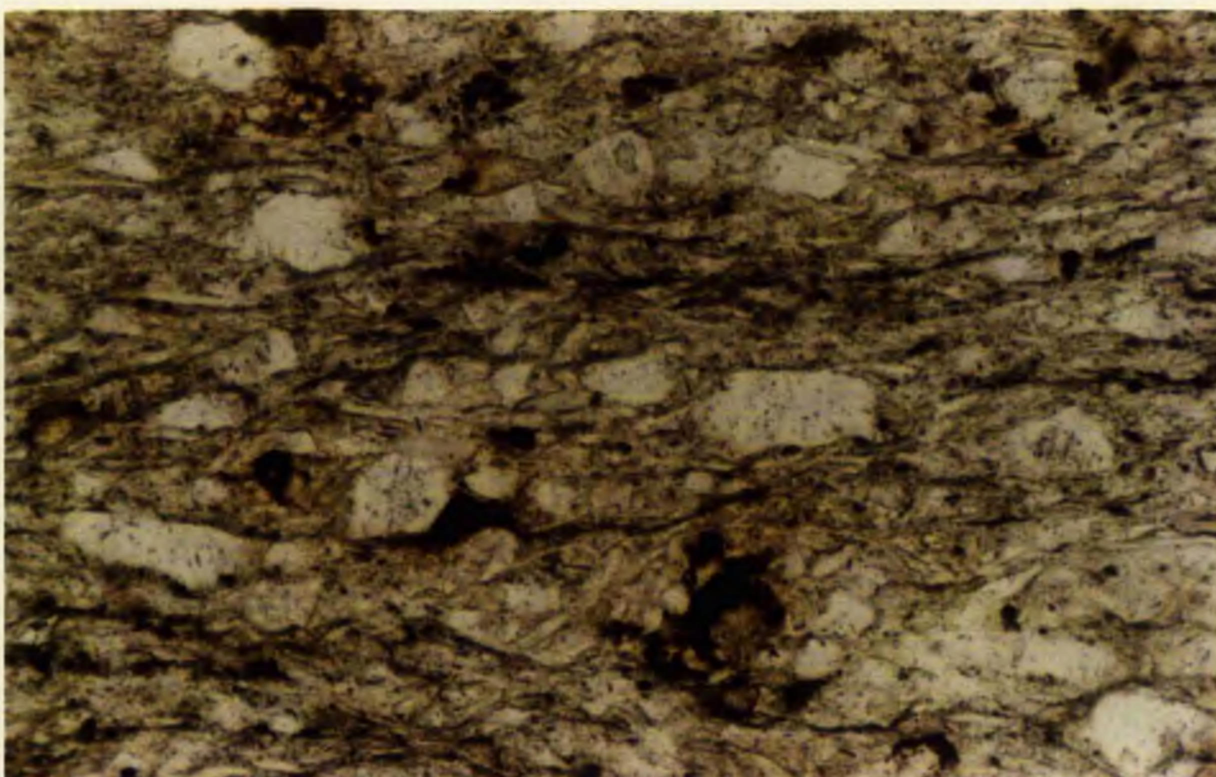
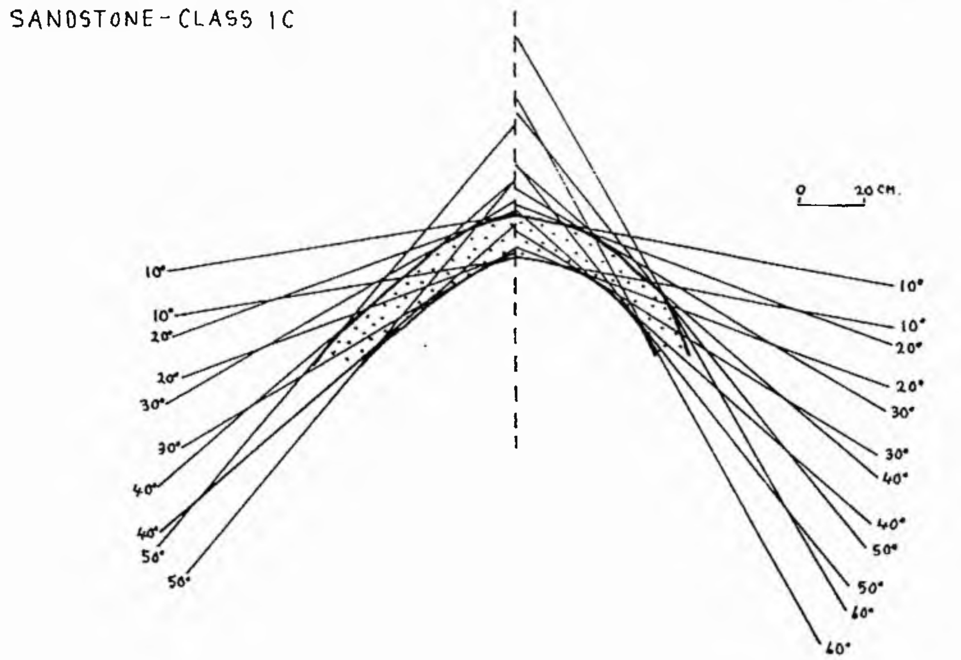
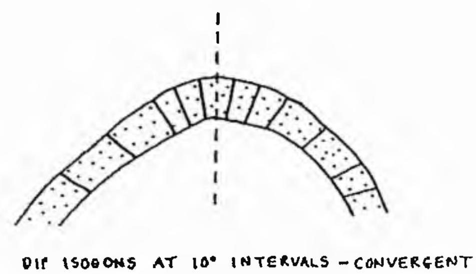


Plate 4.8: Photomicrograph of S_1 cleavage in mudstones - quartz domains are 'truncated' by thin seams of white mica and opaque minerals. Specimen SC1, ordinary light, x200



$T_0 = 6.9$ MMS.		$t_0 = 6.9$ MMS.
ANGLE	T_α (MMS)	t_α (MMS)
10°	6.9	6.7
20°	6.9	6.2
30°	7.2	6.1
40°	7.5	5.8
50°	9.2	5.6
60°	11.0	5.2



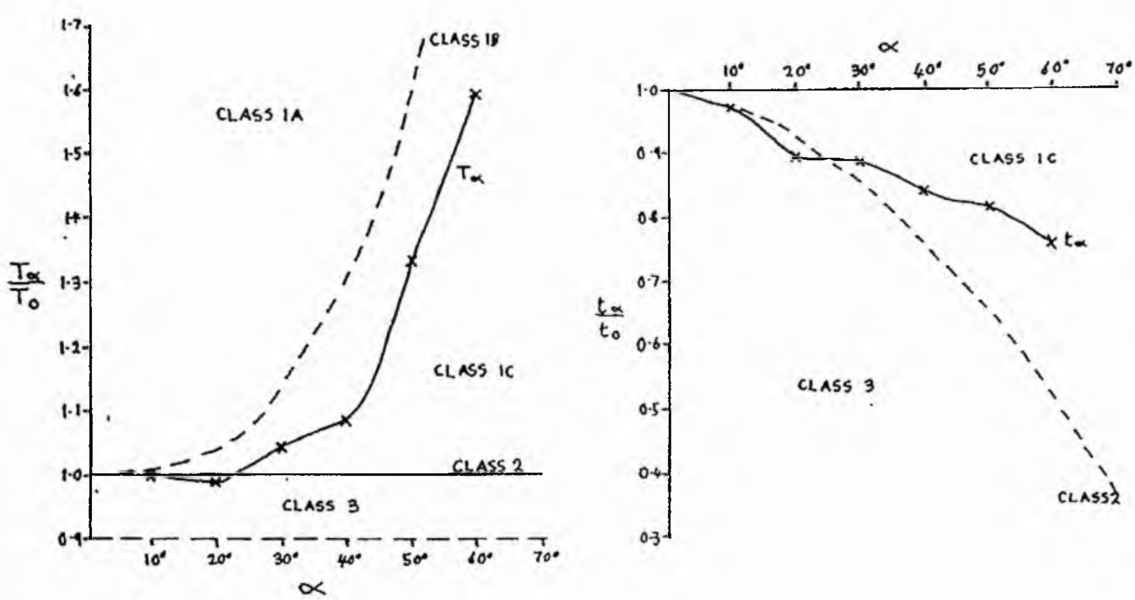
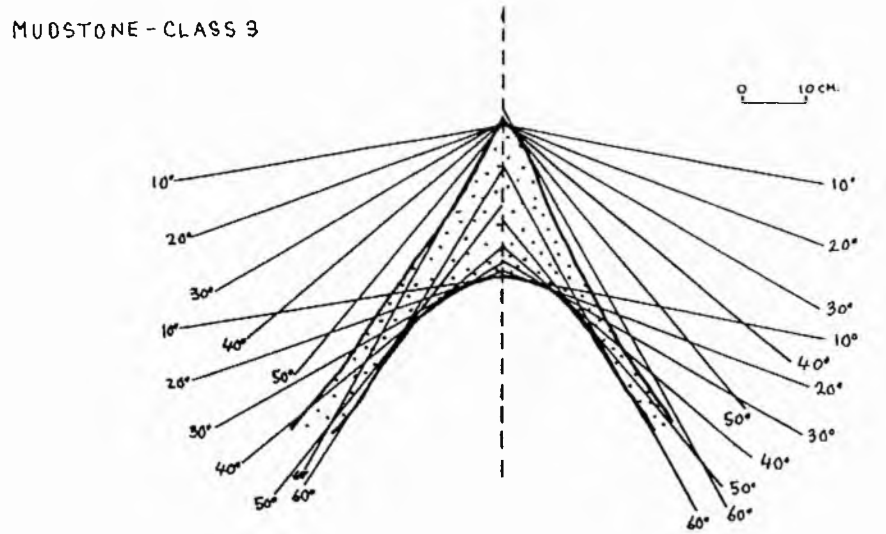
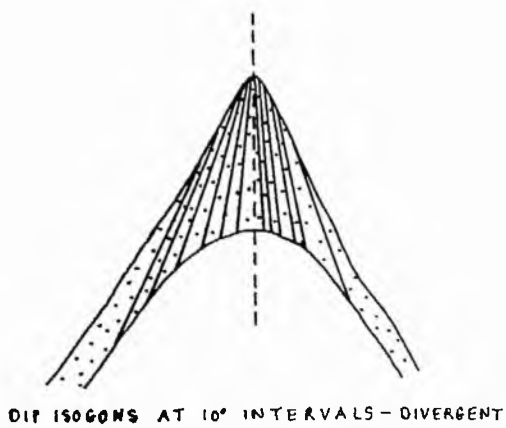


Fig 4.3 (A): Geometrical classification of an F_1 fold in a sandstone bed (see Ramsay 1962).



T_o = 24 MM.	t_o = 24 MM.	
α	Tα (MM)	tα (MM)
10°	24	23
20°	23	21
30°	22	18·7
40°	20	15·2
50°	16	10·8
60°	9	5



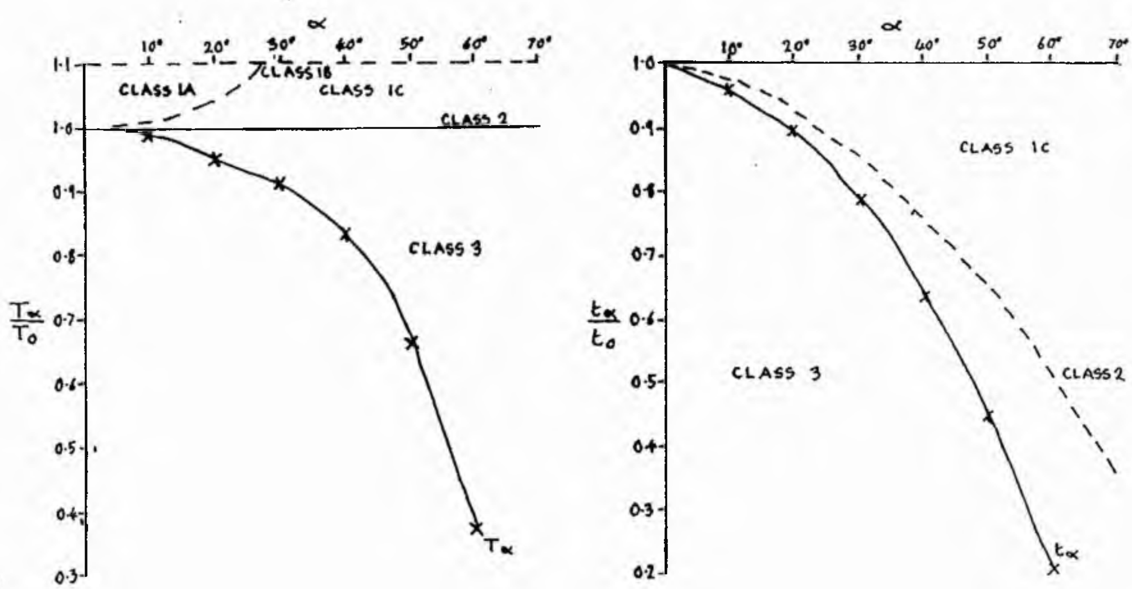


Fig 4.3 (B): Geometrical classification of an F_1 fold in a mudstone (see Ramsay 1962).

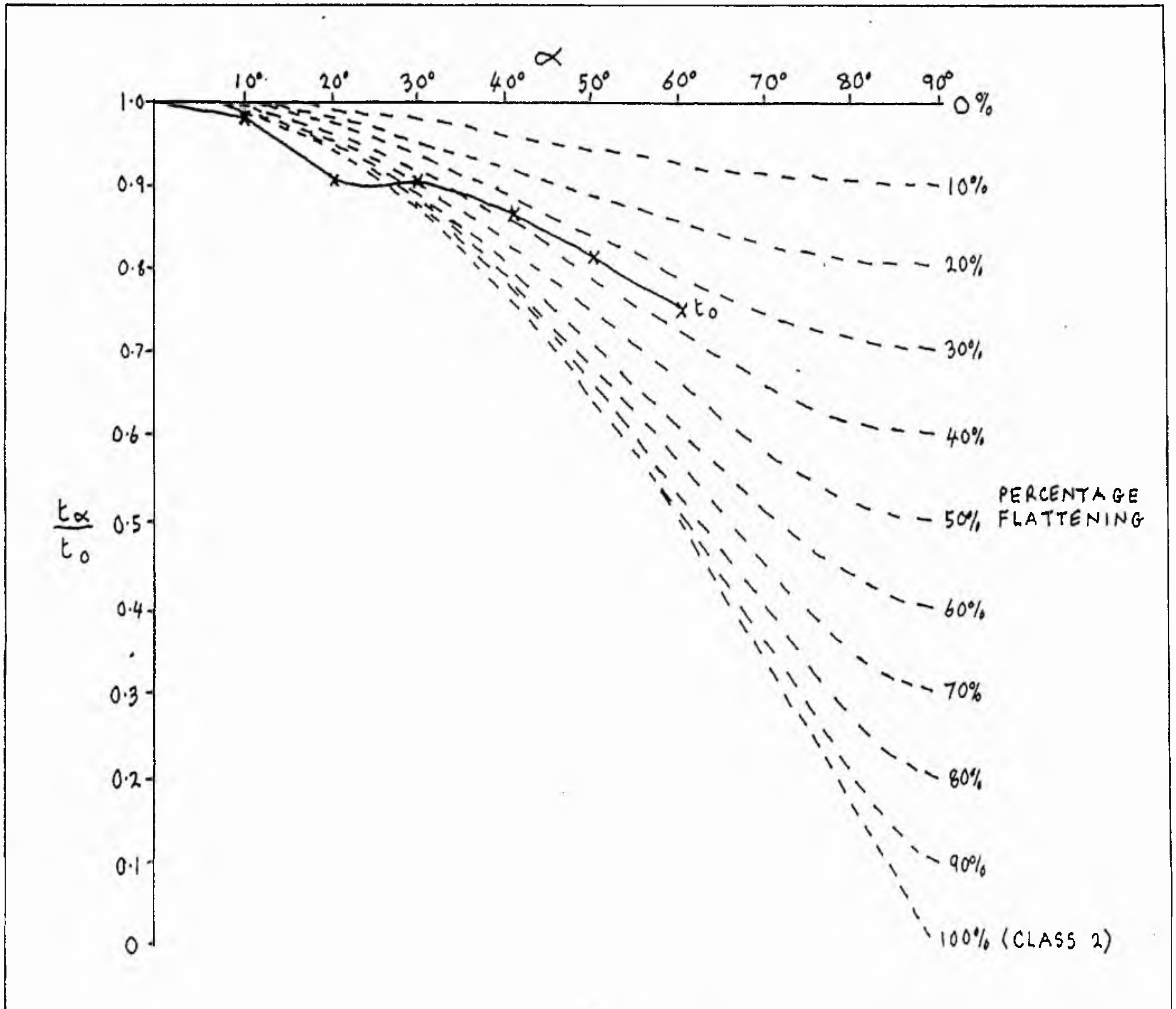


Fig 4.4: Degree of flattening present in the Class 1C fold shown in Fig 4.3 (A) (see Ramsay 1962).

parallel compression causes a shortening and thickening of the layers to a point where buckling initiates as a series of sinusoidal wave forms (Fig. 4.5). As compression continues these folds develop a concentric form characterised by differing wavelengths at different levels within the fold layers. Chevron folding initiates in the cores of these concentric folds where the wavelength is at its lowest by 'elastic yielding' of the hard layers to form angular hinges. The limbs straighten out with fold development as the hinges can no longer support bending motion. Continuing compression causes vertical propagation of the chevron folds from the cores to the crests of the concentric folds. Ultimately the concentric fold pattern is completely replaced by a chevron fold pattern.

The fold geometries encountered S of the Port Logan Bay Fault represent the end member in this transition from sinusoidal folding to concentric folding to chevron folding, whereas the geometries N of the fault represent a transitional stage between concentric folding and chevron folding in which both types of fold co-exist. By adding layer parallel (simple) shear to the pure shear model of Johnson an asymmetry, or sense of vergence, is introduced to the folding.

Layer parallel shortening is a function of the viscosity contrast between layers which in turn can be determined from wavelength/bed thickness ratios of parallel folds within the sequence (Ramberg 1964). Wavelength/bed thickness ratios were worked out for four parallel folded sandstone beds at Ardwell Bay (NX07124529) producing an average valve of 18.7:1. This average was then used to determine the viscosity contrast from plots made by Biot (1961) and Huddleston (1973) and indicated high values of 160 and 246 respectively. Biot's curve does not take into account the effects of initial (pre-folding) layer parallel shortening, but a comparison of the two curves indicates this decreases in importance with increasing viscosity contrast. The Huddleston plot indicates that 9% of the shortening is layer parallel in the beds measured.

Attempts to determine the state of strain in the rock proved inconclusive.

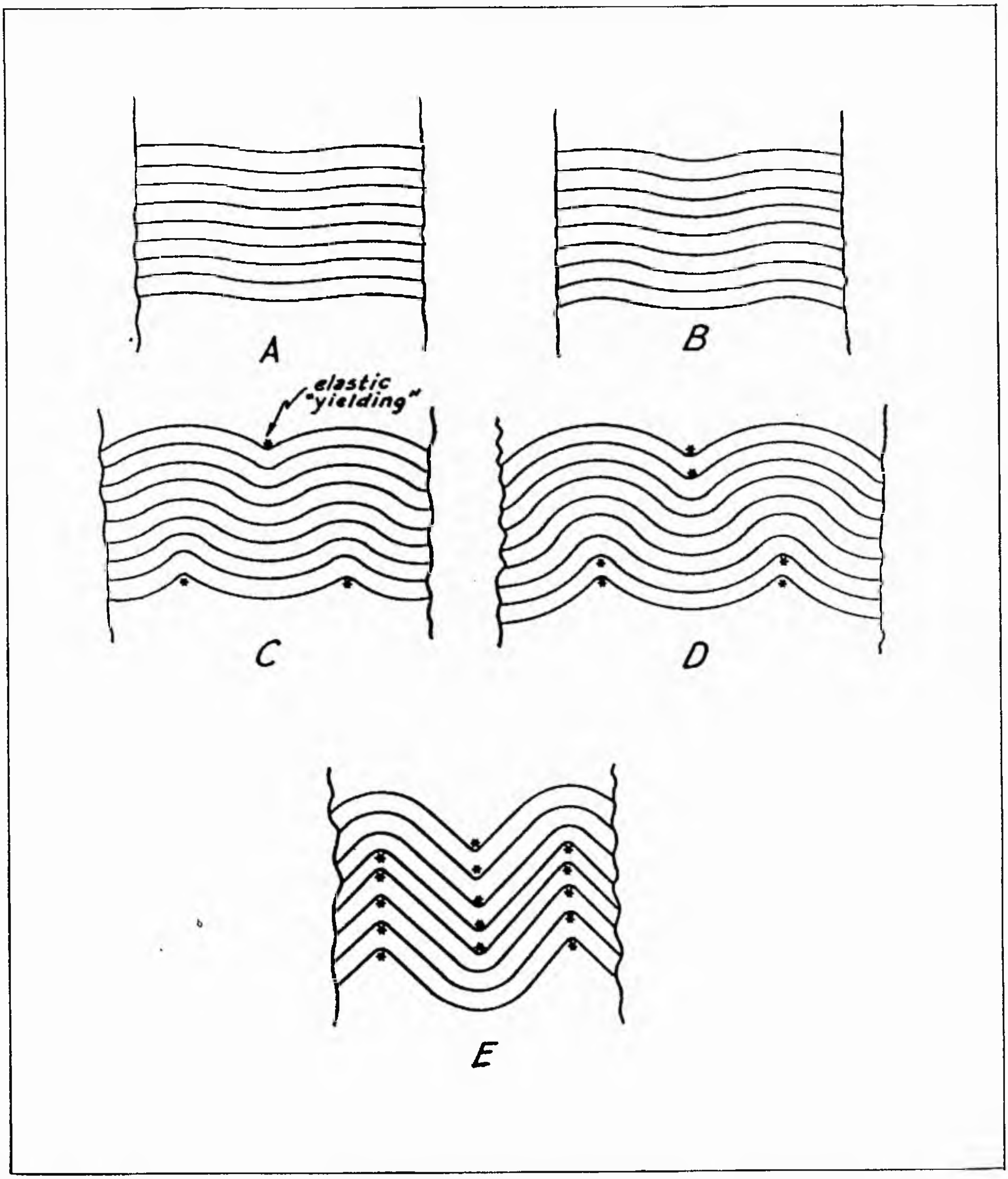


Fig 4.5: Transition from sinusoidal to concentric-like to chevron folding. A. Sinusoidal pattern. B. Beginning of concentric-like pattern, characterized by different wavelengths at different places in multilayer. C. Elastic "yielding" in stiff layers at cores of folds initiates development of chevron pattern. D. Chevron pattern grows at expense of concentric pattern. E. "Yielding" of hinge throughout much of the multilayer produces a pattern of chevron folds, leaving only remnants of concentric-like folds (from Johnson 1977).

Strain measurements taken from diagenetic carbonate-rich concretions developed parallel to bedding in the sandstones of the Money Head Formation and Float Bay Formation were plotted on a Flinn (1962) diagram and indicated varying degrees of oblate strain. Out of fifteen concretions measures, only four gave interpretable results indicating an average rotation out of bedding towards cleavage of 39%. The original shape of the concretions is not known and throws some doubt on the results.

A stretching lineating (X_1) developed as an alignment of micaceous fibres on cleavage surfaces in mudstones was identified at a few localities in two area: the 500 m section between Port Logan Bay and Cairnywellan Head (NX09053985); and in the Carrickamickie (NX1218342) area. At all the localities X_1 was sub-horizontal and plunged gently NE or SW. The absence of an identifiable stretching lineation on S_1 cleavage surfaces elsewhere in the Rhinns possibly indicates a state of oblate strain was the norm with sub-horizontal extension occurring in exceptional conditions. It may however simply result from stretching being too small for a lineation to develop.

S_1 cleavage - this is developed as a widespread, closely spaced (less than 1 mm), penetrative fabric in argillaceous and siltstone deposits and as more widely spaced (less than 50 mm), irregular partings in the fold hinges of sandstones. In thin sections of cleaved mudstones it appears domainal (Powell 1979) in character with thin (less than 0.01 mm) dark seams of white mica (sub-parallel to the cleavage direction), opaque minerals and clay minerals, separating much wider (0.01 - 0.2 mm), light domains of quartz, feldspar and mica, which are orientated sub-parallel to the cleavage where it is intensely developed (Plate 4.8). The dark seams correspond to the mesoscopic cleavage partings and often anastomose to enclose the light domains. In some cases the dark seams 'truncate' the clastic quartz grains and bearded overgrowths of phyllosilicates and quartz develop in the cleavage direction and often connect with adjacent quartz grains.

In thin sections of cleaved sandstones a weak, preferred dimensional orientation of quartz and feldspar grains in light domains is evident sub-parallel to the cleavage, with bearded overgrowths commonly developed where the cleavage is most intense. Micas are aligned in the cleavage direction in dark domains which are similar to those in the mudstones apart from being more widely spaced.

Williams (1972) interpreted the dark domains as the result of selective removal of quartz by pressure solution and this is supported by the presence of 'truncated' quartz grains. Such a process can result in the buckling of an initial bedding parallel fabric defined by detrital mica flakes to produce an S_1 crenulation cleavage. This has not been unequivocally observed in the Rhinns though pressure solution cleavage planes are often made evident in the field by the buckling of bedding parallel calcite and quartz veins and adjacent bedding planes (Plate 4.9). Such effects are commonly observed in the Port Logan Block and more particularly in the Cardrain Block and Mull of Galloway Block, but are rare elsewhere.

S_1 cleavage fans are convergent in sandstones and divergent in siltstones and mudstones with dihedral angles of up to 45^o (as recorded from a fold 150 m SSW of Scrangie (NX09044002)). Finite neutral points are well developed locally in the thickened hinges of mudstone layers. Cleavage refraction between beds of different competence and most noticeably between sandstone and mudstone is in the order of 5^o-40^o (Plate 4.10). A number of features, essentially as recorded by Stringer and Treagus (1980), point to the important conclusion that S_1 cleavage formation was synchronous with F_1 folding:

(1) the cleavage is most intense at fold hinges;

(2) the cleavage is more strongly developed in tighter folds;

(3) cleavage fans in all folds are centred about the axial plane;

(4) finite neutral points are well developed locally in mudstones; and

(5) cleavage orientation remains sub-parallel to curves in the axial plane orientation in folds.

In the Rhinns the S_1 cleavage orientation matches F_1 fold overturn in changing

Plate 4.9: Buckling of bedding parallel quartz vein in mudstones by S_1 pressure solution seams at Carrickcallan (NX11803142)

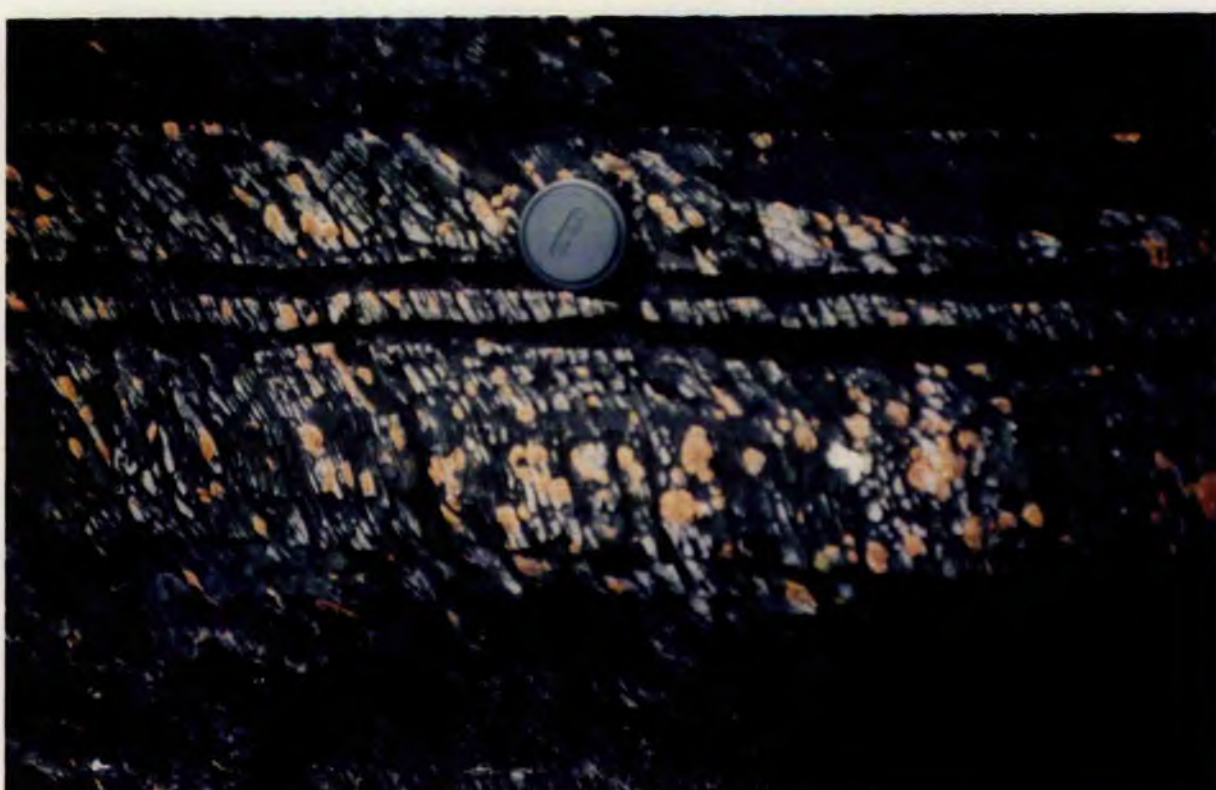


Plate 4.10: S_1 cleavage refraction between mudstones and siltstones 170 m S of Scrangie (NX090440022)

across the Port Logan Bay Fault. N of the fault the modal orientation is 81→158 (Fig. 4.6(A)), whereas to the S of the fault it is 82→345 (Fig. 4.6 (B)). On both sides of the fault the S1 cleavage clearly clockwise transects F_1 fold hinges (Fig. 4.7 and Plate 4.11). Downward facing bedding/S_1 cleavage relationships and clockwise fold transection by S_1 cleavage has been observed in all the tectonic blocks in the Rhinns (including the Ordovician age Portayew Block) apart from the Cairngarroch Block and Money Head Block which contain no F_1 fold hinges and an upward facing cleavage. This upward facing cleavage does not necessarily indicate that the cleavage in the blocks is axial planar, rather fails to prove it is non-axial planar. As S_1 cleavage transection is consistently clockwise of F_1 hinges, the cleavage is either downward facing or sub-parallel to bedding on NW-facing limbs, with the bedding/cleavage intersection lineation (L_1) plunging gently NE or SW. On SE-facing limbs the cleavage is upward facing, with the L_1 intersection lineating plunging steeply SE. This geometry holds true regardless of fold vergence resulting in the extensive development of downward facing cleavage N of the Port Logan Bay Fault and its localisation in NW-facing, short limbs S of the fault. Differing values of L_1 intersection lineation on adjacent limbs of a fold hinge are the surest indication of non-axial planar cleavage . In profile section the cleavage in some hinges appears, and possibly is, axial planar, though L_1 measurements on the limbs indicate cleavage is non-axial planar. Similarly major hinges such as those at Strones Bay (NX09553868) and Green Saddle (NX09293932) have an apparent axial planar cleavage, whereas parasitic minor folds on their limbs clearly possess a clockwise transecting cleavage. Such anomalies are due to the localised stress differences that build up in hinge zones, usually stress is more confined and intensifies in hinge zones, but they make it difficult to assess the true extent of non-axial planar cleavage in a given area. In the Rhinns clockwise transection of F_1 fold hinges by S_1 cleavage is the norm, but localised zones occur in which the cleavage is essentially axial planar.

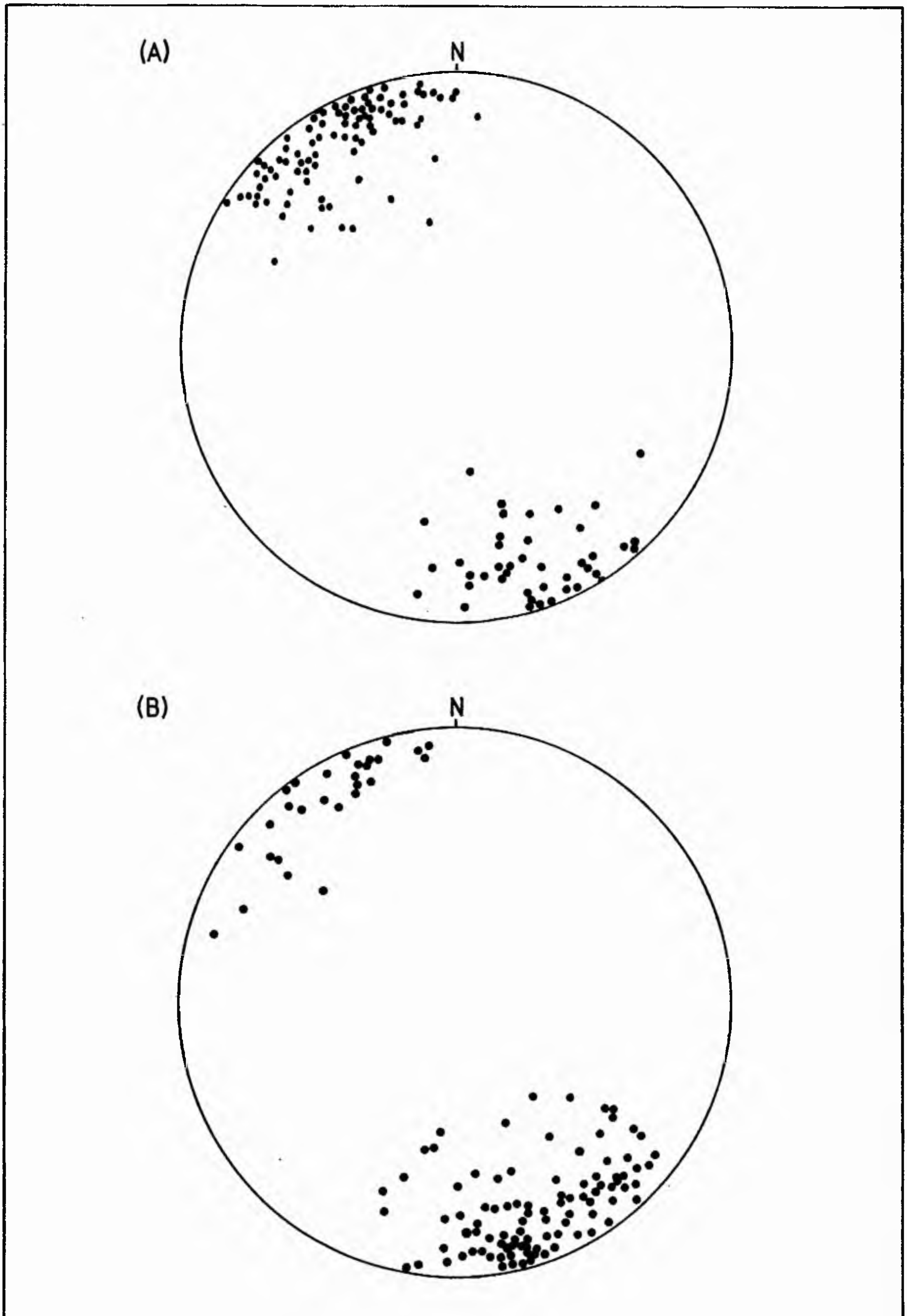


Fig 4.6: Stereograms of poles to S_1 cleavage planes (A) N of Port Logan Bay Fault (130), and (B) S of the Port Logan Bay Fault (126).

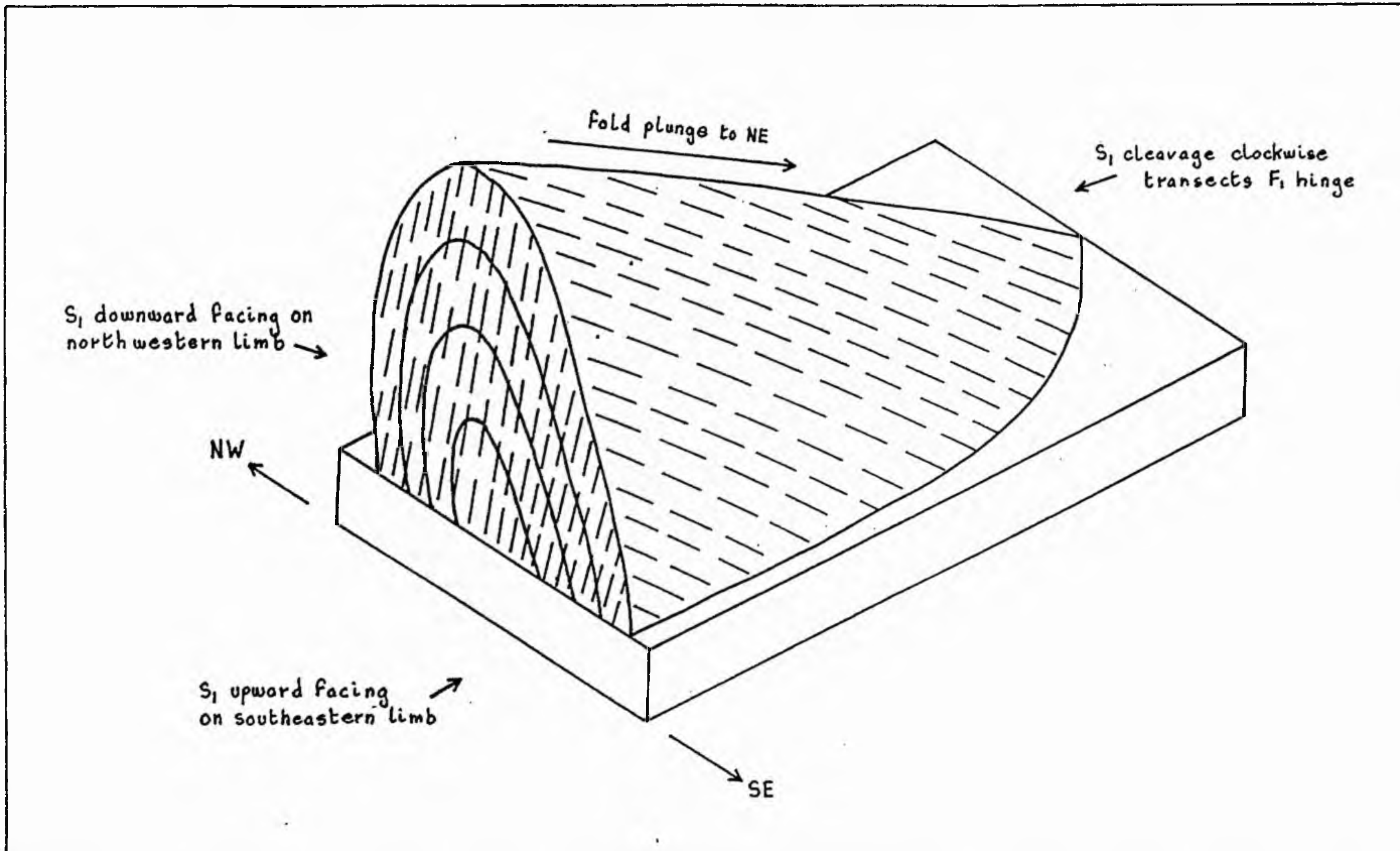


Fig 4.7: Transecting cleavage geometry in a tight F_1 anticline overturned to the N (after Anderson 1987).

Plate 4.11: S_1 cleavage clockwise transecting F_1 synclinal hinge 70 m S of Scrangie (NX09044002). Axial surface orientation indicated by pencil

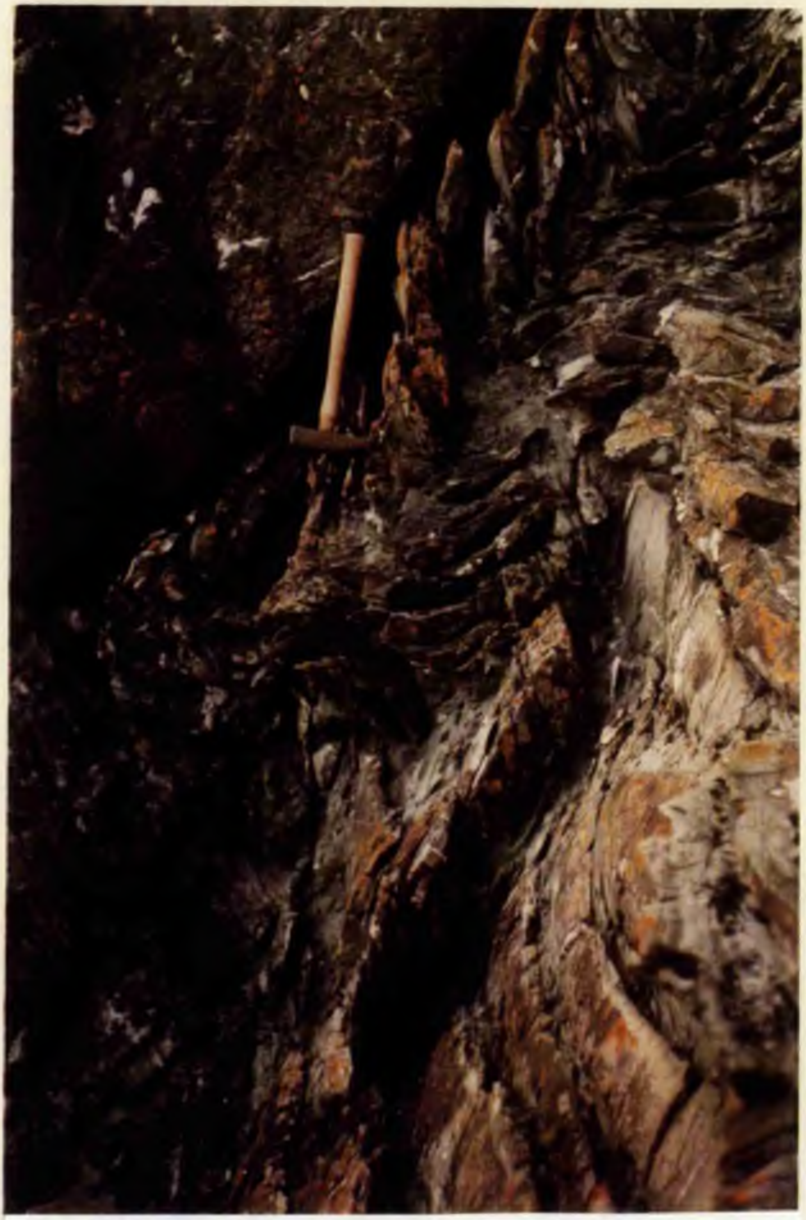


Plate 4.12: SE-verging F_2 fold deforming F_1 fold mullions in an F_1 synclinal hinge at Carrickgill (NX13453092)

Examples include the folded sections in the Cairnie Finnart Member at Bonny Well Bay (NX08454165) and in the Leucarron Member at Portavaddie (NX14463123).

Clockwise transecting S_1 cleavage is best displayed in a sequence of eight neutral to NW-verging, upright F_1 folds exposed in a 25 m wide outcrop immediately N of Ardwell Bay (NX07124529). A detailed geometrical analysis of these folds was undertaken and the results are shown in Table 4.2. The folds vary from tight to open and have curvi-linear hinges that plunge gently to moderately to the SW (Fig. 4.8). Axial planes are inclined steeply SE and are spaced 0.4 to 4 m apart. A vertical strike fault is developed in one synclinal hinge and has a minor northwesterly downthrow. The clearly clockwise transecting S_1 cleavage is typically downward facing in NW-younging limbs and upward facing in SE-younging limbs. The folded sedimentary sequence consists of 0.2-0.5 m thick interbeds of medium grained sandstone and mudstone with a low sand/shale ratio. Data collected from the mudstones are less reliable due to the difficulty in taking accurate field measurements.

Clockwise rotation of the cleavage relative to the axial surfaces is demonstrated with the former inclined predominantly at a steep angle to the SE and the latter similarly to the NW (Fig. 4.9). The mean angle of rotation of the cleavage out of the axial surface is 14^o in the sandstones and 12^o in the mudstones. Although fold plunge is to the SW, the L_1 intersection lineation plunges gently to the NE or SW in SE-facing limbs (Fig. 4.10) and plunges moderately SW in NW-facing limbs (Fig. 4.11). Thus L_1 commonly plunges in opposite directions on adjacent limbs of a fold. The mean fold interlimb angle is 63^o in sandstones (62^o in mudstones) and the mean dihedral angle of cleavage fans is 22^o in sandstones (20^o in mudstones).

These results show the main characteristics of transected folds as well as the degree of variation in the amount of transection that can occur over a small area. The transection angle of 27^o recorded from one of the folds (see Table 4.2) is the highest found in the Rhinns with more typical values in the range 5^o-20^o.

Explanations of non-axial planar cleavage development are many and varied

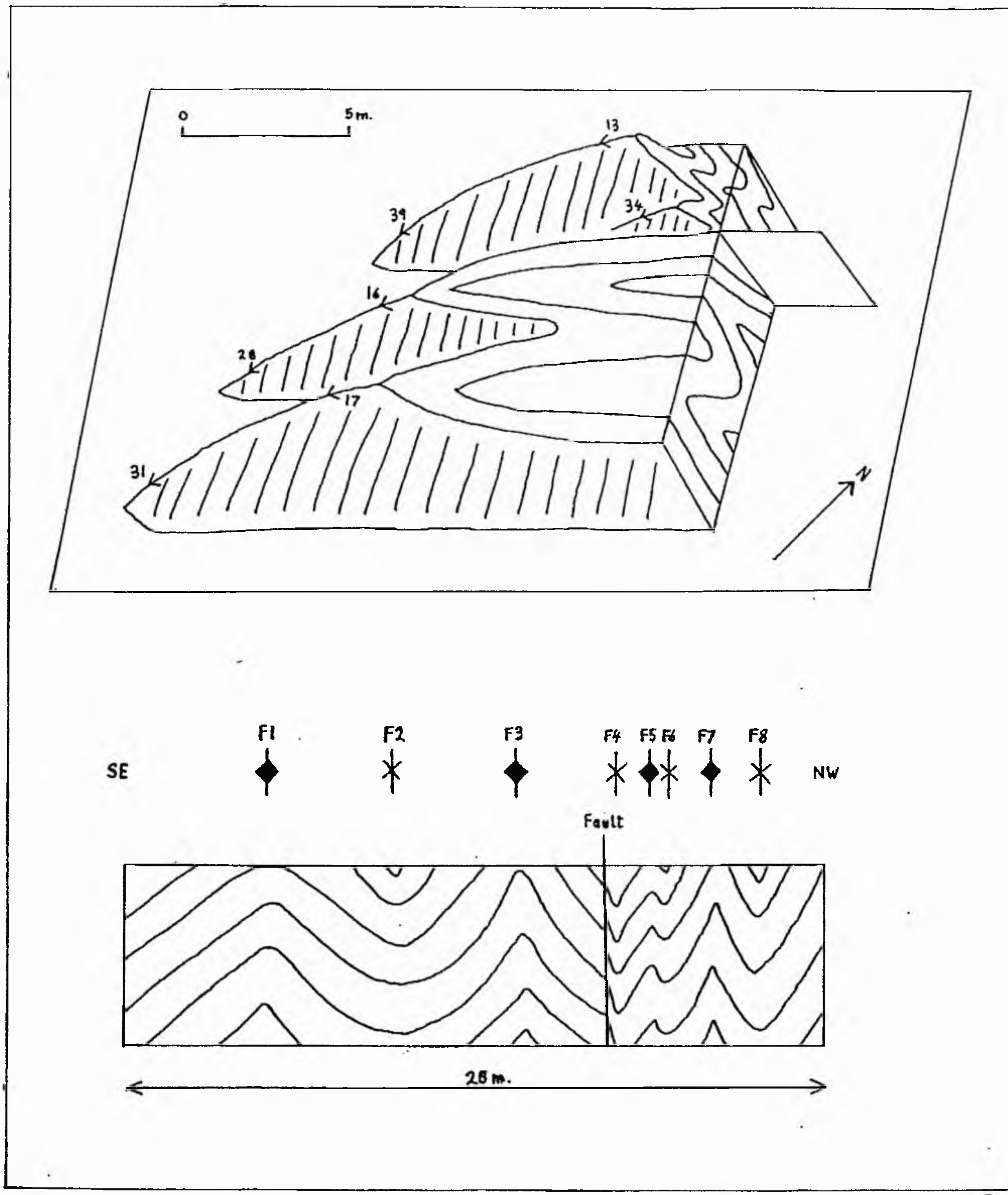


Fig 4.8: Outcrop N of Ardwell Bay (NX07124529) of eight F_1 fold hinges with non-axial planar S_1 cleavage.

		A	B	C	D	E	F	G	H
HINGE 1 (anticline)	S'ST M'ST	18°→243° 21°→245°	91° 95°	88°→153° 87°→335°	7° 10°	84°→338° 86°→342°	10° 12°	11°→249° 11°→255°	- -
HINGE 2 (syncline)	S'ST M'ST	22°→246° 22°→240°	74° 83°	82°→154° 89°→149°	25° 22°	88°→162° 82°→329°	10° 14°	- -	26°→251° 29°→254°
HINGE 3 (anticline)	S'ST M'ST	22°→246° 25°→242°	46° 41°	84°→160° 84°→156°	36° 33°	87°→352° V 80°/260°	15° 16°	7°→255° 38°→235°	- -
HINGE 4 (syncline)	S'ST M'ST	15°→239° 15°→239°	34° 34°	84°→151° 84°→151°	22° 22°	82°→164° 82°→164°	13° 13°	- -	52°→260° 52°→260°
HINGE 5 (anticline)	S'ST M'ST	34°→232° 31°→228°	67° 60°	88°→312° V 47°/227°	20° 22°	81°→338° 81°→154°	27° 19°	37°→075° 30°→168°	- -
HINGE 6 (syncline)	S'ST M'ST	25°→237° 15°→232°	55° 48°	83°→149° 88°→142°	19° 19°	86°→160° 80°→336°	14° 13°	- -	48°→249° 28°→245°
HINGE 7 (anticline)	S'ST MST	14°→223° 13°→225°	59° 60°	89°→138° V 45°/225°	16° 10°	84°→334° 83°→327°	17° 14°	29°→069° 2°→057°	- -
HINGE 8 (syncline)	S'ST M'ST	27°→231° 27°→231°	76° 71°	84°→143° 86°→143°	27° 20°	89°→143° 86°→344°	12° 20°	16°→072° 11°→070°	45°→245° 48°→246°
MODAL VALUES	S'ST M'ST	22°→236° 21°→235°	63° 62°	86°→146° 88°→146°	22° 20°	86°→341° 89°→338°	14° 12°	12°→072° 6°→065°	44°→254° 37°→251°

Successive fold hinge are numbered consecutively from SE to NW.

A: F_1 fold plunge
B: Interlimb angle
C: Dip and direction of dip of axial plane
D: Dihedral angle of S_1 cleavage fan
E: Dip and direction of dip of the mean plane to the S_1 cleavage fan
F: Angle between the axial plane and the mean plane to the S_1 cleavage fan
G: L_1 on SE-dipping F_1 fold limb
H: L_1 on NW-diping F_1 fold limb

S'ST: Sandstone; M'ST: Mudstone; V: Vertical

TABLE 4.2 - GEOMETRY OF F_1 FOLDS AND S_1 CLEAVAGE AT THE NORTHERN END OF ARDWELL BAY (NX07124529)

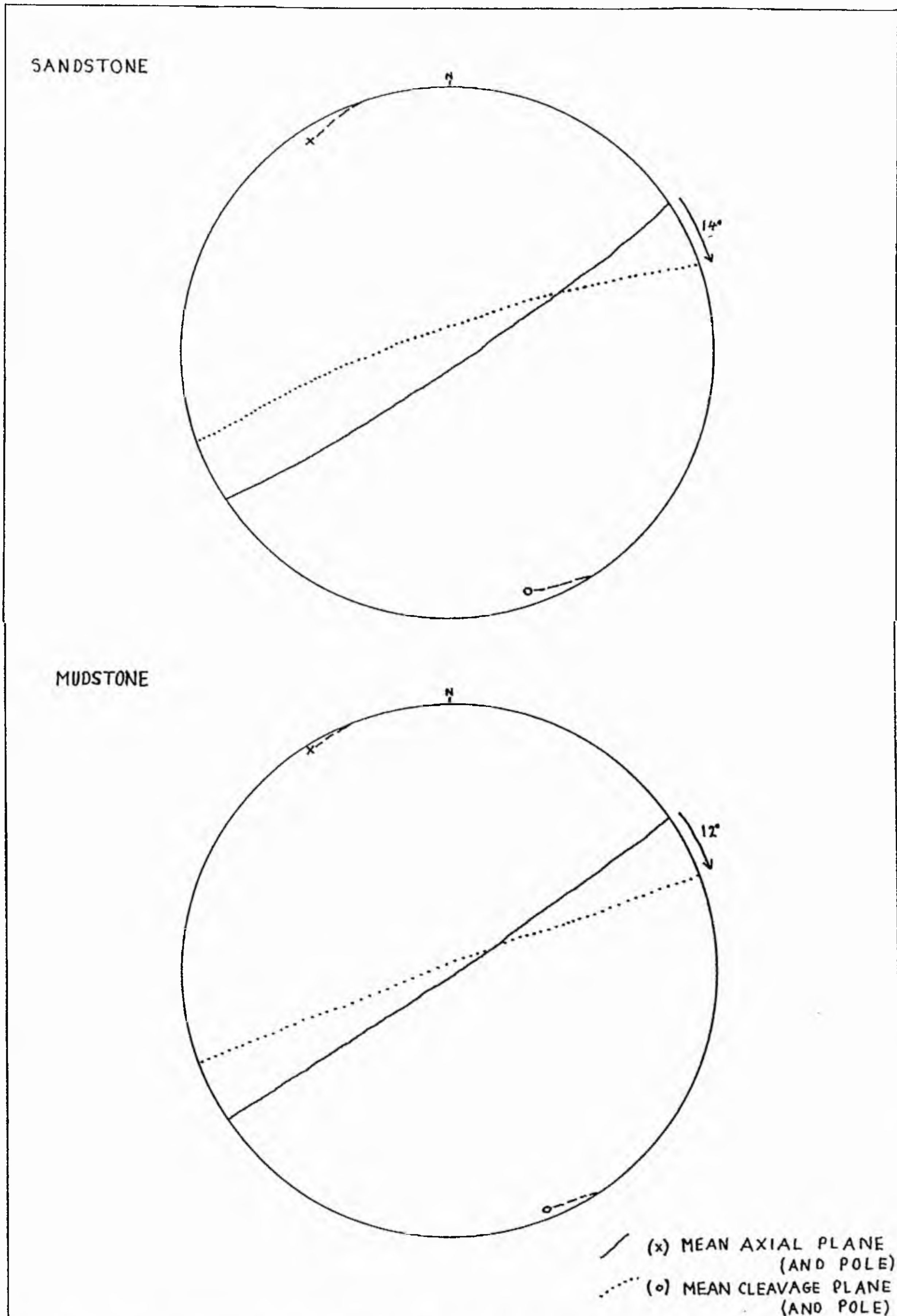


Fig 4.9: Relationship between the axial surface and S_1 cleavage plane in the F_1 folds N of Ardwell Bay.

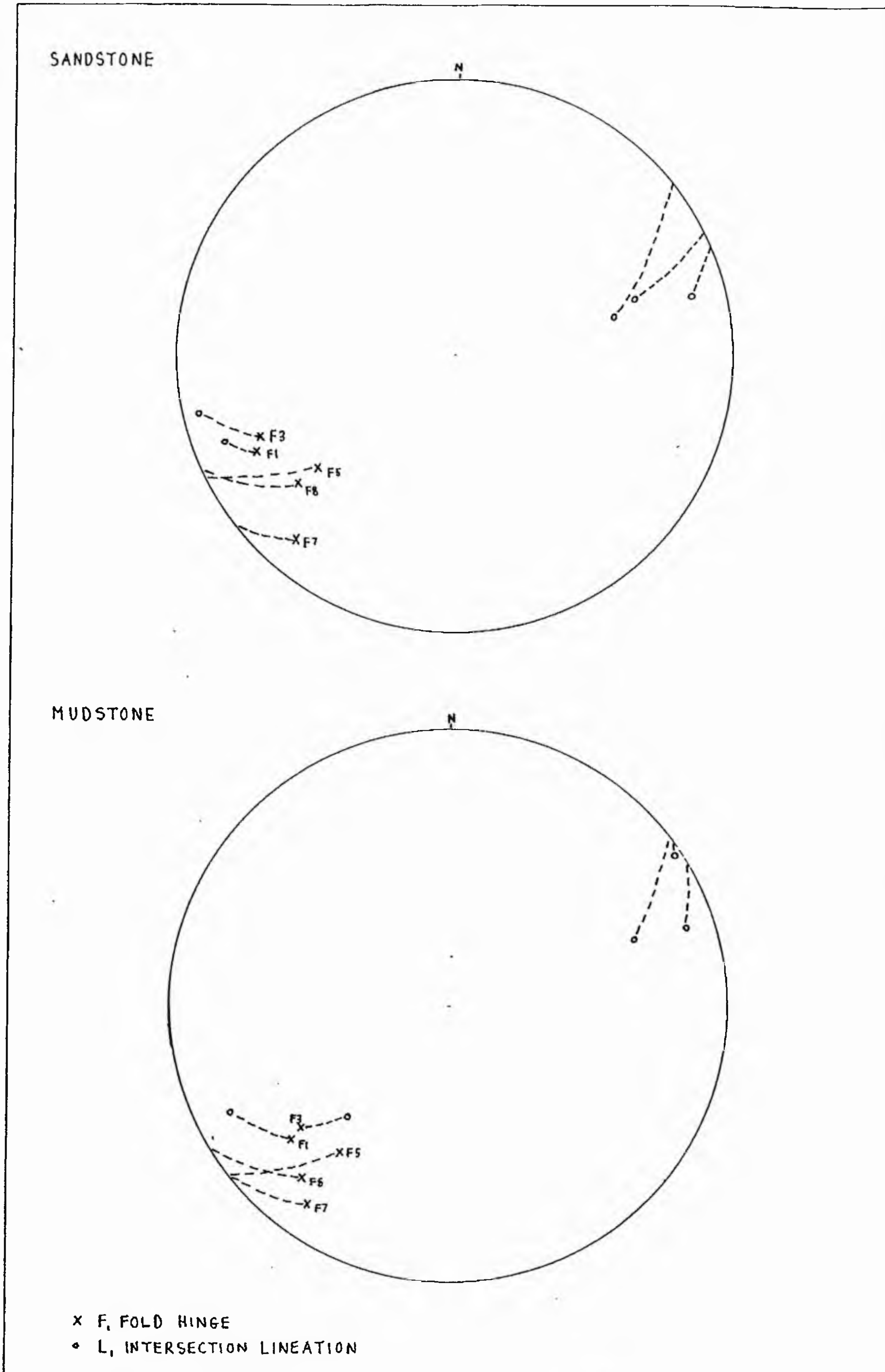


Fig 4.10: Relationship between F_1 fold hinge and L_1 intersection lineation in SE facing fold limbs N of Ardwell Bay.

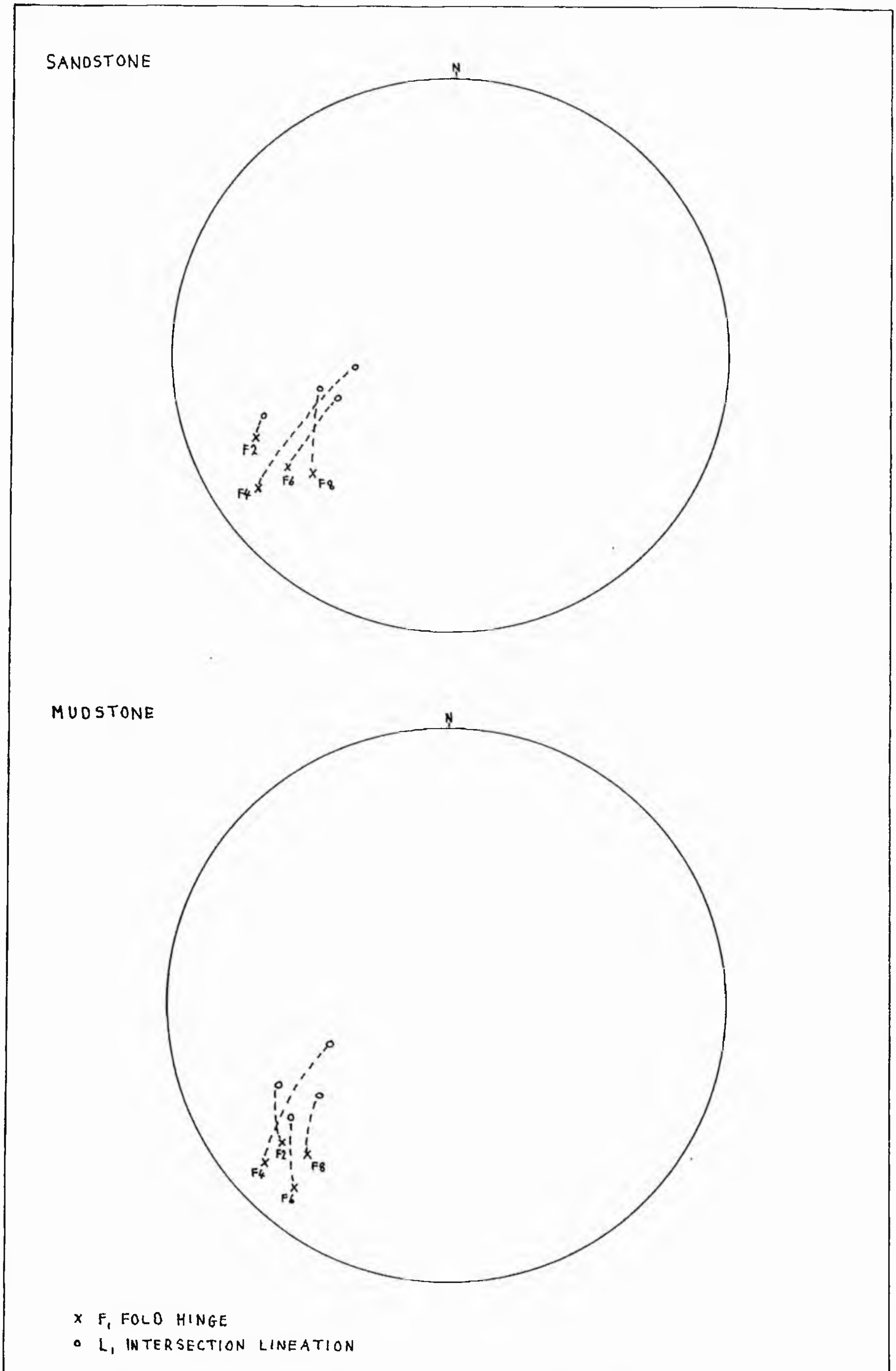


Fig 4.11: Relationship between F_1 fold hinge and L_1 intersection lineation in NW-facing fold limbs N of Ardwell Bay.

(see Borrodaile 1978, Murphy 1985 and Soper 1986 for lists) and all are applicable under specified conditions. However Sanderson *et al* 's (1980) Model 3 can best account for the available facts in a Southern Uplands context and has gained most acceptance in recent studies in this and adjacent areas (see Cameron 1981, Murphy 1985, Anderson 1987). Sanderson *et al* proposed superposition of transcurrent sinistral shear on a vertical plane of pure shear in a model of regional sinistral transpression (Fig. 4.12). The XY plane of the finite strain ellipsoid will define a position intermediate between that of the individual compressive and shear stresses involved and in so doing cleavage as a non material element will rotate clockwise relative to the axial plane which is a material element defined by bedding. An observation made initially by Cameron (1981) and since recorded by Murphy (1985) and Anderson (1987) supports Sanderson *et al* 's Model 3 above all others. Cameron found that where a mineral lineation (X_1) could be determined on S_1 cleavage it was invariably sub-horizontal in the vicinity of axial planar cleavage. This change in orientation of the extension direction is implicit in the Sanderson *et al* model. Cameron (1981) also noted that a ubiquitous transecting cleavage in the Portaferry Block in Lecale becomes localised down plunge to the NE in the Ards Peninsula forming discrete zones interspersed with zones of axial planar cleavage (*cf* Anderson 1987). This he related to a transition from the brittle release of shear stress along strike faults at high structural levels (Ards Peninsula) to ductile shear strain at deeper levels (Lecale). Such a proposition is attractive in helping to explain localised occurrences of axial planar cleavage in the Rhinns as well as along-strike variations in the areal distribution of transecting S_1 cleavage between Lecale, the Ards Peninsula and the Rhinns.

4.3.2 F_2 folding

Minor to intermediate F_2 folds are developed throughout the Rhinns though they become more widespread, more intense and associated with an S_2 crenulation

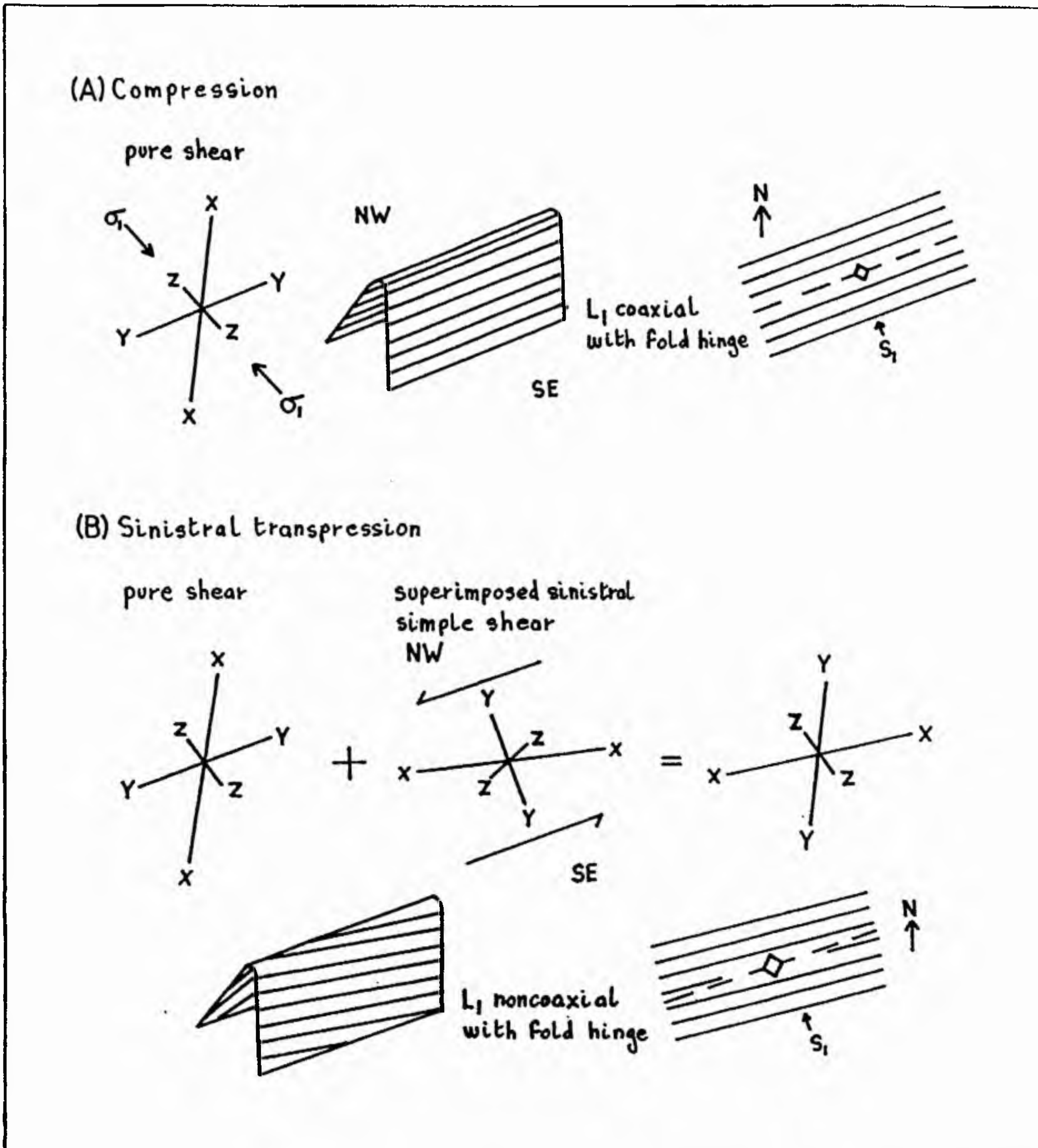


Fig 4.12: Model of S_1 cleavage/F_1 fold relations under: (A) pure shear compression and (B) sinistral transpression (after Sanderson et al 1980, Cameron 1981).

cleavage towards the SE. N of the Port Logan Bay Fault they are somewhat variable in style and orientation (Fig. 4.13), though generally have interlimb angles of more than 90°. The fold hinges are rounded, plunging gently to moderately NE and axial surfaces incline gently to moderately NW (Fig. 4.14 (A)). Spatially they are associated with areas in which F_1 fold hinges are absent. They are common locally between Step Craig (NX07054397) and Hackle Rock (NX06794451) in the Grennan Point Block, and between Strandfoot and Portayew spanning the Ordovician-Silurian boundary. In the siltstone and shale lithologies of the Portayew area they occur as a series of minor, SE-verging kink folds (short limb length less than 22 mm) approximating to a crenulation cleavage, in association with intermediate, SE-verging open folds. SE of Portayew in the massively bedded Cairngarroch Formation and Money Head Formation they form an apparently conjugate set of minor NW- and SE-vergent minor folds with short limb lengths of less than 1 m. Box folding is developed locally. Between Step Craig and Hackle Rock they consist of minor to intermediate, SE-verging, open folds that locally form extensive tracts of conjugate NW- and SE-vergent 'step' (monoformal) folds with sub-horizontal short limbs and steeply inclined long limbs. Outwith these zones F_2 folds are very gentle, neutrally-verging flexures on steeply inclined bedding planes, which at one locality 40 m NW of Portavaddie (NX08994139), are associated with a weak, closely spaced, SE-verging crenulation cleavage (S_2 - Fig. 4.14(A)).

S of the Port Logan Bay Fault F_2 folds and S_2 cleavage become more widespread southeastwards and are most intensely developed in the short limbs ('flat belts') of the major NW-verging F_1 folds. The S_2 cleavage is developed as a SE-verging crenulation (locally NW-verging as at Dunan (NX11653153)) and although rare in the Port Logan Block and Clanyard Bay Block is developed extensively in the Cardrain Block and Mull of Galloway Block. The F_2 folds and S_2 cleavage have matching orientations with fold hinges and L_2 intersection lineations predominantly

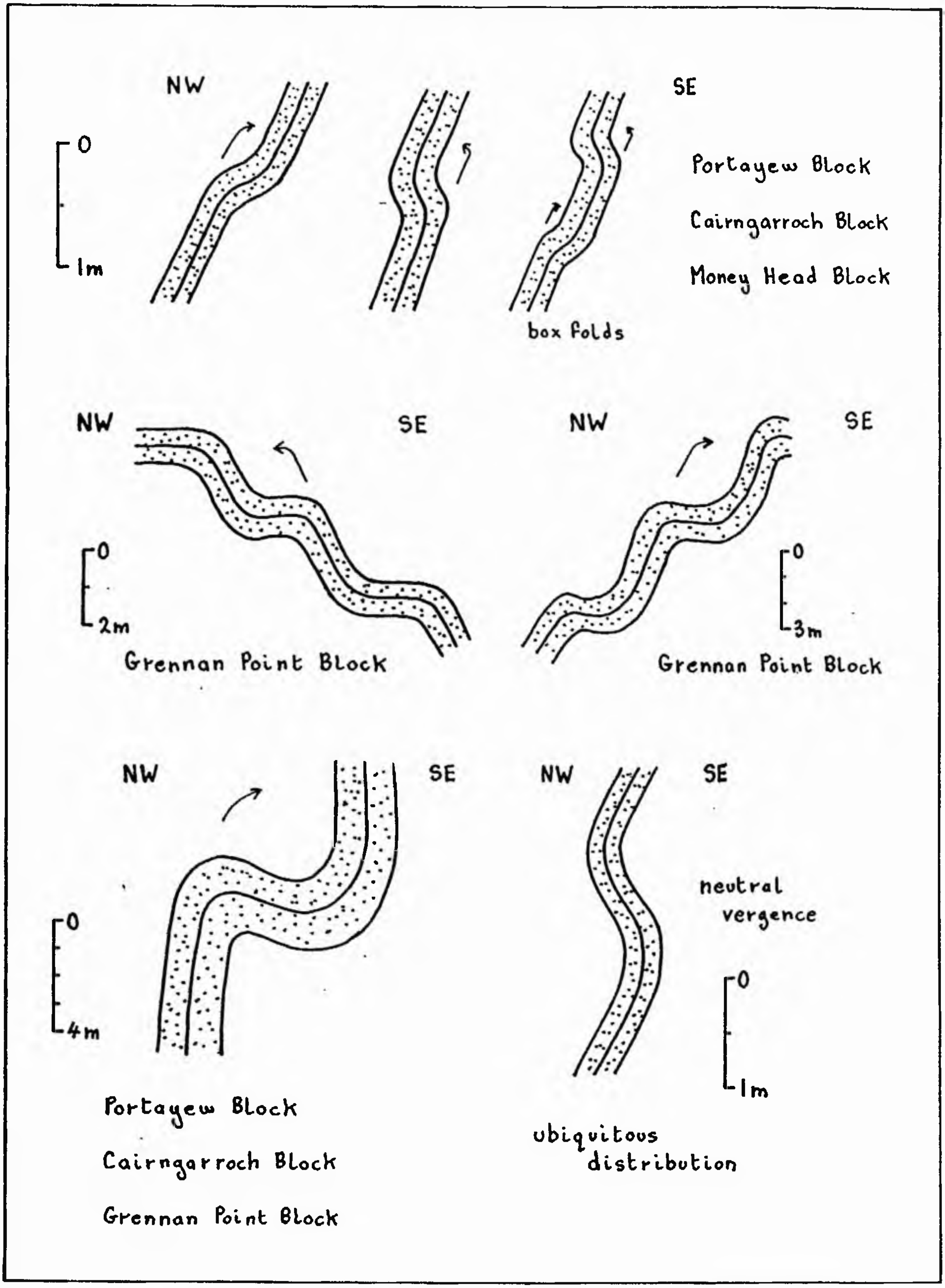


Fig 4.13: F_2 fold styles and distribution N of the Port Logan Bay Fault. Arrow indicates fold vergence.

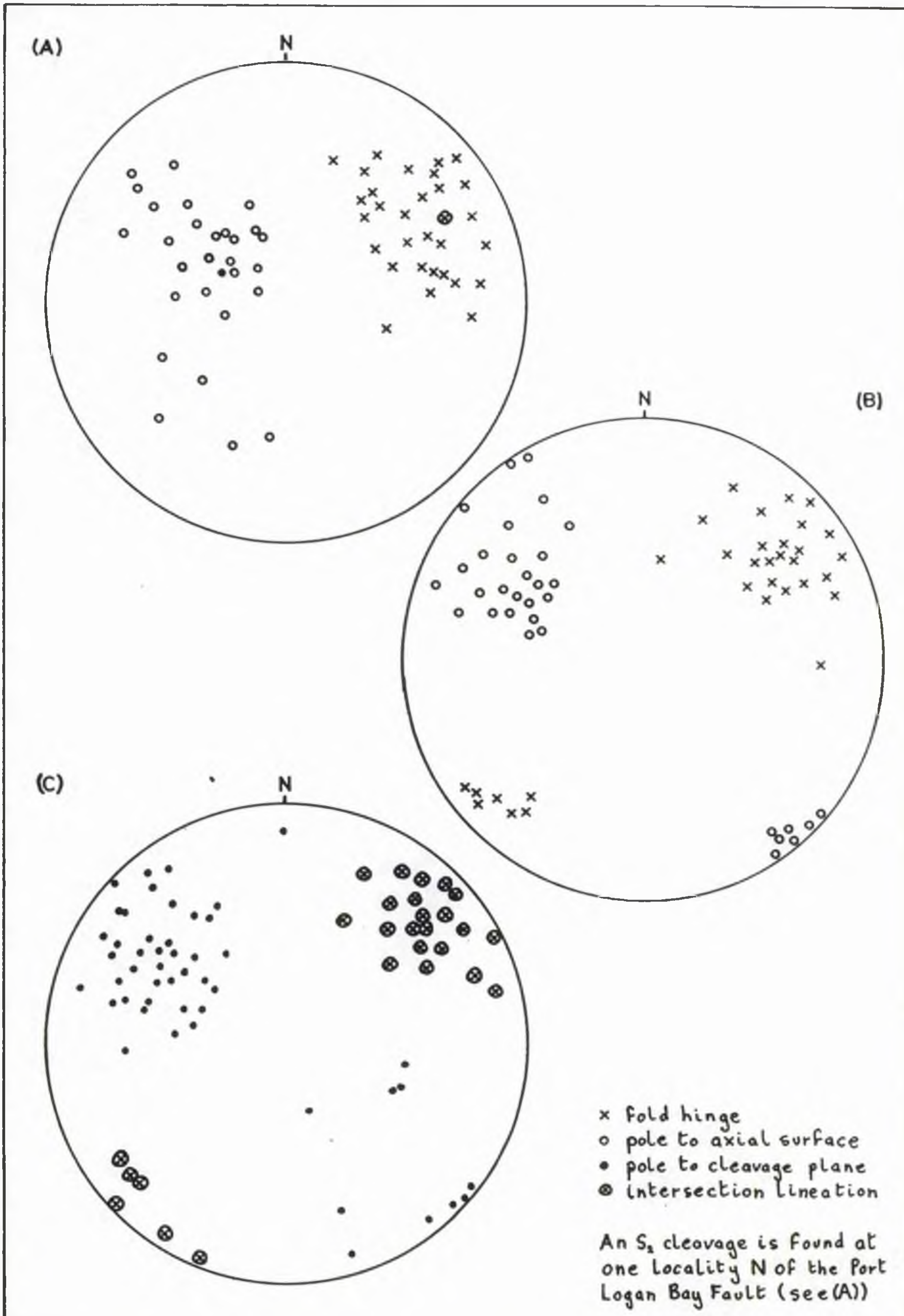


Fig 4.14: Stereograms of (A) poles to axial surfaces, and hinges of F_2 folds (26) N of the Port Logan Bay Fault, (B) poles to axial surfaces, and hinges of F_2 folds (32) S of the Port Logan Bay Fault and (C) poles to S_2 cleavage planes (49), and L_2 intersection lineations (26) S of the Port Logan Bay Fault.

plunging gently to moderately NE and the axial surfaces and cleavage planes predominantly inclined steeply to moderately SE (Fig. 4.14(B)). F_2 folds are dominantly minor to intermediate, SE-verging and close to open, with rounded hinges that become more angular and tight in shale and siltstone units, as in the Slate Heugh Member of the Port Logan Formation (NX39240958) (Fig. 4.15 and Plate 4.12). These folds are best exposed between Leucarron (NX13303100) and Carrickgill (NX13453095) in the Cardrain Block. At two localities, Quarry Bay (NX09264032) in the Port Logan Block and more spectacularly at Inchnagour (NX10003310) in the Clanyard Bay Block, F_2 folds are markedly different in style and orientation consisting of a minor, upright fold pair at the former and a series of six intermediate, upright folds plunging gently SW at the latter (Fig. 4.16 and Plates 4.13(A) and (B)). At both localities the folds have sub-vertical axial surfaces, rounded hinges and have either a neutral or slight southeasterly vergence. They occur in the short 'flat' limbs of major, NW-verging, F_1 fold pairs immediately adjacent to very angular F_1 hinges (see Plate 4.13(B)) and have an S_2 crenulation cleavage developed locally in their hinges. The causes of these differing F_2 geometries are discussed in Chapter 5.

S_2 cleavage - the S_2 cleavage, which is virtually absent N of the Port Logan Bay Fault, occurs locally, though rarely in the Port Logan and Clanyard Bay Blocks. It is developed extensively in the Cardrain and Mull of Galloway Blocks, particularly on the NW-facing limbs of F_1 folds where it is more common than F_2 folds. The cleavage is rarely found in sandstones though occurs in some F_2 hinges as irregularly spaced pressure solution planes. In shales and siltstones it is often weakly defined by SE-verging microfolds up to 5 mm apart. At its most intense it is a true zonal crenulation cleavage (Powell 1979) with a spacing of less than 2 mm and showing pressure solution displacement in the cleavage direction. Both the S_1 fabric and earlier laminae are crenulated. At Dunan the S_2 cleavage is conjugate, as is much of the F_2 folding N of the Port Logan Bay Fault. This conjugate cleavage consists of a

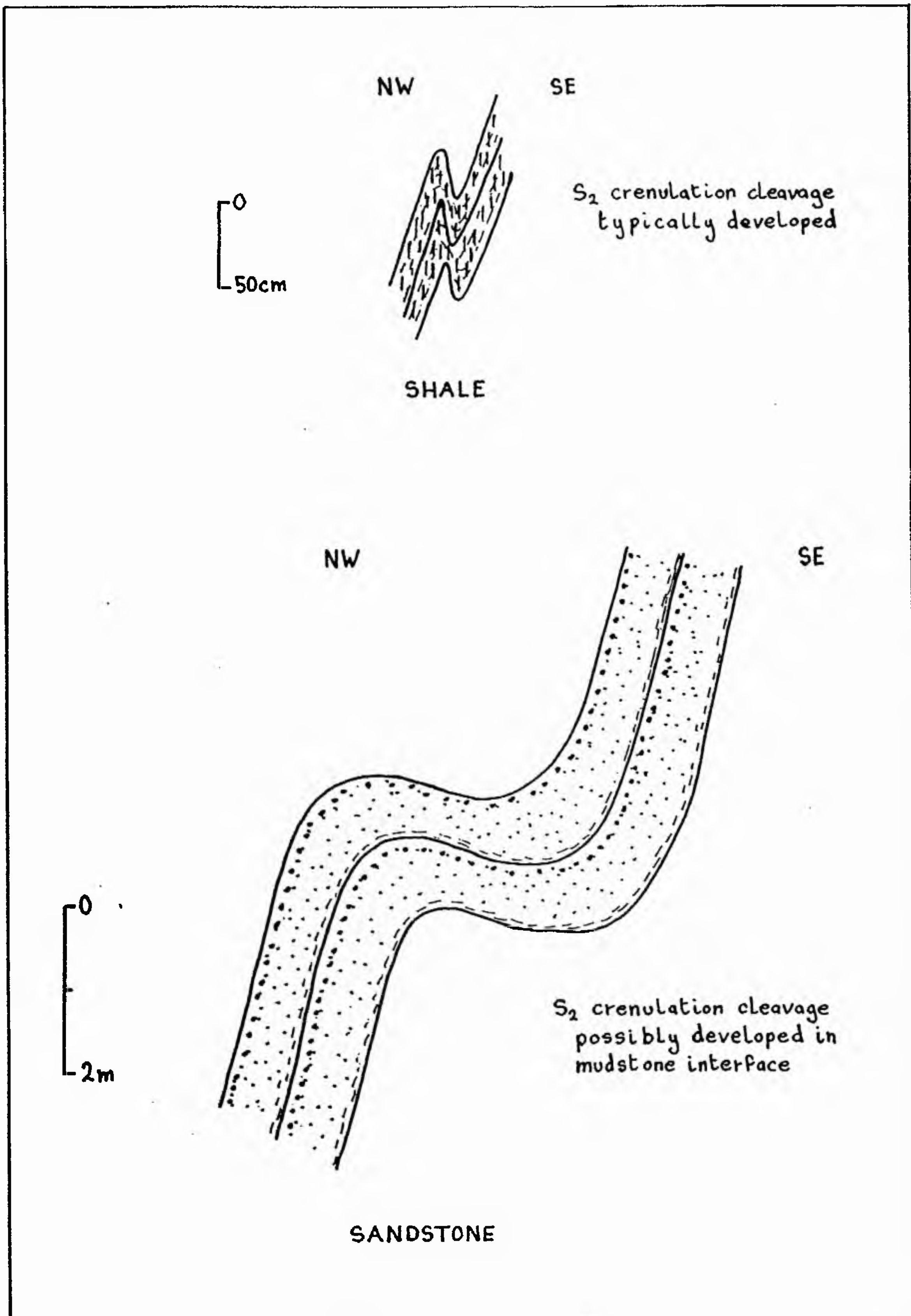


Fig 4.15: F_2 fold style in sandstones and shales S of the Port Logan Bay Fault. Vergence consistently to the SE.

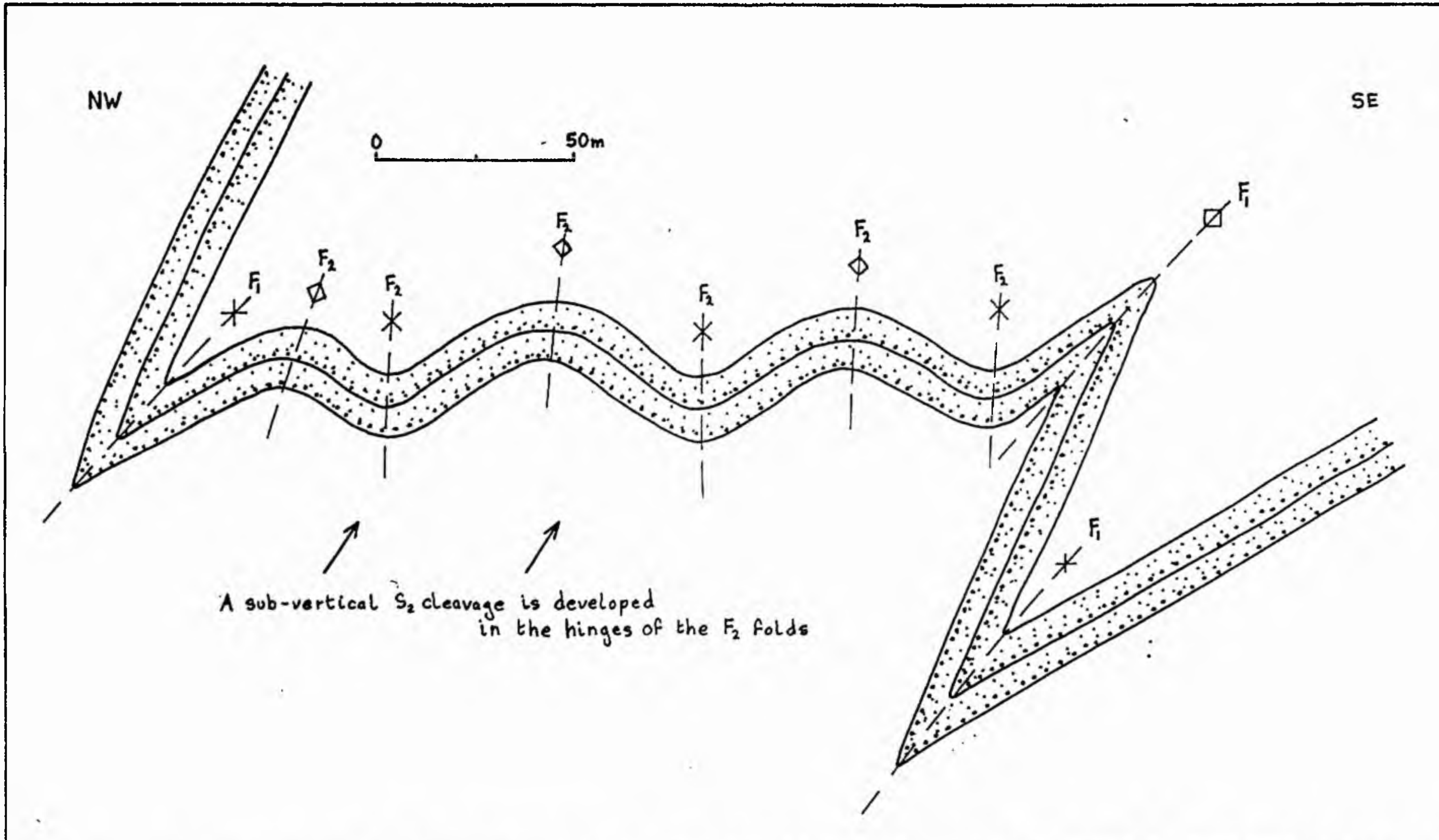


Fig 4.16: Open, symmetric F_2 folds developed in the flat (short) limb of a major NW vergent F_1 fold pair at Inchnagour (NX10003310). Note the extrême angularity of the hinges and planar limbs of the chevron F_1 fold pair relative to the rounded profiles of the F_2 folds.

(A)

(B)

Plates 4.13(A) and (B): Open, symmetric, upright F_2 folds and overturned F_1 chevron fold pair developed on the short limb of a major NW-vergent F_1 fold pair at Inchnagour (NX10003310). Note difference in style of F_1 and F_2 folding

set of opposing NW- and SE- vergent crenulations whose cleavage planes define an angle of 60°-80° symmetrical to the S_1 cleavage.

4.3.3 Post-F_2

Three generations of post-F_2 folds are recognisable in the Rhinns and although demonstrably younger than F_2 the age relations between them are equivocal, but are believed to be from oldest to youngest in the order treated here:

Steeply plunging open folds - these typically occur as isolated, minor, steeply plunging fold pairs with open or gentle, rounded hinges that are locally tighter in siltstone or shale units. They are concentrated in the Clanyard Bay Fault Zone, where they have a predominant sinistral vergence, and between Wallace Hole (NX11343169) and Carrickafliou (NX11883142), where they are exclusively dextrally-verging. Outside these zones they are sporadic in distribution and rare. They occur at only two localities N of the Port Logan Bay Fault: at Anns Cave (NX04604904) immediately S of the Cairngarroch Fault where they form an intermediate, open, sinistrally-verging fold pair; and in the Moffat Shales at Drumbreddan Bay where they have a dextral-vergence and imbricate an enclosed bentonite layer (see Plate 3.12) indicating the relative competence of the strata during deformation. Spatially these folds are closely related to zones of strike faulting and are believed to result from simple shear deformation of the strata caused by strike-slip reactivation of strike faults, with a possible minor dip-slip component of movement. The geometrical relationship between the folds and fault movement is not simple, as demonstrated at Bendoo (NX09793704), where a series of minor folds developed adjacent to a strike fault have a predominant sinistral vergence, but are complemented by the presence of dextrally verging folds and box folds. Slickencrysts developed along the fault plane are sub-parallel to the fold plunge and indicate sub-horizontal sinistral movement. The fold hinges thus appear to have formed perpendicular to the movement direction of the fault, though the vergence of the fold pairs is not necessarily indicative of its shear sense.

Orientation data recorded from throughout the Rhinns and plotted in Fig. 4.17 indicate these folds generally have a steep northwesterly plunge with axial surfaces inclined steeply to the SW or more rarely to the NE. Dextral- and sinistral-verging folds occur in equal numbers and are frequently seen refolding F_1 folds and bending the S_1 cleavage as at Muddioch Rock (NX10333746) and on the peninsula 100 m SE of Bullet (NX11563154). As well as their geometry the folds are distinctive in the sporadic development of an associated cleavage in their hinges and its local development elsewhere (Fig. 4.17). At Carrickamickie (NX12183142) the cleavage is a weak, closely spaced (less than 2mm) zonal crenulation with a sinistral vergence, cutting across an earlier S_2 crenulation and buckling the S_1 fabric. 100 m NW of Carrickamurlin (NX14333202) it similarly deforms both the S_1 and S_2 cleavage though has a dextral vergence. It is typically developed as a zonal crenulation of opposing dextral or sinistral vergence. Where most intense, in fold hinges at Stable Alane (NX09763694) and 100 m SE of Bullet, it forms pressure solution seams in the crenulation plane which effect discrete displacements of the pre-existing fabric.

NW-verging recumbent folds - apart from two fold pairs present at Port Mona (NX10503265), these distinctive folds are only found NW of the Cairngarroch Fault in the Cairngarroch and Portayew Blocks and SE of the Nick of Kindram Fault in the Cardrain and Mull of Galloway Blocks. They are virtually absent from the area between where the more massive and competent lithologies of the Gala Group occur. The folds are remarkably homogenous in style throughout their outcrop, having minor to intermediate, NW-verging, open profiles (interlimb angle typically 90°-100°) with distinctive angular hinges producing a chevron like form (Plate 4.14). They are recumbently orientated with fold hinges plunging gently NE and axial planes predominantly inclined gently NW (Fig. 4.18). These folds are associated with minor, gently inclined, NW-directed thrusts that are often developed in their hinge

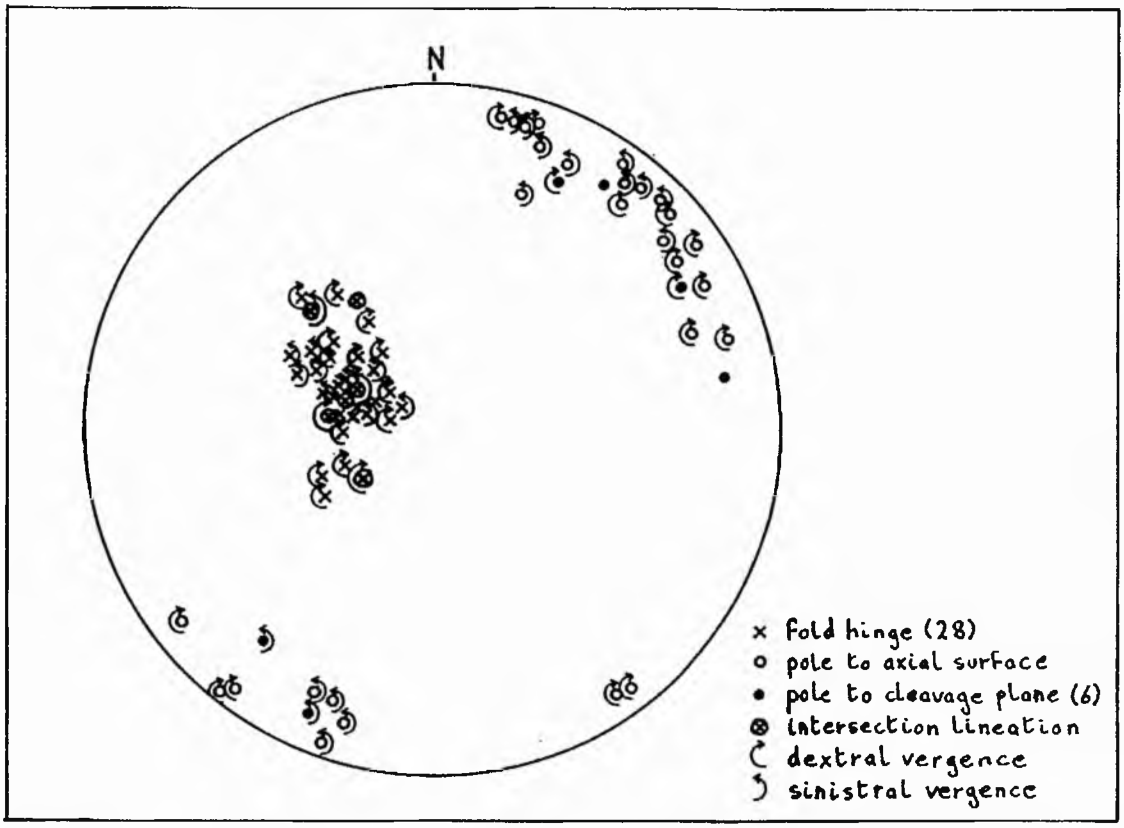


Fig 4.17: Stereogram of post-F_2 steeply plunging folds, and related cleavage orientation data.

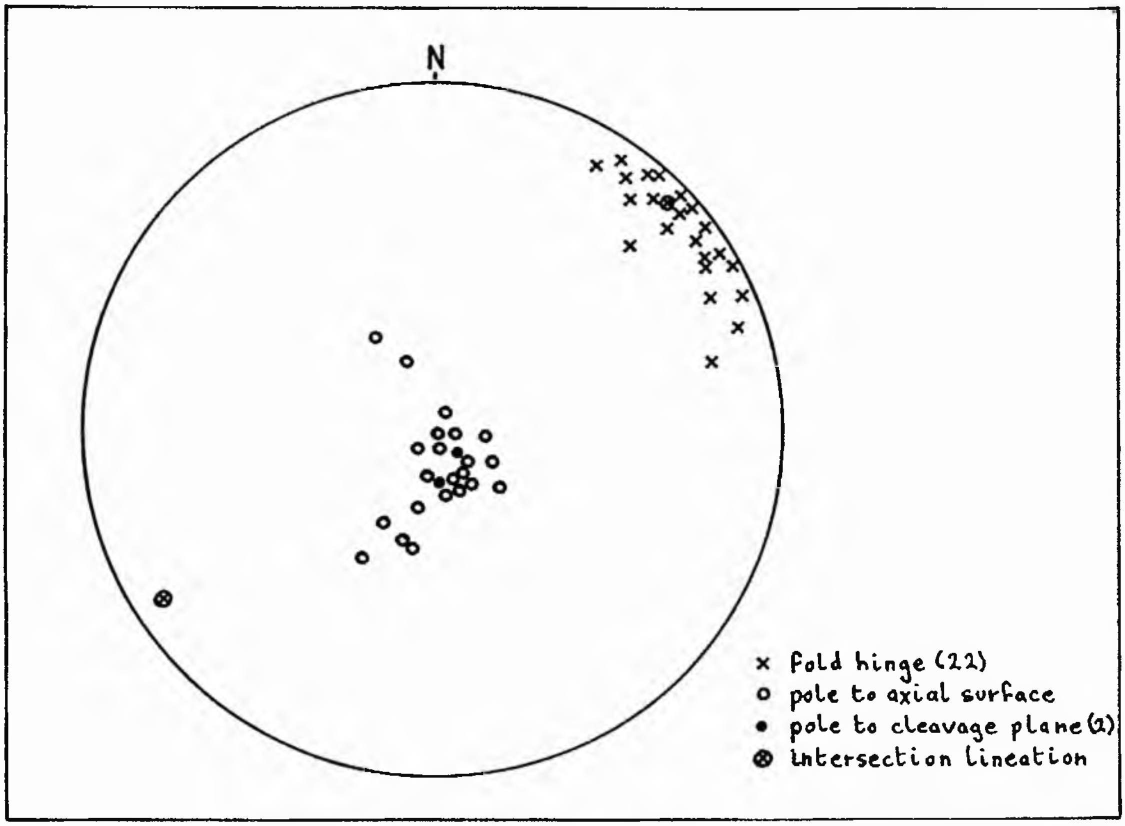


Fig 4.18: Stereogram of post-F_2 NW-vergent recumbent folds, and related cleavage orientation data.

Plate 4.14: NW-vergent recumbent folds at Cove Hip (NX03974994) in the Cairngarroch Block

Plate 4.15: Dextral kink band in Slate Heugh Member siltstones at Slate Heugh Bay (NX09263957)

zones and are discussed later in Section 4.4.3. No fabric has been found in close association with the folds, however a recumbent, NW-verging, zonal cleavage observed crenulating S_2 pressure solution seams and the S_1 cleavage at Wallace Hole and Carrickamickie Bay (NX12063147) is believed to be related.

Kink bands - kink bands are sporadically developed throughout the Rhinns, though locally concentrated in the thicker shale and siltstone units. They possess markedly different geometries either side of the Port Logan Bay Fault. Geometrical analyses of the kink bands have been carried out on those concentrated in thick shaley units where measurements can be taken more accurately and the relationship to bedding and cleavage determined more easily.

S of the Port Logan Bay Fault kink bands are uncommon, though two major concentrations occur, in the Slate Heugh Member of the Port Logan Formation at Slate Heugh Bay (NX09253960) and in the Mull of Galloway Formation at Wallace Hole. Deformation is by slip along bedding which is more sharply defined than cleavage in the thinly interlayered laminated siltstone and shale units. At Slate Heugh Bay this is evidenced by the consistent dextral displacement along bedding planes of quartz veins developed perpendicular to bedding in the long limbs of the kink folds (Fig. 4.19). Dextral vergence (Plate 4.15) predominates over sinistral in the ratio 5:1 with the respective kink planes having modal orientations of $70^{o}\rightarrow064^{o}$ (Fig. 4.20(A)). Booth (1975) demonstrates that conjugate kink bands are always symmetrically disposed about σ_1 regardless of the orientation of the foliation. Assuming that the kink bands S of the Port Logan Bay Fault are members of a single system, a monoclinic symmetry is exhibited both locally and regionally with σ_1 orientated about 10^{o} anticlockwise of bedding and having a sub-horizontal E-W trend (Fig. 4.20(A)). The obliquity in orientation of σ_1 and the foliation (bedding) results in a preponderance of high angle dextral kinks (kink places orientated oblique to the foliation by more than 45^{o}) over low angle sinistral kinks (kink planes orientated oblique to the foliation by

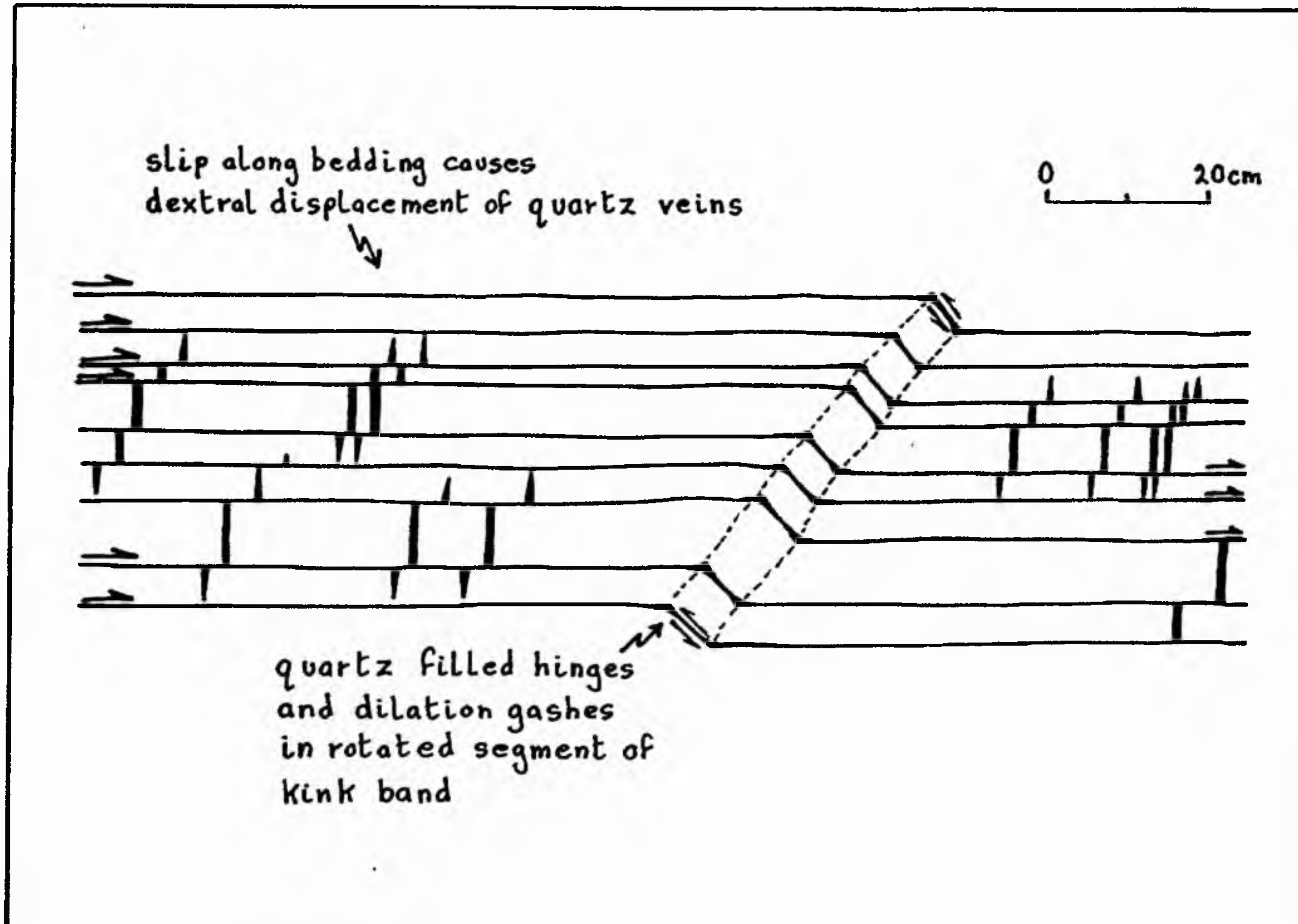


Fig 4.19: The dextral displacement of quartz veins along bedding in the long limbs of dextral kink bands at Slate Heugh Bay (NX09253960) provides evidence that rotation was accomplished by flexural slip. Solid black indicates quartz infill.

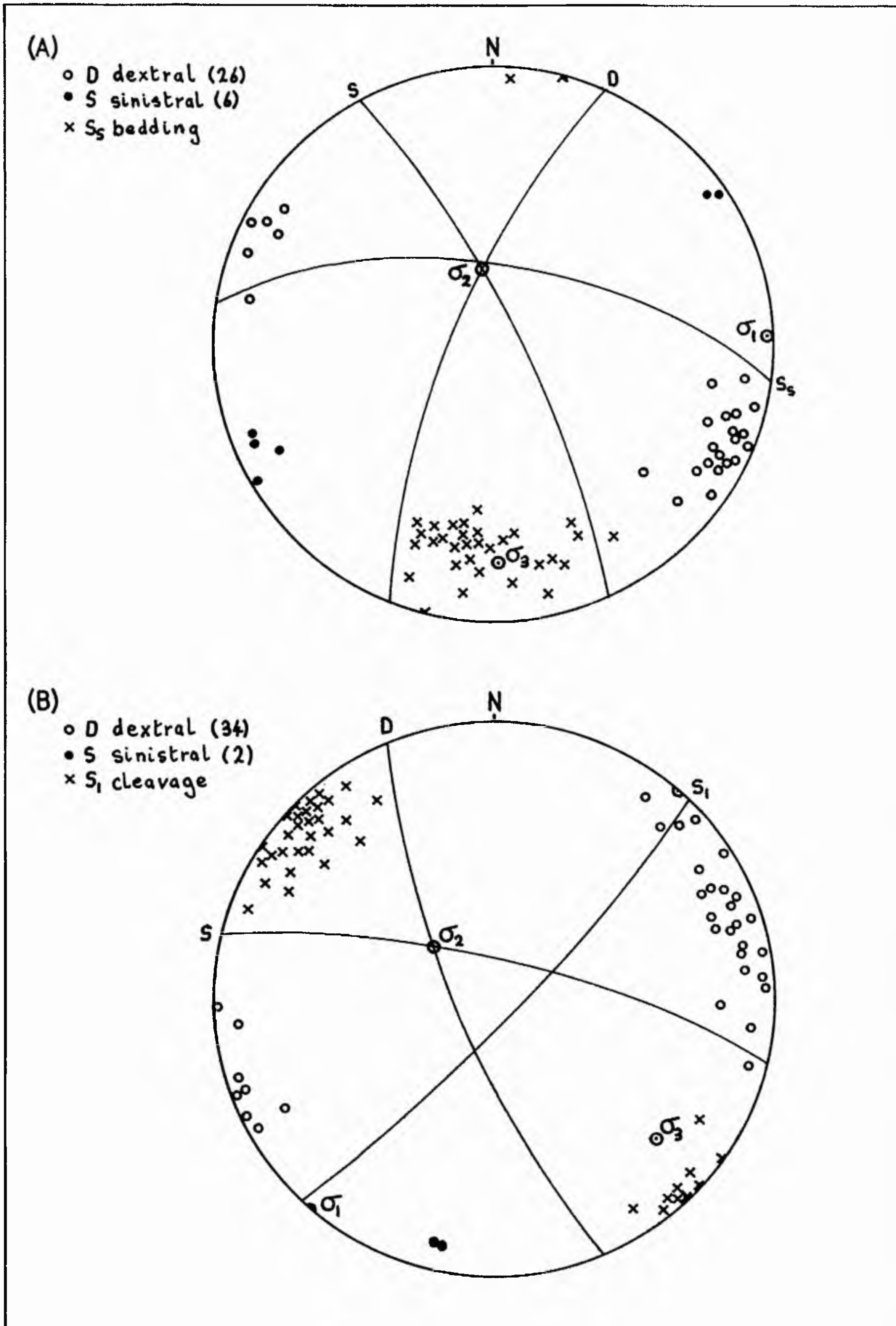


Fig 4.20: Stereogram of poles to kink planes and symmetry of kink band systems with inferred principle stress orientations (A) S of the Port Logan Bay Fault and (B) N of the Port Logan Bay Fault.

less than 45°) as observed (see Dewey 1964).

N of the Port Logan Bay Fault the kink bands are developed in more homogenous shale units and are concentrated in two localities: at Parkers Point (NX07744338); and along the foreshore at Ersbals Caves (NX06894625). Here the slip develops along the S_1 slaty cleavage and in all but one kink band the rotation sense is dextral. The modal orientation of the dextral kink planes is $78° \rightarrow 250°$ and for the two sinistral kink planes is $78° \rightarrow 016°$ (Fig. 4.20(B)). A triclinic symmetry is exhibited in which σ_1 is horizontal, has a NE-SW trend and is sub-parallel to the S_1 cleavage. σ_2 and σ_3 occur in a plane perpendicular to the cleavage (Fig. 4.20(B)). Booth (1975) suggests that triclinic systems could result from slight inclination of σ_1 to the foliation. Where this is inferred, kink bands of one sense should predominate, as is apparent in the Rhinns N of the Port Logan Bay Fault. The 45° change in orientation of σ_1 either side of the Port Logan Bay Fault remains to be explained.

The kink bands vary remarkably little in morphology. They typically have very angular or rare sub-rounded hinges, the latter particularly developed in sandstones. The maximum length of a rotated segment in a kink band is 70 mm at Parkers Point and the longest kink band measured 8 m at Slate Heugh Bay. The geometry of each kink band is described in terms of the angles α, β and γ which relate to angular differences between the external foliation, rotated foliation and kink plane, as defined by Anderson (1969) (Fig. 4.21). The α value varies between kink bands of opposing vergence where σ_1 is oblique to the foliation. This as expected results in different mean α values of 71° and 59° respectively for the dextral and sinistral kink bands S of the Port Logan Bay Fault. The angle β is always greater than the angle α in the kink bands of the Rhinns indicating rotation was accomplished by flexural slip with dilation gashes (usually quartz filled) often forming in the rotated limb (particularly in sandstones). These are well displayed on the foreshore at Slate Heugh Bay where additional evidence of slip is provided by the displacement of quartz veins

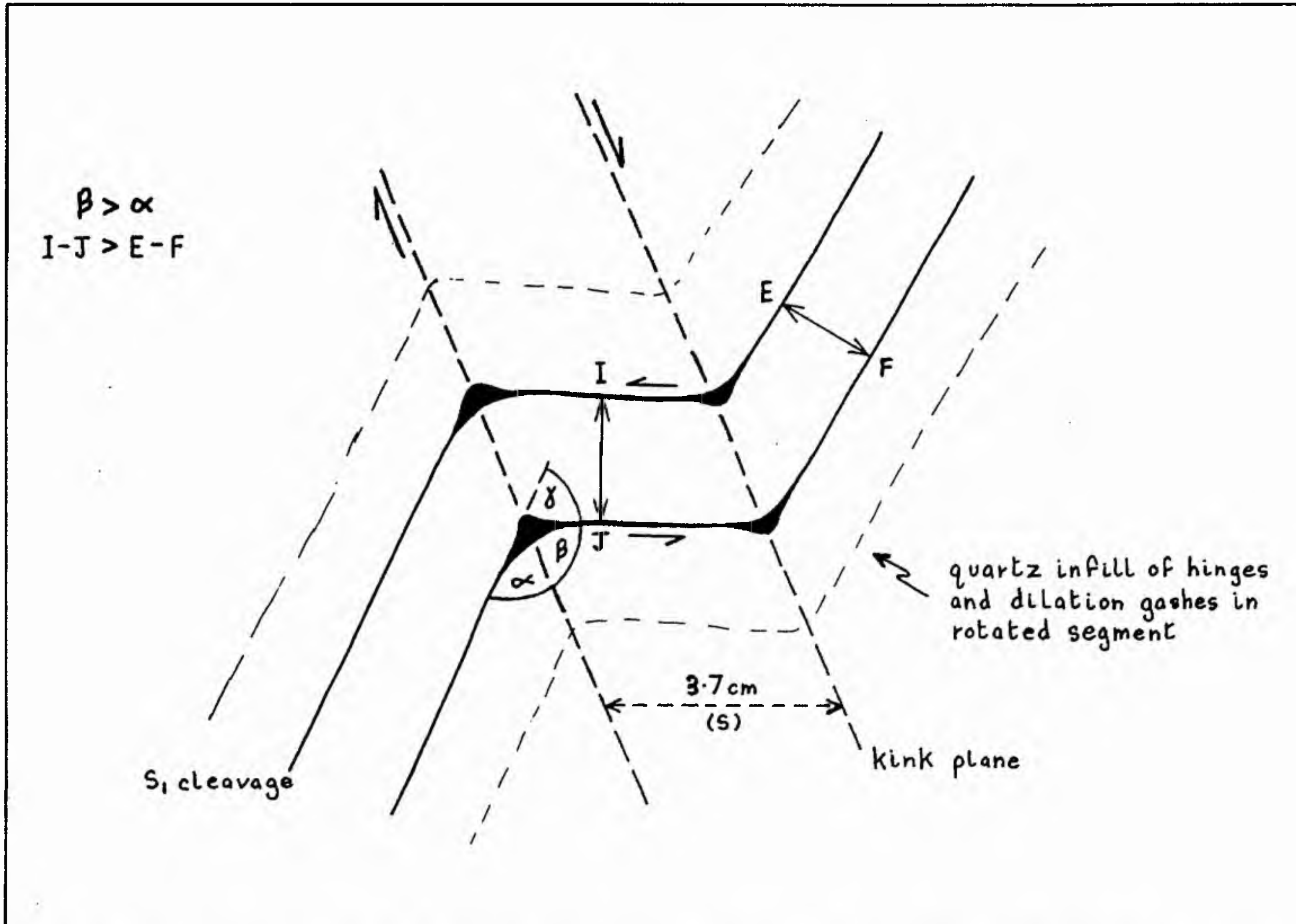


Fig 4.21: Typical geometry of Rhinns kink band. Notation after Anderson (1969). Solid black indicates quartz infill.

along bedding as described earlier (Fig. 4.19).

Kink bands deform the S_1 slaty cleavage regionally and the S_2 crenulation cleavage locally at Wallace Hole. Their restricted occurrence and realigned stress axes suggest they represent the last increments of fold deformation. Rust (1965a and Anderson (1969) working in adjacent areas along-strike, established they pre-date younger lamprophyre dyke intrusion implying a Caledonian age.

4.3.4 Tarbet folds

The Tarbet folds are an enigmatic group of folds that take their name from West Tarbet (NX13953100) where they are spectacularly exposed between the Tarbet Fault and the Mull Glen Fault. They occur mainly in the Cardrain Block and Clanyard Bay Fault Zone N of Clanyard Bay and although widely distributed show a strong local association with strike faults. Their age is uncertain though as they fold the S_1 cleavage about their hinges they are post-D_1. A minor fold exposed 100 m NW of Dunan (NX11563152) bends the S_1 cleavage about its hinge and is interpreted as a Tarbet fold, a SE-verging S_2 crenulation cleavage on its southeastern limb becomes NW-verging on its northwestern limb in response to the changing orientation of the S_1 foliation. If this critical locality is interpreted correctly it places the age of the Tarbet folds between F_1 and F_2. Further evidence in support of this age is presented later.

The folds possess four distinctive characteristics:-

(1) They are very localised in occurrence, often in planar zones affecting only a few beds and usually closely associated with a strike fault.

(2) Fold hinges at any one locality are sub-parallel and have steep to moderate plunges. Axial planes by contrast show a broad scatter of orientations. Modal fold orientation data differs between localities.

(3) The sense of vergence at any one locality is consistent, either sinistral, or less commonly, dextral, despite the variation in fold shape.

(4) In profile the folds are typically parallel (Class 1A - Ramsay 1967) and where

most fully developed have a chevron geometry. They display either no or very little flattening and contain no associated axial planar foliation.

The folds are described below at the two localities they are best exposed, West Tarbet in the Cardrain Block, and Dunbuck (NX09613851) in the Clanyard Bay Fault Zone.

At West Tarbet the folds are exposed along a 150 m section of coastline between the N-S trending sinistral Mull Glen Fault and the ENE-WSW trending Tarbet Fault (Fig. 4.22). Between 50 m and 100 m from the Tarbet Fault the folds have a strong sinistral vergence, with interlimb angles of 50^o-90^o and a well developed chevron like geometry (Plates 4.16(A) and (B)). Short limb lengths reach a maximum of 8 m, though are usually less than 2 m. The folds are typically parallel and disharmonic and a number have antiforms developed on their long limbs adjacent to fold hinges (see Plates 4.16(A) and (B)). Towards the fault bedding becomes more brecciated, the folds develop a more neutral vergence and co-axial refolding occurs (Plate 4.17). Unlike the other localities where Tarbet folds are exposed there is a progressive change in fold orientation with distance from the fault (Fig. 4.23). As the fault is approached the fold hinges change from having a moderate plunge to the NE to a moderate to steep plunge to the SE. Similarly the axial plane dip changes from moderate to the NE to moderate to steep to the SE.

At Dunbuck, a 10 m S-younging sequence, juxtaposed between two intensely brecciated strike fault zones dipping at $72^o \rightarrow 343^o$ to the N and $68^o \rightarrow 338^o$ to the S, is intensely folded by Tarbet folds. These folds have a dextral vergence and interlimb angles varying from 30^o to 150^o. Fold hinges are angular and plunge moderately to steeply WNW with axial planes inclined steeply to the S or SE (Fig. 4.24). In one fold pair a superbly developed imbricate sequence affects three successive siltstone beds less than 20 cm thick. This imbrication is clearly later than S_1 cleavage development and like the folding has a dextral vergence.

A number of interesting and important features are found at the localities

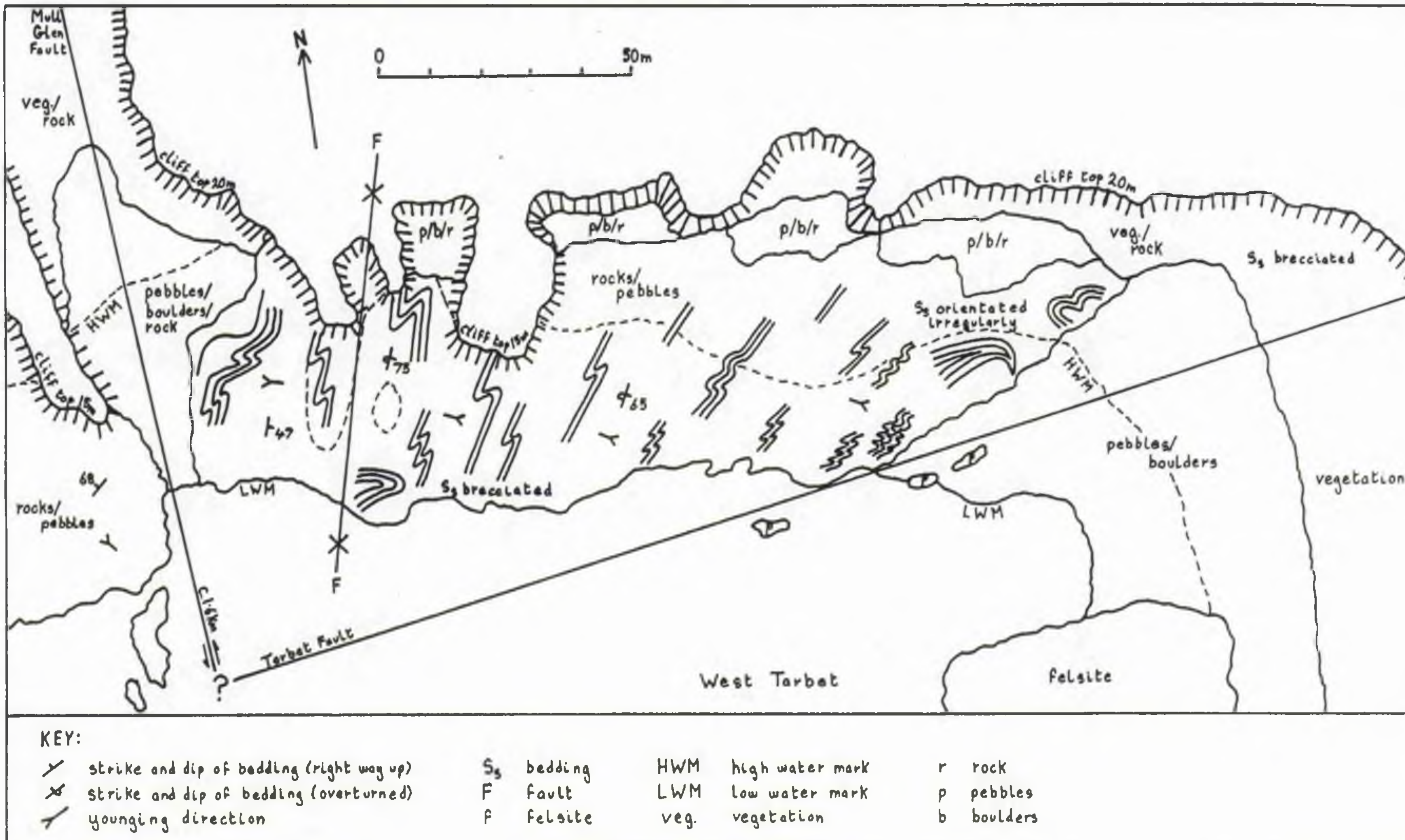


Fig 4.22: Sketch map of West Tarbet (NX14003093) showing outcrop of Tarbet folds.

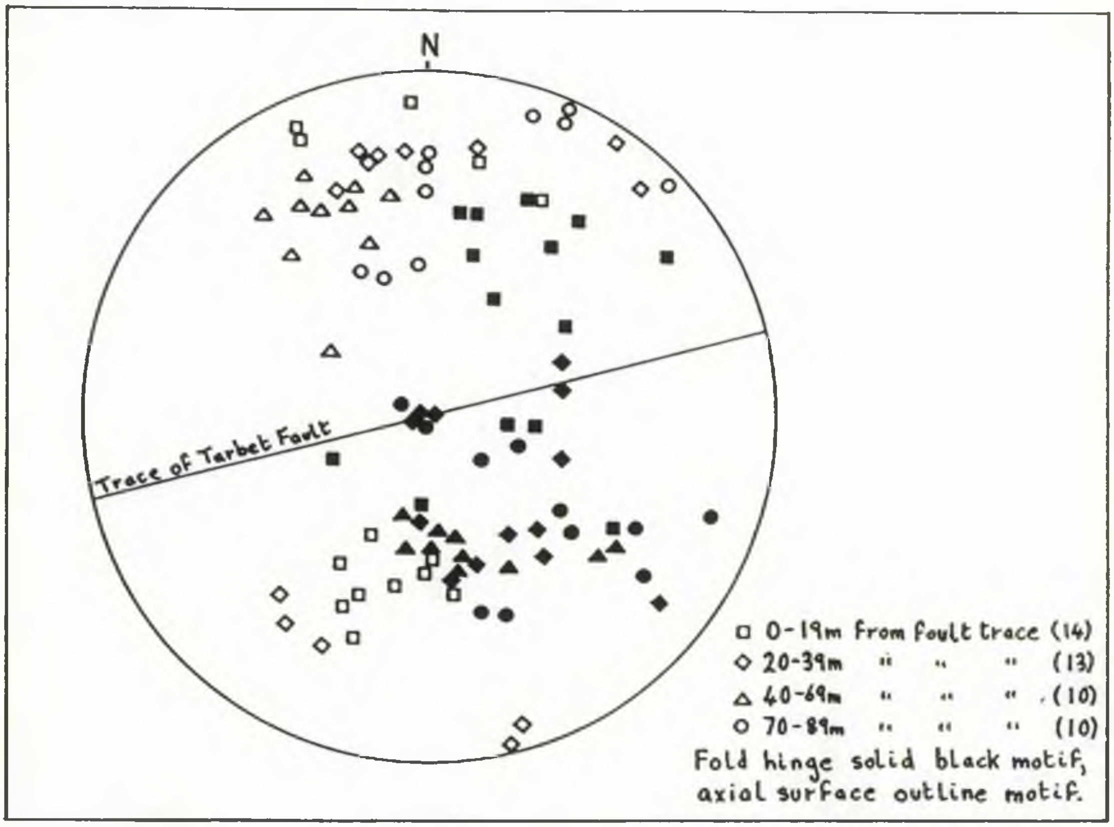


Fig 4.23: Stereogram of fold hinges and poles to axial surfaces of Tarbet folds with distance from the Tarbet Fault trace at West Tarbet (NX13953100).

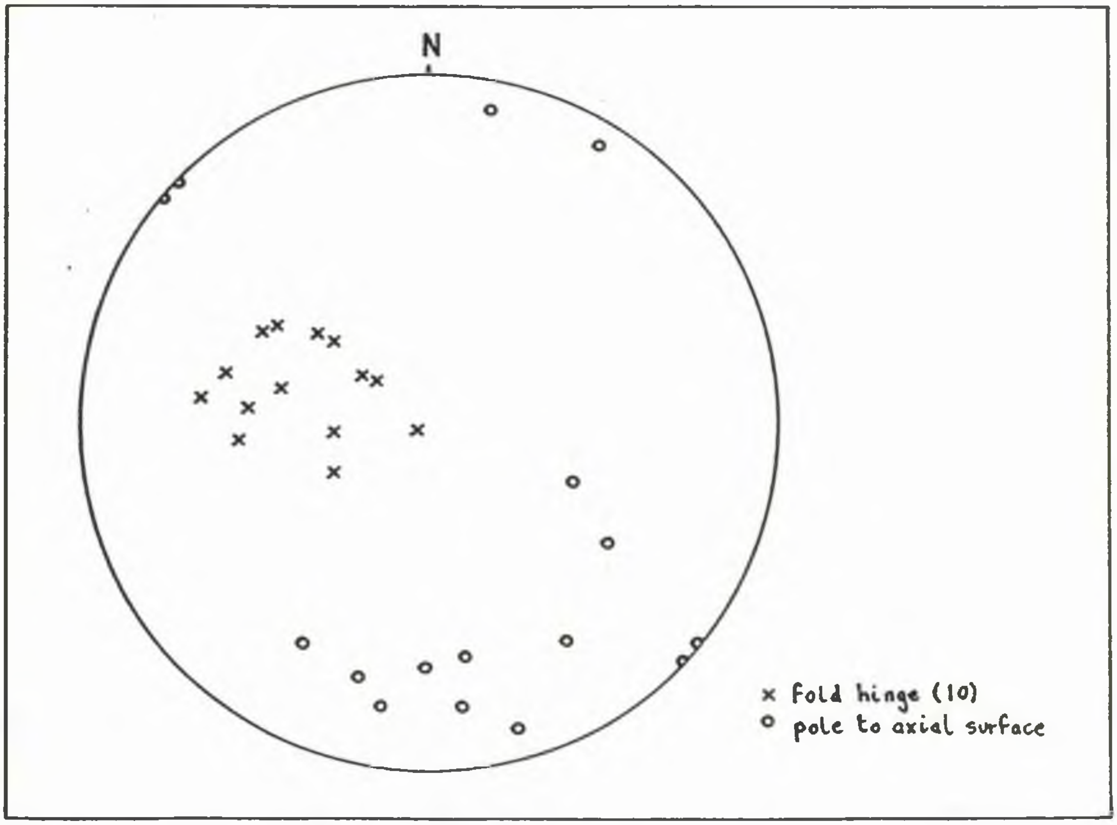


Fig 4.24: Stereogram of fold hinges and poles to axial surfaces of Tarbet folds at Dunbuck (NX09613851).

(A)

(B)

Plates 4.16(A) and (B): Sinistral-verging Tarbet folds at West Tarbet (NX13883105). Note low sand/shale ratio, chevron geometry and development of antiforms adjacent to the uppermost hinge

Plate 4.17: Tarbet fold refold at West Tarbet (NX13923102)

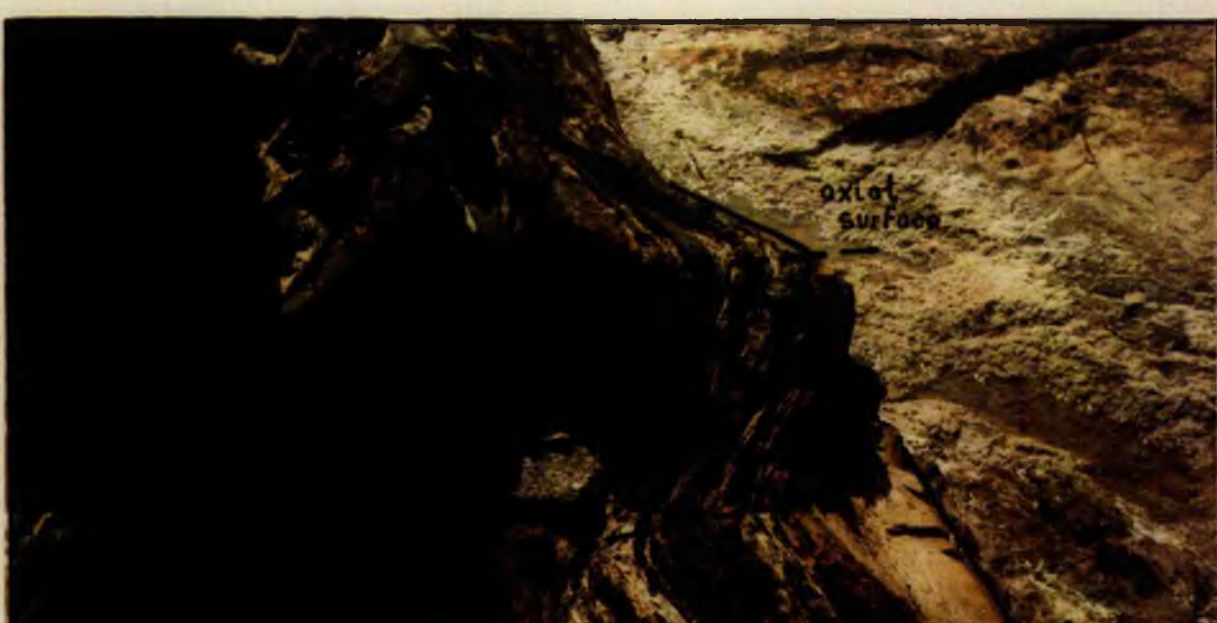


Plate 4.18: Complex series of Tarbet fold refolds at East Tarbet (NX14473124)

below. In a 1 m^2 outcrop 100 m N of East Tarbet (NX14453122) four Tarbet folds mutually interface, with fold hinges and axial planes orientated perpendicular to one another (Plate 4.18). Two of the folds have co-axial hinges while the other two have sub-parallel axial planes. The folds have angular hinges and are close to open. The exact age relations between all four folds are equivocal. At Carrickamickie (NX12223143) a 4 m thick sequence of siltstones and shales is present within a much thicker and more competent sequence of sandy turbidites. The less competent 4 m sequence is intensely deformed along-strike (050°-230°) by Tarbet folds of two main styles. Towards the centre of the sequence the folds are chevron like and have a neutral vergence. The hinges are very angular and interlimb angles range from 70° to 90°. Fold hinges plunge moderately SW and axial planes dip moderately to steeply SE. Towards the margins of the sequence the folds are open with interlimb angles greater than 90°, they have a dextral vergence and less angular hinges. Fold hinges are co-axial with those in the centre of the sequence though axial planes dip moderately to steeply SW giving an overall box fold geometry. Some of the folds appear refolded by SE-verging F_2 folds. On a sea-stack at Carlin House Bay (NX09823822) an F_1 fold adjacent to a strike fault has clearly been refolded by drag along the fault. This has formed a Tarbet fold, with an angular hinge, straight limbs and an interlimb angle of about 50° .

Three pieces of evidence point to the age of the Tarbet folds as between F_1 and F_2: the apparent cross-cutting relationship and change of vergence of the S_2 cleavage on either limb of a Tarbet fold 100 m NW of Dunan; the refolding of Tarbet folds by F_2 folds at Carrickamickie; and the shearing of Tarbet folds along with F_1 folds in the Clanyard Bay Fault Zone at Dunbuck.

Tarbet folds are believed to result from simple shear along major strike faults, i.e. the friction acting across the fault exerts sufficient drag to form folds. This is evidenced by the localisation of the folds to the vicinity of strike faults and their consistent orientation and vergence sense at each locality. The shear stress decreases rapidly away from the fault causing the localisation in folding observed (see Suppe 1985). The folds are found only in the less 'proximal' lithologies such as the Mull of Galloway Formation and particularly where the sand/shale ratio is low, i.e. less than 1. At Carrickamickie the folds formed in less competent shaley units within a more competent sequence, i.e where the resistance to shear stress is lowest. Thus the folds are confined to planar zones adjacent to faults. The sense of vergence of the folds is believed to reflect the movement sense of the fault with which they are associated and the constant orientation of fold hinges at each locality would suggest they are sub-perpendicular to the slip direction of the fault. The change in orientation of the folds and refolding seen approaching the Tarbet Fault at West Tarbet (Fig. 4.23) possibly reflects dextral reactivation of the fault subsequent to an earlier major sinistral slip movement.

Two important and related features suggest the folds formed at high structural levels where both the confining pressure and temperature are low: the absence of flattening; and the absence of a related cleavage (see Iwamatsu 1984). The folds initiated in a layer in which shear stress exceeded shear resistance and buckling of the layer proceeded forming concentric and eventually chevron folds by the process described in Section 4.3.1. Once chevron geometry was established the fold locked and buckling occurred elsewhere along the layer. Minor thrust deformation only developing once strain hardening of the whole zone had occurred. The presence of antiforms adjacent to chevron fold hinges at West Tarbet (see Plates 4.16(A) and (B)) suggests that once locking occurred strain was initially taken up by slip along bedding in the long limbs causing new folds to nucleate immediately adjacent to the old hinges before they too locked. One other factor that may help explain Tarbet fold formation is strain rate (this has proved impossible to gauge independently in the Rhinns). As the folds formed between F_1 and F_2 and no other evidence from this period supports deformation at a high structural level, it seems likely that a high strain rate was an important factor in their development.

4.4 FAULTING

The outcrop pattern in the Rhinns and indeed the whole of the Southern Uplands is dominated by faulting of two main types, early strike parallel faulting with dip-slip displacements and late wrench faulting at high oblique angles to the strike. Two minor fault sets, sub-horizontal thrusts related to F_3 and late normal faults, also affect the succession.

4.4.1 Strike faults

Maps A-D show the importance of strike faulting in the Rhinns. All the major tectonic blocks are defined by strike faults and within each block many other strike faults of varying importance occur. This plan view hides what in three dimensions is an anastomosing sequence of bedding parallel faults that join together and bifurcate at depth producing a network of tectonic lenses developed at all scales within (and without) the area. These faults are thrusts, as evidenced by:-

(A) their development sub-parallel to bedding,

(B) the common occurrence of recognisable hanging wall anticlines and footwall synclines,

(C) their displacement up-section,

(D) the repetition of stratigraphy across them, and

(E) the recognition of a distinct décollement horizon, the Moffat Shale Group.

Such a complex pattern of thrusting is difficult to unravel both spatially and temporally. However the Rhinns is a suitable area in which to undertake such studies as the faults are superbly exposed in vertical section in the cliffs and the early and late thrust movements are reversed over a large part of the area (S of the Port Logan Bay Fault), thus helping to differentiate between the two. Three main phases of thrust development took place and are discussed below. These were early F_1, late F_1 and F_2.

Early F_1 - early thrusting initiated in the Moffat Shale Group which acted as a décollement horizon. However the response was fundamentally different N and S of the Port Logan Bay Fault. N of the fault thrusting preceded major fold development, whereas S of the fault major folding preceded thrust development. This is shown by the arrangement of Moffat Shale inliers in the Moffat Shale imbricate zones N and S of the fault. N of the fault Moffat Shale imbricate inliers are found in the Portayew Fault Zone (400 m), the Strandfoot Fault Zone (350 m) and the Drumbreddan Bay Fault Zone (1050 m). The detailed stratigraphy in each of these fault zones is described in the relevant sections in Chapter 2. In each the Moffat Shales are NW-younging and succeeded, locally conformably, by NW-younging turbidite successions. These inliers represent a family of thrusts developed from a sole thrust. This sole thrust forms the southeastern boundary of the block.

S of the Port Logan Bay Fault a fundamentally different structure obtains. Although bedding is consistently SE-younging within the Clanyard Bay Fault Zone (1.6 km) the Moffat Shale inliers at the northern and southern ends of Clanyard Bay and in Breddock Bay are NW-younging, as is the turbidite succession between them. This anomaly is explained by the initiation of thrusting within the short limb of a major NW-verging fold pair (Fig. 4.25). A sole thrust formed (and is now exposed 120 m NW of Dunbuck) and a family of thrusts developed southeastwards from it forming imbricate inliers of Moffat Shale and overlying Clanyard Bay Formation turbidites. Thus the fundamental response to compression changed from thrusting along a Moffat Shale décollement N of the fault to major folding nucleated on the Moffat Shales and subsequent thrust development in the short limbs of the folds S of the fault. The reasons for this change in response are developed in the tectonic summary in Chapter 5.

The Moffat Shales are well suited to act as a locus for thrust development.

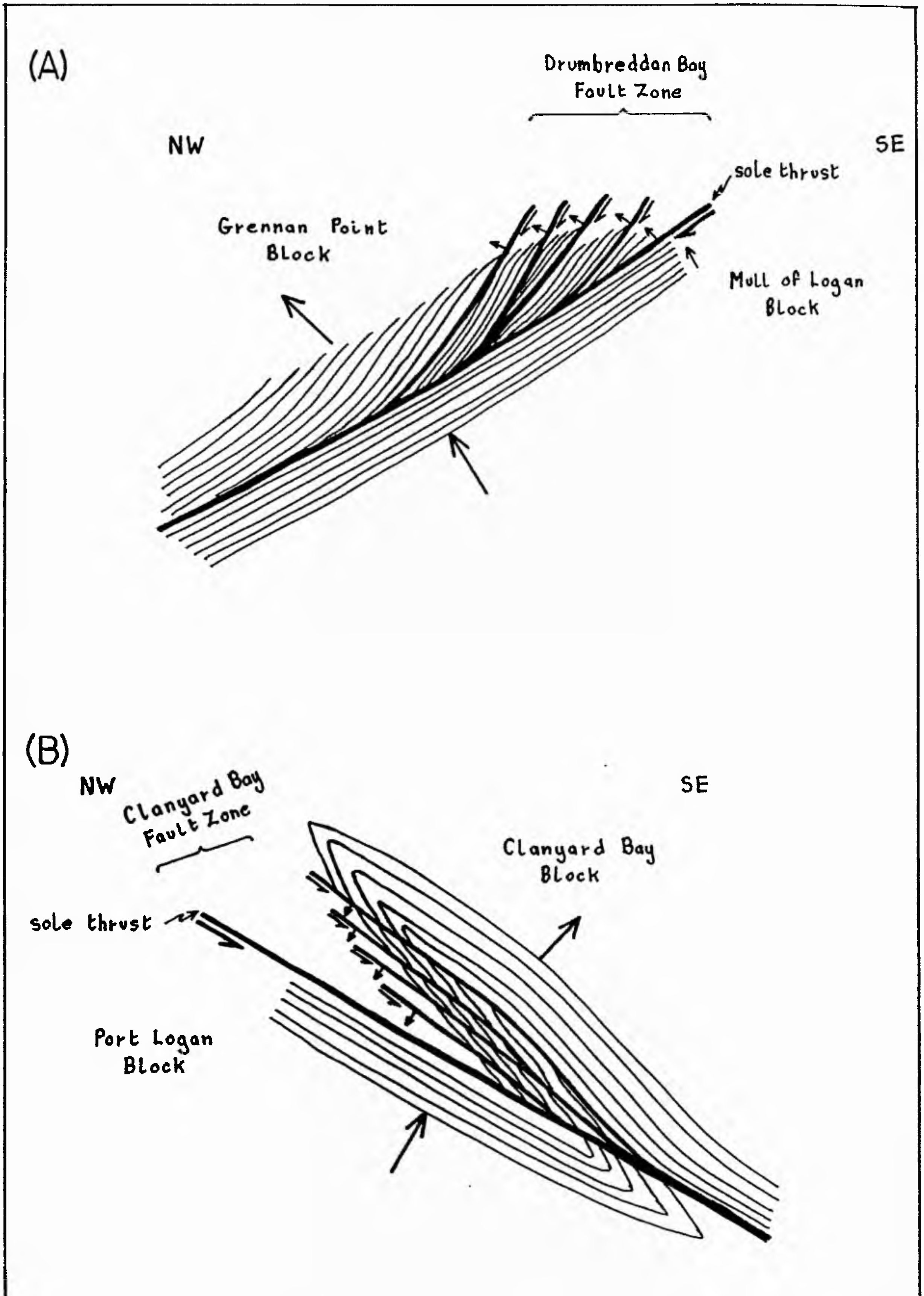


Fig 4.25: Changes in early F_1 thrust style N and S of the Port Logan Bay Fault: (A) N of the fault thrusting precedes major fold development; (B) S of the fault thrusting is later than major fold development. Full arrows indicate younging, half arrows indicate downthrow, solid black indicates Moffat Shale Group decollement

The 40 m (maximum) thick sequence of shales and siltstones have a capacity to trap large volumes of water in pore spaces (up to 80% by volume - Rieke and Chilingarian 1974). This factor is further enhanced by the presence of smectite-rich bentonites whose structure, low permeability and extremely small grain size make them particularly effective water traps. Lithostatic pressure causes overpressuring of the layer which significantly weakens and acts as a décollement horizon along which strain is concentrated. The deformation at this time is essentially wet or ductile and it this characteristic which differentiates early F_1 from late F_1 thrusts. Thrust shortening is more visibly concentrated within the Moffat Shales though probably it also occurred along other weak overpressured horizons within the turbidite succession. However these are now difficult to recognise due to subsequent brittle deformation.

Minor to intermediate folding occurred prior to some thrusting N of the Port Logan Bay Fault as in the Drumbreddan Bay Fault Zone at Grennan Bay (NX07504385) where some early thrusts are developed in the short limbs of SE-vergent fold pairs. Thrusts within the Moffat Shales developed preferentially along bentonite horizons due to their enhanced water trapping capacity and increased slip potential and are seen deforming F_1 folds at Grennan Bay in Plate 4.19. Early thrust planes are best exposed in the Moffat Shales where they are sharp, well defined and unveined.

These early thrusts defined the major tectonic blocks now identified in the Rhinns and slip was concentrated along them. Subsequent deformation rotated the tectonic blocks into their present sub-vertical orientations as shown in the dip sections on Maps A-D. Just as the orientation and sense of vergence of F_1 folds changes across the Port Logan Bay Fault so does the orientation and displacement sense of these early thrusts. N of the fault the thrusts ar sub-vertical or steeply inclined to the SE, the succession is NW-younging yet the tectonic blocks are progressively younger southeastwards necessitating major southeasterly downthrow on the thrusts. S of the fault the thrusts are steeply to moderately inclined to the NW, both the succession and the tectonic blocks are progressively younger southeastwards and the thrusts have a northwesterly downthrow (see Plate 4.20).

The significance of the Port Logan Bay Fault is discussed in Chapter 5. It is not exposed, but shows strong topographic expression as an 800 m wide bay devoid of exposure on both coasts of the Rhinns and joined by a 2.5 km wide isthmus of low-lying land.

Late F_1 - as earlier F_1 thrusting proceeded, mechanical dewatering of the sediment pile was enhanced by the development of fractures, with the thrust zones acting as dewatering conduits. This resulted in strengthening and strain hardening of the consolidating sediment initiating major fold development within the tectonic blocks as the strain is taken up less by the thrusts. This was the first major fold development in the rocks N of the Port Logan Bay Fault, but only accentuated folding S of the fault, where folding initiated prior to thrust development. As dewatering continued and the rock strengthened localised strain hardening led to the locking of folds and the development of thrusts, particularly in the short limbs of F_1 folds. Thrust deformation at this stage is essentially brittle as opposed to the earlier ductile or wet thrusting, the latter becoming progressively more brittle as it develops. The late F_1 thrusts are sub-parallel and have the same displacement sense as the early F_1 thrusts and form the majority of strike faults indicated on Maps A-D. They are particularly well displayed S of the Port Logan Bay Fault where their movement sense is often indicated by the development of duplex structures along the fault plane (see Plate 4.21).

These thrusts are often associated with major zones of brecciation such that sequences throughout the Rhinns can be characterised as one of three zones in the manner of Bachman (1982). Bachman based his zonation on similar stratal disruption in the Coastal Belt of the Franciscan in California. Zone 1 (Plate 4.22(A)) consists of

Plate 4.19: F_1 thrust developed along a bentonite horizon (B) in the Moffat Shale Group (MSG) at Grennan Bay (NX07524382)

Plate 4.20: Northwesterly downthrow on a major F_1 thrust forming the northwestern boundary of the Moffat Shale inlier at the northern end of Clanyard Bay (NX10103809)

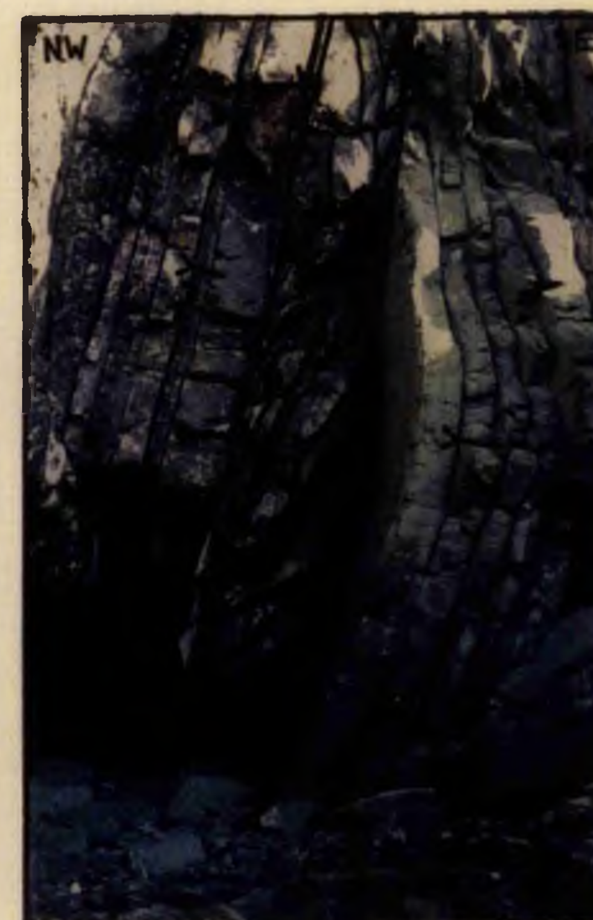


Plate 4.21: Northwesterly downthrow on a major F_1 thrust at Carrickgill Cave (NX13523098) (younging indicated)

saucer shaped or elongate phacoids or boudins set in a sheared mudstone matrix in which bedding cannot be traced laterally. Zone 2 (Plate 4.22(B)) consists of bedding that can be traced laterally, but has undergone pinch and swell, boudinage or extension faulting and commonly has tension joints developed perpendicular to bedding planes. Zone 3 (Plate 4.22(C)) consists of coherently bedded strata that has undergone only minor deformation. Zone 1 is usually developed only in the immediate vicinity of major thrusts as at Slouchgaria (NX09573757) and Ersbals Caves (NX06904625), however Zone 2 is more widespread and is developed extensively in the Clanyard Bay Fault Zone and in the Mull of Galloway Block. Brecciation is indicated in the dip sections on Maps A-D by broken wavy lines. This brecciation is clearly later than the F_1 folding (see Plate 4.23) and is spatially associated with steeply plunging F_1 folds. Thin section examination of the ends of elongate phacoid lenses and boudin necks where strain was greatest indicate that deformation was by ductile flow and intergranular movements. No cataclasis or significant intragranular deformation has occurred. Bachman (1982) in the Franciscan sediments and Needham and Knipe (1986) in similar studies in the Southern Uplands concluded the lack of brittle deformation at a microscopic level indicated the sediments were poorly consolidated at the time of deformation, i.e. soft sediment deformation. However in the Rhinns brecciation is broadly synchronous with S_1 slaty cleavage formation with S_1 developed earlier than brecciation at some places (Plate 4.24) and later than brecciation at others. Wood (in Bachman 1982) found essentially similar microscopic relations in the Gwna olistostrome in Anglesey and it seems more probable the lack of intragranular deformation is due to mesoscopic ductile flow in conditions of low grade metamorphism.

Stringer and Treagus (1980) proposed that steeply plunging F_1 folds were formed by the bodily rotation of 'packets' of folds between strike dislocations. This is a much more attractive proposal than invoking inhomogenous F_1 strains to account

Plate 4.22(A): Zone 1 - elongate phacoids or boudins set in sheared mudstone matrix. Bedding cannot be traced laterally. Slouchgarle (NX09573761)

Plate 4.22(B): Zone 2 - bedding has undergone pinch and swell, boudinage or extensional faulting but can be traced laterally. Tension joints are developed perpendicular to the bedding planes. Slouchgarle (NX09573761)

Plate 4.22(C): Zone 3 - coherently bedded and unbrecciated. Quarry Bay (NX09254035)

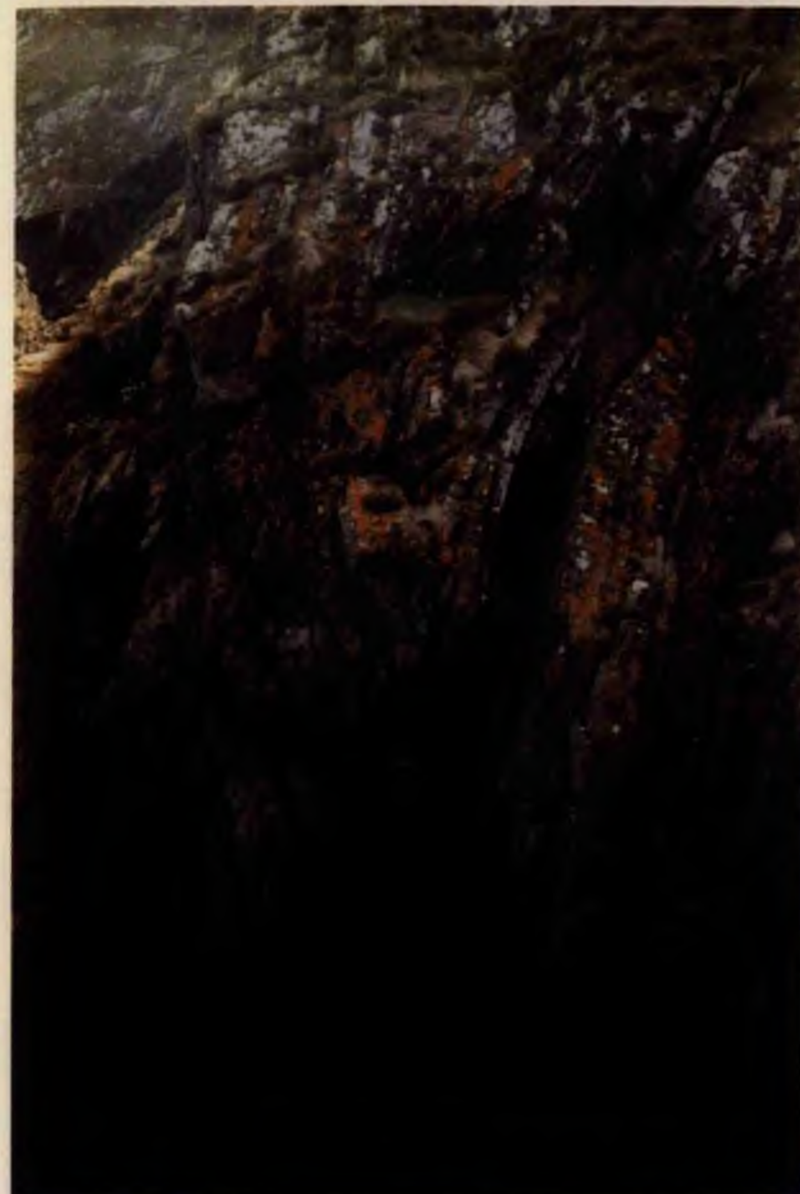


Plate 4.23: F_1 syncline at Slouchgarie 9NX09433752) with one limb Zone 2 brecciated and the other limb Zone 3 coherent

Plate 4.24: Juxtaposed coherently bedded and brecciated zones at Slate Hole (NX09703769). The relative positions of bedding and S_1 cleavage remain unchanged indicating brecciation occurred post-S_1 cleavage formation

for their development as there is no evidence to suggest that they have undergone greater strain than gently plunging F_1 folds. The interlimb angles, fold profiles and cleavage relations (including non-axial planar cleavage relations) are all essentially the same as in gently plunging folds. The essential difference is that the steeply plunging folds are spatially associated with brecciation zones.

The brecciation commonly found in association with the Moffat Shale inliers provides evidence of early F_1 ductile thrusts having undergone later brittle deformation. In the Moffat Shale inlier at the northern end of Clanyard Bay a thrust developed along a bentonite horizon now separating Barren Mudstones and Birkhill Shales has clearly undergone later brittle deformation subsequent to early ductile thrusting. Similarly during thrust imbrication of the Money Head and Float Bay Blocks, Moffat Shales from the base of the former block become incorporated as tectonic lenses in the top of the latter and are exposed in the Strandfoot Fault Zone at Strandfoot. Moore and Byrne (1987) offer a novel hypothesis to explain the development of brecciation zones in association with thrusts. They suggest that thrusts acting as dewatering conduits will strengthen and strain harden earlier than the surrounding sediment as they can dewater faster. A thrust will thus propagate by widening into adjacent overpressured and weaker sediments to form a wide zone of brecciation. This process may help explain the early growth of the thrusts, but at later stages the sediment would be too consolidated for it to operate.

F_2 thrusts - the main response to F_2 deformation was neither F_2 folding nor S_2 crenulation cleavage development, but rather thrusting. The thrusts have a southeastwards translation sense and are well developed throughout the Rhinns, though are much more extensive S of the Port Logan Bay Fault where they are easily identified as their displacement sense is the opposite to that of the F_1 thrusts. N of the Port Logan Bay Fault they are much more difficult to differentiate from F_1 thrusts and F_2 slip reactivation of F_1 thrusts is believed to be common. Where they do occur, as

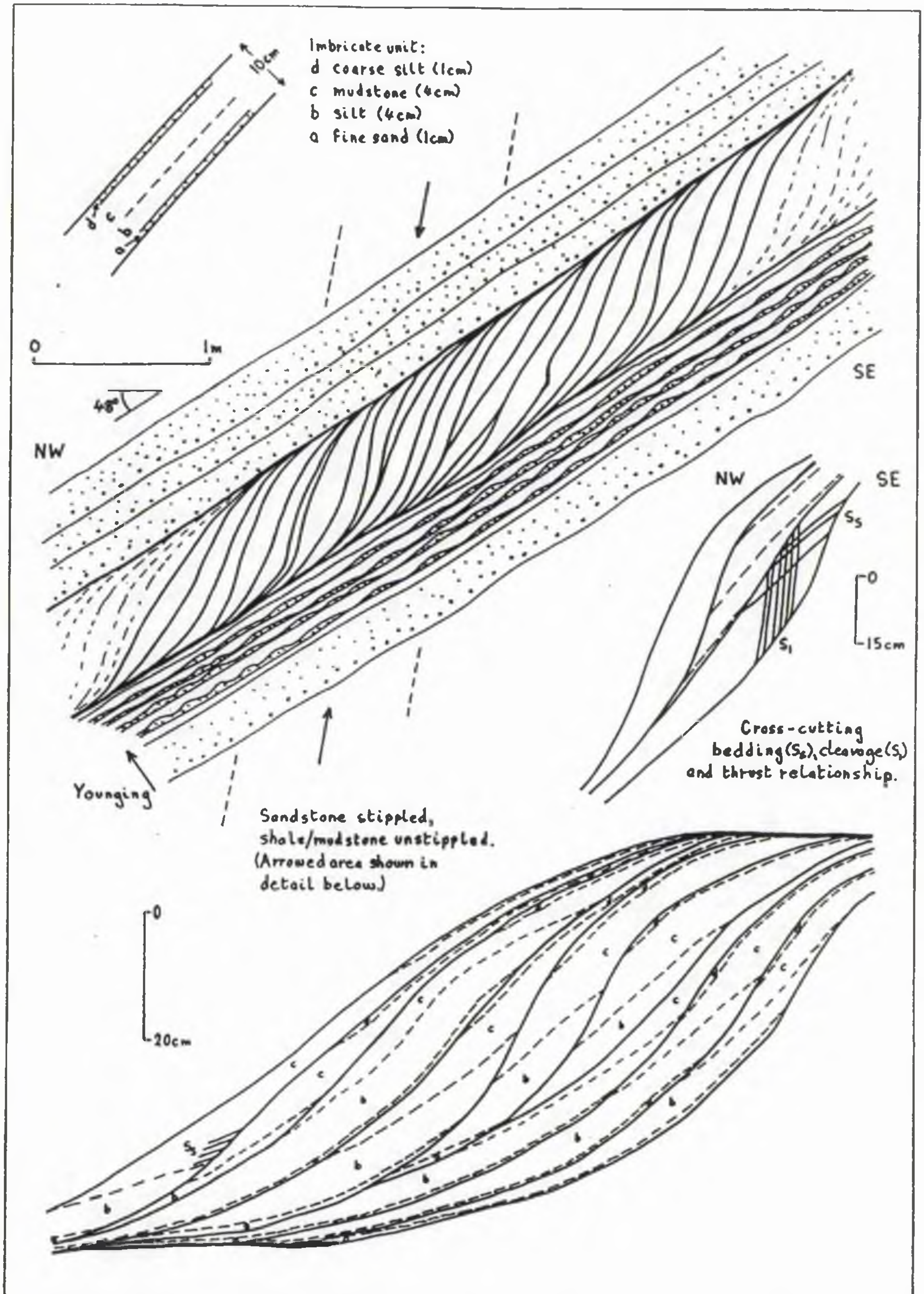


Fig 4.26: F_2 duplex at Carrickamickie Bay (NX12123148).

(A)

(B)

Plates 4.25: F_2 thrusts with southeasterly downthrows at (A) Carrickamickie Bay (NX12133152) and (B) Slate Hole (NX09703769)

Plate 4.26: F_1 fold pair sheared by an F_2 thrust with a southeasterly downthrow at Bullet (NX11563155)

at Slunkrainy (NS05524773), they are moderately to steeply inclined to the NW. S of the Port Logan Bay Fault they have a moderate dip of 35°-55° NW and are developed preferentially parallel to bedding along the short limbs of major NW-verging fold pairs or at a high angle to bedding in the SE-younging long limbs. Their orientation indicates that the tectonic blocks had by this stage undergone major rotation towards the vertical. The thrust style varies from deformation concentrated along a simple bed, producing superbly developed duplex structures as at Carrickamickie Bay (NX12123148) (Plate 4.25(A) and Fig. 4.26), to deformation concentrated along closely spaced thrust sets at a high angle to bedding causing extensive brecciation of the strata (Plate 4.25(B)). In both cases the S_1 cleavage is always deformed. The thrusts are extensively developed and are commonly seen displacing F_1 thrusts with movements of metres to decimetres typical, however some F_2 thrusts clearly effect major translations as at Carrickamickie Bay and 50 m SE of Bullet (NX115531155) (see Plates 4.3(A) and 4.26). F_2 folds are found in areas in which F_2 thrusting is poorly developed and so the two rarely occur together.

Strike-slip reactivation - the Cairngarroch Fault has been identified as the along-strike equivalent of the Orlock Bridge Fault in Ireland, a major sinistral strike-slip fault of late Caledonian age with an inferred displacement in excess of 400 km (Anderson and Oliver 1986). Critical fabric elements, including phyllonite, protomylonite and S-C fabrics, uniquely developed in the Rhinns in a small 2 m x 1 m stack at Calves Hole (NX04644905), correspond with those identified along the trace of the fault in Ireland. This in conjunction with stratigraphic evidence suggesting the presence of a major fault at the southern end of Cairngarroch Bay provides the basis for their correlation. A full description of the outcrop at Cairngarroch Bay and a detailed map of the area are included in their paper (Anderson and Oliver *op. cit.*).

Although the fault fabric is only exposed at Calves Hole in the Rhinns, in this study the Cairngarroch Fault has been traced along-strike using stratigraphic evidence and thin section analysis as detailed in Section 2.2 of Chapter 2. A major finding has been the identification of a splay 1 km SE of the main fault and developed preferentially along a thick Moffat Shale sequence in the headstreams of a tributary of the Cairnweil Burn 200 m NW of Gruzy Glen (NX08704958). Although the deformation in the Moffat Shales is essentially brittle it is the intensity and extent of the deformation which marks out the fault fabric at this outcrop as distinctive. The splay consists of a zone at least 50 m wide intensely and uniformly sheared by anastomosing shear surfaces into mesoscopic microlithons. In thin section the S_1 cleavage is overprinted by pressure solution seams developed within an incipient phyllonitic fabric with rarely formed quartz segregation veins (Plate 4.27). The sense of shear is indeterminate at the outcrop, however the splay does not crop out on the coast 3.5 km SW along-strike suggesting it migrates from the Moffat Shales of the Strandfoot Fault Zone and joins with the main Cairngarroch Fault, as shown on Map A. This would give it a sinistral displacement sense. At its outcrop the splay is clearly cut by a NW-SE trending dextral wrench, with a slip in excess of 250 m, the drag from which has produced an E-W trend in the fault fabric (*cf.* Craig 1982).

Anderson and Oliver (1986) note the systematic decrease in the width of the fault zone of the Orlock Bridge Fault northeastwards from Ireland into Scotland. They postulate that towards the NE progressively higher levels of the fault are exposed and that as the deformation becomes increasingly more brittle possible splay faults develop. This is the first major splay from the fault to be identified. The fault fabrics exposed at Calves Hole and 200 m NW of Gruzy Glen are unique in the Rhinns, however it does not seem unlikely that such a major sinistral movement as that proposed for the Orlock Bridge Fault would cause sinistral, strike-slip reactivation of many of the strike faults.

There is much evidence in the form of displaced dykes, faults and sedimentary sequences, as well as slickencryst development along strike-fault surfaces, indicating

Plate 4.27: Incipient phyllonitic fabric developed in the Cairngarroch Fault splay 200 m NW of Gruzy Glen (NX08854945.). Specimen 84A, ordinary light, x100

Plate 4.28: Banding developed in hornfels adjacent to the contact with the Portencorkrie granite-diorite intrusion at Cuff (NX09373375)

late strike-slip reactivation. Reactivated displacements (or slips) tend to be small however, at less than 50 m. Sinistral displacement predominates over dextral displacement in a ratio of about 2:1. Some of this reactivation is very late as evidenced by the sinistral displacement of a N-S trending wrench at Dove Cove (NX05884740) and the sinistral displacement of a Tertiary dolerite dyke at Daw Point (NX07784158). As σ_1 was orientated sub-parallel to the strike of bedding during kink band formation, it is not unlikely that strike-slip movements took place along some strike faults at this time. The pre-F_2 Tarbet folds and post-F_2 steeply plunging open folds are both thought to be related to strike-slip movements along strike faults, indeed the strike fault at Bendoo (NO09793704), along which many of the latter are found, has a well developed set of slickencrysts indicating sub-horizontal sinistral displacement. No unequivocal evidence of major strike-slips reactivation of strike faults has been found, although this does not preclude its occurrence.

4.4.2 Wrench faults

The strike faults formed during F_1 and F_2 are displaced by a set of conjugate wrenches some of which effect major sinistral translations. N of the port Logan Bay Fault sinistral wrenches outnumber dextral wrenches in a ratio of 3:2 (*cf.* 2:1 Ards Peninsula - Anderson (1987)) and show respective modal trends of 190° and 150° (Fig. 4.27(A)). Despite the predominance of sinistral wrenches the maximum observed displacements are effected by dextral wrenches with slips in excess of 200 m displacing the Strandfoot Fault Zone at Strandfoot (NX05204815) and the Cairngarroch Fault splay at Gruzy Glen (NX08854945). The maximum observed slip along a sinistral wrench is 60 m at Back Drug (NX06834617).

S of the Port Logan Bay Fault sinistral wrenches outnumber dextral wrenches in a ratio of 2:1. The trends of the faults are more varied than N of the fault (Fig. 4.27(B)). The dominant modal trend is 170° for sinistral wrenches and 150° for dextral wrenches, however a subsidiary sinistral modal trend is developed 40°

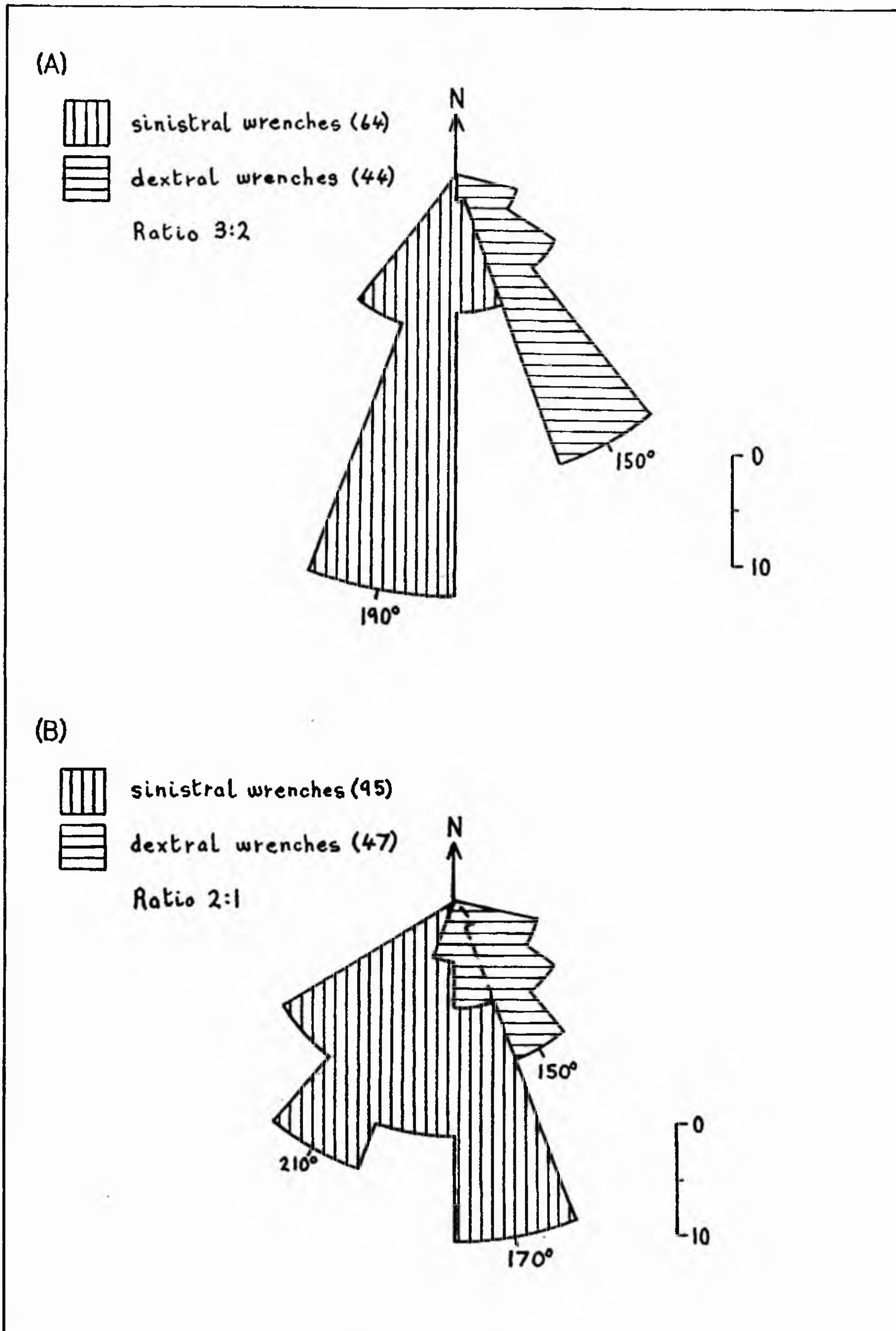


Fig 4.27: Rose diagram of wrench fault trends: (A) N of the Port Logan Bay Fault; and (B) S of the Port Logan Bay Fault.

clockwise of the dominant trend at 210°. This may result from a reorientation of the stress system, although it is more likely a consequence of bifurcation and splay development from sinistral faults, particularly as some of the sinistral wrenches effect major translations. The Nick of Kindram Fault has a sinistral slip in excess of 2.1 km while the Mull Glen Fault has a sinistral slip in excess of 1.6 km. The latter is not exposed but is topographically expressed reaching the coast along the NNW-SSE trending Mull Glen at West Tarbet (NX13883100). By contrast the Nick of Kindram Fault shows little topographic expression but is well exposed on the coast at (NX10903208), where it undergoes a remarkable 40° change in orientation from trending 005°-185° to 145°-325°. Minor, steep plunging fault bend folds and accommodation shears occur at the bend. The fault is exposed in a 10 m wide gully, is sub-vertical and shows many features typical of wrench faults in the Rhinns. Deformation is very brittle with a 10 m wide fault breccia developed and locally a fault gouge. Irregular quartz veins cut the breccia and are themselves brecciated in places. Deformation is concentrated within this zone and minor fault drag affects bedding adjacent to it. Iron staining from a possible Permian cover has imparted a strong red colour to the fault zone and surrounding rock. Similar features are found on a lesser cm-scale along many more minor wrench faults.

The wrench trends (Fig. 4.27) indicate that σ_1 had a Caledonoid alignment of approximately 170°-350° N of the Port Logan Bay Fault and 160°-340° S of it during wrench formation

4.4.3. Minor faults

Two sets of minor faults affected the succession once the tectonic blocks had been rotated into sub-vertical orientation. NW-vergent recumbent thrusts formed prior to the development of wrench faulting and late normal faulting occurred after wrench faulting.

NW-vergent recumbent thrusts - these thrusts are sub-horizontal or may be gently inclined at up to 30° both to the NW and SE. They cut bedding at a high angle and have a consistent northwestwards sense of translation. The thrusts often form in the hinges of post-F_2 NW-vergent recumbent folds, with which they are closely associated. Irregular quartz veining is commonly developed along the thrust planes. The displacement along the thrusts is of the order of a few metres. These thrusts are found throughout the Rhinns, but like the NW-vergent recumbent folds are best developed in the Portayew, Cairngarroch and Cardrain Blocks.

Late normal faults - late normal faults are sporadically developed throughout the Rhinns providing evidence of late extension. They are inclined at moderate to steep angles to the NW and have a northwesterly downthrow. Bedding is typically extensively brecciated immediately adjacent to the fault plane, although the throw is usually only a few metres. These faults were the last regional fault set to develop and are seen to displace all other fault sets. They are particularly well exposed on the coast between Dungarroch (NX11103198) and Dunan (NX11703148).

4.5 IGNEOUS INTRUSIONS AND METAMORPHISM

No comprehensive examination of the numerous igneous intrusions or metamorphism in the Rhinns has been carried out in this study, though general comments, particularly on their relationship with the deformation, are provided here.

4.5.1 Igneous intrusions

All the igneous intrusions in the Rhinns have been categorised and are indicated on Maps A-D. Dykes are abundant while a number of much larger intrusions are developed in Cairngarroch Bay. A major, 5 km^2 pluton is emplaced in the Clanyard Bay Block at Portencorkrie. Identifications are based on mesoscopic examination and more rarely thin section analysis. The vast bulk of intrusions are Caledonian in age and belong to a calc-alkaline magmatic suite in which acidic, intermediate and lamprophyric varieties are all developed.

The Portencorkrie pluton has an outer rim of pyroxene, hornblende and mica-rich diorite surrounding an inner core of adamellite (Holgate 1943). At Cairngarroch Bay a 100 m wide linear tract of micro-monzogranite follows the trace of the Cairngarroch Fault inland for over 1 km. Between 200 m and 800 m NW of the micro-monzogranite, a second intrusive complex, consisting of diorite, quartz-monzodiorite and monzogranite, is present and was emplaced in the order given. These intrusions are developed in the roof zone of a much larger intrusive mass whose undulatory contact is visible in the 125 m high cliffs backing the bay. The presence of hornfels for 500 m NW from the intrusion suggests this roof zone is inclined gently NW. Similarly the development of a 1 km wide hornfelsed belt extending NE from Cairngarroch Bay sub-parallel to the Cairngarroch Fault indicates the presence of a large, linear intrusion along or parallel to the fault trace. The negligable disturbance of the country rock surrounding the Portencorkrie pluton and Cairngarroch intrusions suggests emplacement was by stoping and assimilation.

After an initial early pulse of lamprophyre intrusion, early formed dykes are typically pale, aphyric felsites with a micro-monzogranitic composition, while later formed dykes become increasingly more mafic. With increasing mafic content the dykes develop a porphyritic texture containing euhedral plagioclase and mafic phenocrysts in what are compositionally micro-monzonites to micro-diorites. The youngest Caledonian dykes, like the oldest, are lamprophyres and in composition are vogesites, spessartites and diopside minettes, the latter occurring well NW of the northwestern limit stated by Read (1926) for their development.

A small number of amygdaloidal and undersaturated analcite bearing olivine dolerites are present in the Rhinns and as similar alkaline, analcite bearing dolerites occur in Permian rocks near Stranraer, are believed to the Tertiary, rather than Carboniferous, in age. Their general WNW-ESE trend (Fig. 4.28) suggests they belong to the Mull swarm. At Carrickacundie (NX34021435), a 50 m wide volcanic breccia in which sandstone and shale clasts are enclosed in a matrix with monzonitic, carbonate and sedimentary components has been identified in this study (Map D). It is of unknown age but may be analogous with late Caledonian sub-volcanic vents recently described from Kirkcudbright (Rock *et al* 1986). Modal Caledonian dyke trends in the Rhinns are indicated in Fig. 4.28 and are sub-parallel to those of F_1 and F_2 strike faults and later wrench faults.

Early formed lamprophyres are rare occurring at only a few localities, i.e. Slate Heugh Bay (NX09253960), Calliedown Bay (NX09703845) and Iron Slunk (NX06924408). They are distinctive in that they are post-F_1 folding yet show the S_1 cleavage and have a system of tension joints developed perpendicular to their walls. They are equivalent to the 'Older Series' lamprophyres identified by Reynolds (1931) in the Ards Peninsula. The lamprophyres are developed sub-parallel to bedding and are best exposed in Calliedown Bay where they intrude a sequence brecciated by late F_1 strike faults. Some of the dykes have clearly been involved in the shearing and show minor brecciation, while others appear to cross-cut the brecciation. It is inferred they were intruded in pulses during the later stages of strike fault development, though earlier than S_1 cleavage formation. The cleavage is sub-vertical and is most noticeable when developed oblique to the dyke walls. The obliquity is such that cleavage is clockwise of the dykes in plan view (Fig. 4.29). The cleavage occurs as a penetrative foliation defined by the sub-parallel alignment of mafic phenocrysts, typically pseudomorphed by chlorite. The phenocrysts are set in a groundmass of lath shaped mafic minerals, pseudomorphed by chlorite and aligned sub-parallel to the phenocrysts. The tension joints are closely spaced, at less than 20 cm, and are developed perpendicular to the cleavage (Fig. 4.29). The evidence suggests the dykes were intruded during periods of relative tension between periods of late F_1 compression. Renewed compression led to the development of S_1 cleavage prior to consolidation of the dyke and tension joints formed post-consolidation. On the peninsula 100 m SE of Bullet (NX11603152) a lamprophyre dyke has ben sheared

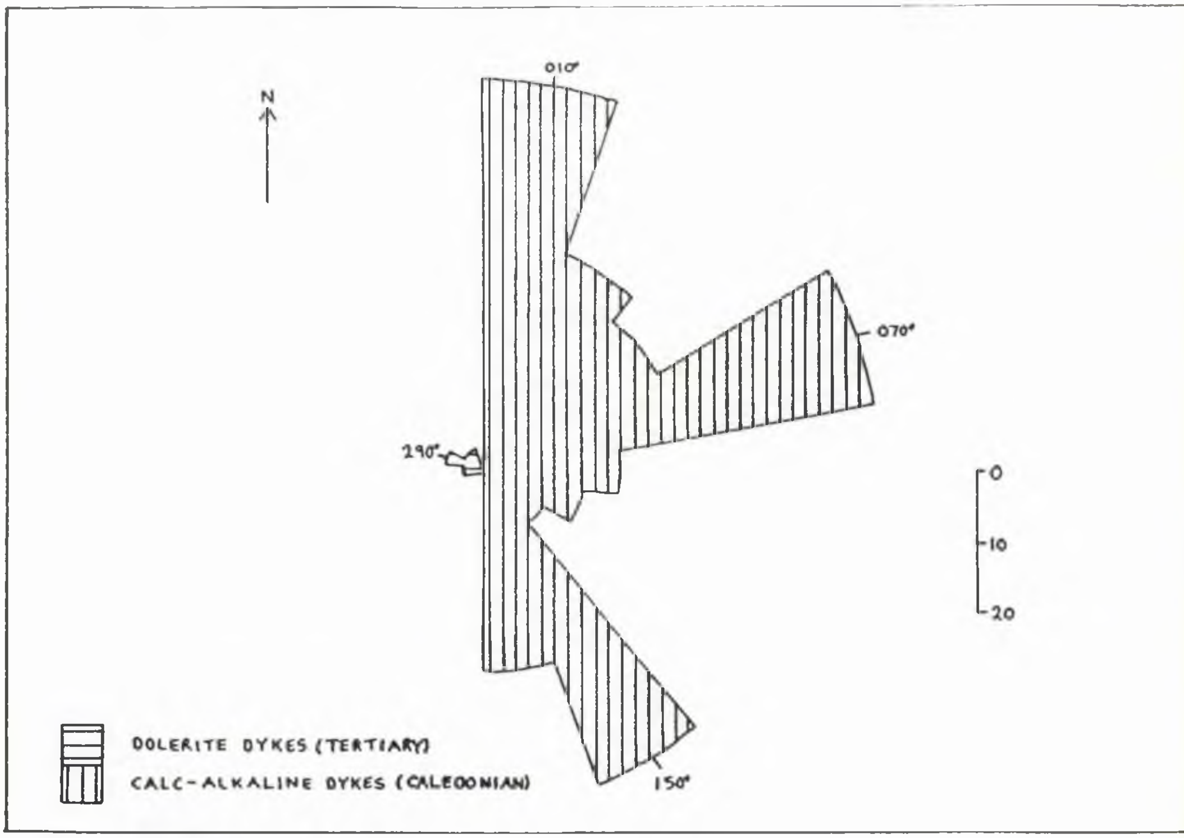


Fig 4.28: Rose diagram of dyke trends.

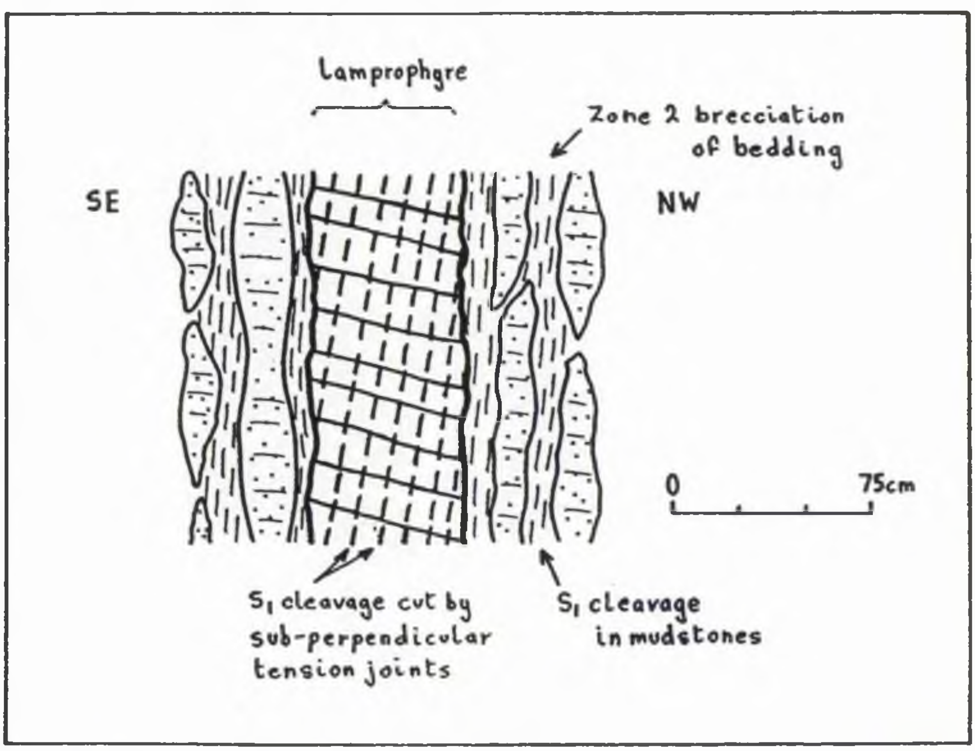


Fig 4.29: S_1 cleavage in a lamprophyre dyke at Calliedown Bay (NX09703845).

and extended by an F_2 strike fault, but does not appear to contain the S_1 cleavage. This suggests lamprophyre intrusion continued during periods of tension after the S_1 cleavage had formed.

Apart from the early formed lamprophyres, all other dykes cut across F_1 and F_2 structures and are believed later than the Tarbet folds and steeply plunging open folds. NW-vergent recumbent folds are the only folds seen to bend, or in most cases shear, pre-existing dykes (mostly acidic in composition). The intrusions developed along the Cairngarroch Fault are clearly later than its initiation, however in places they have undergone brittle deformation in the fault zone indicating movement occurred after their emplacement. Movement along the Nick of Kindram Fault was essentially complete prior to emplacement of the Portencorkrie pluton as the metamorphic aureole surrounding it does not appear displaced. The dyke trends shown in Fig. 4.28 indicate most intrusions occurred after wrench formation. Most of the dykes displaced by initial wrench movements are acidic in composition. Dykes filling the wrench faults and dykes displaced by later reactivations include acidic, intermediate and lamprophyric varieties. Evidence of minor wrench fault reactivation is widespread in the form of brecciation of the dyke margins along fault planes, as at Fox Rattle (NX0464878). More rarely it is evidenced through reversed displacement senses, as at Garrahaspin (NX05024817), where the dextral wrench displacing the Strandfoot Fault Zone by at least 200 m is also seen to sinistrally displace cross-cutting micro-monzonite and micro-syenite dykes by 25 m. The age relations of these minor wrench movements are difficult to assess. The sinistral displacement of wrench faults along reactivated strike faults, as at Dove Cave (NX05894740), is of Tertiary age, as evidenced by the sinistral displacement of a dolerite dyke along a strike fault 100 m ESE of Daw Point (NX07784158).

4.5.2 Metamorphism

Regional metamorphism - as demonstrated in Chapter 3 (Section 3.2) the greywackes of the Rhinns are highly quartzose with a corresponding lack of chemically reactive clastic mineral and lithic fragments. As a result they do not show the effects of metamorphic recrystallisation that are seen in more basic compositions. That metamorphic recrystallisation has taken place is evidenced by the high matrix content which ranges from 10% to 54% (Appendix 3). Hubert (1964) has shown that modern deep-sea sands contain less than 12% matrix, while Keunen (1966) demonstrated experimentally that turbidites contain less than 10% matrix when deposited. The high matrix content in the Rhinns is the result of chemical breakdown of unstable Ca, Mg and Fe bearing minerals producing new mineral growth in the matrix. A cleavage is developed locally (see Section 4.3.1). Thin section analysis and X-ray diffraction examination show that quartz, chlorite, illite and carbonate are all present in the matrix, with the higher matrix values caused by enrichment in carbonate.

Plagioclase feldspars are invariably albite, where composition is determinable, suggesting they have been albitised (see Oliver and Leggett 1980). They usually have a turbid appearance due to alteration, though are more rarely replaced by sericite or carbonate. Initially replacement is selective along cleavage planes, but in the more carbonate-rich formations complete pseudomorphing by carbonate is common. At least two sets of quartz and calcite veins are present with calcite commonly replacing quartz within veins. Sulphide mineralisation in the form of pyrite development is sometimes associated with the veining and rare plagioclase crystals occur locally within a few of the veins.

Prehnite is developed extensively in two thin sections taken from the feromagnesian mineral rich Money Head Formation where it selectively replaces plagioclase along cleavage planes and occurs as irregular, anhedral crystalline aggregates in andesitic and more basic fragments. It is more rarely developed as radiating sheaves within a few of the shale clasts. Prehnite veins have not been identified in the present study area, but were found in association with pumpellyite 5 km to the NW in a quarry at Portpatrick (NX00105380) in the Northern Belt (see also Oliver and Leggett 1980). The veins occur within an area of Zone 2 brecciation and although they cut the S_1 cleavage they appear folded in the more ductile shales indicating the zone was still active during their formation. The prehnite-pumpellyite veins are themselves cut by later quartz veins. These features indicate that metamorphism was synchronous with very late F_1 or F_2 deformation.

A sample traverse of the greywackes and shales in the Rhinns undertaken by Oliver *et al* (1984) as part of a regional study of illite crystallinity in the Southern Uplands indicated anchizone conditions equivalent to prehnite-pumpellyite facies metamorphism. This confirmed the findings of an earlier regional study of the metamorphic index minerals and mineral chemistry in the Southern Uplands (Oliver and Leggett 1980). Watson (1976) measured the reflectivity of a graptolite from the Moffat Shales at Clanyard Bay producing a value of 3.3. This suggested a semi-anthracite rank, again consistent with prehnite-pumpellyite facies metamorphism. Oliver *et al* (1984) estimated the temperature of metamorphism affecting the Central Belt of the Southern Uplands at about 350°C.

Contact metamorphism - the petrographic features of the metamorphic aureole surrounding the Portencorkrie pluton were described by Holgate (1943), though the aureole is much wider, at approximately 1.5 km (Maps C and D), than he states. The aureole is not significantly displaced by the Nick of Kindram Fault (*cf.* Holgate *op. cit.*) indicating pluton emplacement occurred later than major sinistral wrench movement. The lithologies within the aureole and increasingly towards the pluton are hornfelsed, having a dark, hardened appearance and a splintery, conchoidal fracture.

The aureole consists of a broad outer zone (*c.*1200 m) of albite-epidote hornfels facies metamorphism and a narrow inner zone (*c.* 300 m) of hornblende hornfels facies metamorphism. Incipient metamorphism at the outer edges of the aureole involves recrystallisation of the greywacke matrix to a fine grained quartz aggregate. Towards the pluton biotite and rare muscovite are produced in the matrix and in places align sub-parallel to the pre-existing S_1 foliation. The clast boundaries become diffuse and have recystallised internally with quartz polygonised, feldspars altered and some lithic fragments having developed biotite or chlorite. Actinolite is developed sporadically as radiating sheaves and a few late diopside veins cut the hornfels. Approaching the margin actinolite and chlorite are absent and the rock becomes totally reconstituted to a quartz-biotite hornfels with rare plagioclase and cordierite and a dominant granoblastic-polygonal texture. For distances of up to 50 m from the margin cordierite porphyroblasts are well developed though often pseudomorphed by pinite and the rock is defined as a quartz-biotite-plagioclase-cordierite hornfels.

Both exposed coastal contacts of the pluton at Laggantalluch Head (NX08443636) to the N and Cuff (NS09373375) to the S are sharp, sub-vertical faults and an irregular banding is developed in the country rock adjacent to the latter. This banding is in two sizes with broad, light coloured, course units alternating with dark coloured, fine units on a cm-m scale. Both dark and light units possess an internal colour banding on a mm-cm scale (Plate 4.28). The colour variation is caused by distinct changes in the proportion of quartz to biotite, with increasing mica content producing darker colours. The broader banding is believed to represent the relict interbedding of sandstone and shale units. In one of the broad dark bands a relict S_1 cleavage is discernible and is clearly overprinted by the contact metamorphism.

The 1 km wide linear aureole associated with the intrusions in Cairngarroch Bay and their unexposed along-strike equivalents (Map A), shows only incipient metamorphism over much of its outcrop. This metamorphism causes recrystallisation of the matrix to a fine grained quartz aggregate and polygonisation of the quartz clasts. The metamorphism is most intense adjacent to the contact of the intrusion in Cairngarroch Bay and at various localities along-strike, e.g. Cairngarroch Quarry

(NX05934965) and Ballochalee Quarry (NX09005060). At these localities it forms a quartz-biotite-muscovite hornfels, though recrystallisation is never complete. The metamorphism probably belongs to the albite-epidote hornfels facies, though whether hornblende hornfels facies metamorphism is in part developed is equivocal. The intensity of metamorphism decreases northwards from the Cairngarroch Bay intrusions, while the rocks S of the Cairngarroch Fault at Calves Hole are not contact metamorphased. By contrast 4.5 km NE along-strike at Ballochalee Quarry the aureole is most intensely metamorphosed towards its centre and decreases in intensity across-strike both to the NW and SE. This difference may result from displacement of the aureole along the fault at Calves Hole.

Contact metamorphism by dykes is not common and where present extends for only a few centimetres from the contact.

4.6 HISTORY OF DEFORMATION

The deformation history of the Rhinns is shown in Table 4.3. It represents a transition from early ductile to late brittle deformation propagated in a Caledonian stress regime and punctuated by intervals of dyke intrusion. The chronological sequence is built up from observed field relations. No unequivocal evidence exists as to the relative ages of the steeply plunging open folds and NW-vergent recumbent folds. The kink bands and normal faults are believed to be Caledonian in age by analogy with similar structures dated by cross-cutting relations with Caledonian dykes in the Ards Peninsula (Anderson and Cameron 1979) and northern Rhinns (Kelling 1961). Each discrete deformation phase and the style, symmetry and orientation of the structures produced, relates to changes in orientation of the principle stress axes relative to layering. Much of this was achieved by the progressive rotation during deformation of early formed structures into the sub-vertical attitudes they now occupy. This rotation was essentially complete prior to the initiation of wrench faulting.

Deformation Stage	Fold Phase	Cleavage	Faults	Vergence	Igenous Intrusions	Age
D_1	F_1		Early D_1 thrusts (Primarily developed as a decollement along Moffat Shales)	N ⇐ PLBF ⇒ S SE NW		
	(Local rotation into steep plunges)	S_1	Late D_1 thrusts	SE NW		
	Regional imposition of sinistral shear either during or late in D_1 deformation caused clockwise rotation of S_1 cleavage, sinistral slip along strike faults (rotated thrusts), the possible initiation of sinistral movement along the Cairngarroch Fault and formation of the Tarbet folds.				Early lamprophyres	
D_2	F_2	S_2	D_2 thrusts	SE		
Post-D_2	Steeply-plunging open folds	Localised crenulation found mostly in hinges	Slip reactivation of strike faults (rotated thrusts)	Sinistral and less commonly dextral	Portencorkrie granite-diorite pluton and Cairngarroch Bay intrusives; main phase of dyke intrusion - mafic content increases with decreasing age (ie. early felsites to late lamprophyres); volcanic breccia - Carrickacundie	Caledonian
	NW-vergent recumbent folds	Rare crenulation	NW-vergent recumbent thrusts	NW		
			Wrench faults	(slip: sinistral and less commonly dextral)		
	Kink bands		Slip reactivation of (some) wrenches with an opposite slip sense to original movement	Dextral and rarely sinistral	?	
			Nomal faults	(Throw: down to NW and rarely to SE)		
			Sinistral slip reactivation of of strike faults (rotated thrusts)		Olivine dolerites	Tertiary

PLBF: Port Logan Bay Fault

TABLE 4.3 - DEFORMATION HISTORY OF THE RHINNS

4.7 REGIONAL CORRELATION

The major structure of the Rhinns is markedly different from that described elsewhere in the Southern Uplands in that the vergence of D_1 deformation changes across the Port Logan Bay Fault and to the S of the fault is the opposite to that throughout the rest of the region. The reasons for this geometry and its consequences for the tectonic modelling of the area are presented in full in Chapter 5. Other aspects of D_1 deformation such as the clockwise transection of F_1 hinges by S_1 cleavage and the localised development of steeply plunging F_1 folds are more typical and are documented extensively in the Southern Uplands literature, e.g. Stringer and Treagus (1980), Cameron (1981) Leggett *et al* (1982), Anderson (1987). Similarly the D_2 deformation, NW-vergent recumbent folds and thrusts, wrench faults and kink bands have all been recognised regionally, e.g. Walton (1965), Anderson (1969), McKerrow *et al* (1977) Knipe and Needham (1986), as have the two main intrusive phases, e.g. Rock *et al* (1986) Barnes *et al* (1987) - (Appendix 2). By contrast the fault related fold phases, i.e. Tarbet folds and steeply plunging open folds, do not occur SW of the Rhinns in Ireland (Anderson - pers. comm.) and have not been identified to the NW along-strike in the Southern Uplands. Observations by the author at various Southern Uplands localities suggest they are present and have been variously fitted into the deformation histories of other workers. Outside the Rhinns late normal faulting has been recorded regionally in the Central Belt by McKerrow *et al* (1977) and locally in the northern Rhinns (Kelling 1961), Wigtown Peninsula (Rust 1965a) and SE of Hawick (Warren 1964). A detailed structural correlation with the Ards Peninsula and Wigtown Peninsula immediately along-strike from the Rhinns to the SW and NE respectively has been carried out in conjunction with Dr. T.B. Anderson and Dr. R.P. Barnes and the results are presented in Appendix 2.

The structure of the Rhinns is highly varied and displays many features previously unrecorded in the Southern Uplands. The anomalous vergence of D_1

structure S of the Port Logan Bay Fault has proved of great value in elucidating the processes at work during D_1 and D_2 deformation and in differentiating between them as the vergence of the D_1 and D_2 structures is opposing in this area. The Rhinns provides probably the best exposed dip section through the Southern Uplands Central Belt and is strategically positioned within the Southern Uplands-Down-Longford terrane bridging the gap in exposure between the bulk of the Scottish outcrop to the NE and Ireland. Ironically it also has one of the most unusual structural configurations in the terrane as a whole, though as evidenced in the succeeding chapter, perhaps it is indicative of a greater structural diversity than has previously been recognised in the terrane.

CHAPTER FIVE : PLATE-TECTONIC SYNTHESIS

5.1 INTRODUCTION

Plate-tectonic interpretations of the British Caledonides all agree that the Southern Uplands-Down-Longford terrane is an imbricate thrust stack formed during Caledonian deformation along the southeastern margin of the Laurentian continental plate. Disagreements exist as to the tectonic setting of deposition and the timing of deformation (see McKerrow (1987) and related thematic set of papers for discussion).

Following the advent of plate theory in the Caledonides (Dewey 1969) the terrane was interpreted as an accretionary prism formed by underthrusting of pelagic and clastic sediments deposited on the floor of the Iapetus Ocean and within a trench above a NW-dipping subduction zone (Mitchell and McKerrow 1975, McKerrow *et al* 1977, Leggett *et al* 1979). Deformation was, by definition, diachronous over an approximate 30 million year period extending from the Caradoc to the Wenlock. This accretionary forearc interpretation has held sway and been elaborated upon throughout most of the 1980's with only a few dissenters, notably Moseley (1977, 1978) and Morris (1979).

More recently two alternative tectonic hypotheses have been proposed. The first of these envisages NW subduction of Iapetus oceanic crust and subsequent formation of a volcanic island arc along the Northern Belt/Central Belt boundary with deposition of the Northern Belt sediments in a marginal basin (Murphy and Hutton 1986, Hutton and Murphy 1987, Morris 1987). Impingement of continental crust from the SE on the volcanic arc at the end of the Ordovician caused subduction to cease, the marginal basin to deform and an essentially symmetrical successor basin to develop to the SE. This successor basin gradually filled with sediment throughout the Llandovery and Wenlock and climactically deformed due to terminal collision of Cadomia and Laurentia at the end of the Silurian or early Devonian to form the Central and Southern Belts. Major sinistral strike-slip movement along the Orlock Bridge Fault (Anderson and Oliver 1986) during collision removed the remnant arc between the Northern and Central Belt.

By contrast Stone *et al* (1986) envisage NW subduction of Iapetus Ocean to the SE of the Southern Uplands with deposition of all pre-*M. griestoniensis* Zone sediments in a marginal basin located NW of a volcanic arc. Oblique collision of the two continental margins to the SE in the *C. cyphus* Zone led to underthrusting by the southeastern margin and the development of a SE-propagating thrust stack in the marginal basin which subsequently narrowed. Complete closure of the basin was accomplished by *M. griestoniensis* Zone and was succeeded by ramping of the thrust stack over the remnant arc to the SE. Deposition of the Hawick Group and Wenlock rocks was effected in a foreland basin ahead of the rising thrust stack. Deformation was thus diachronous from the *C. cyphus* Zone onwards.

In this concluding chapter the stratigraphy, sedimentology and more particularly the structure of the Rhinns, and adjacent areas where relevant, will be examined in relation to these three models in an attempt to determine more precisely a plate-tectonic scenario for Southern Uplands-Down-Longford terrane.

5.2 TECTONIC IMPLICATIONS OF THE STRATIGRAPHY AND SEDIMENTOLOGY

The tectonostratigraphy of the Rhinns, as demonstrated in Fig. 2.2 and discussed in Chapter 2, in which the Moffat Shale Group is tectonically repeated across-strike along with the overlying turbidite formations, is clearly that of an imbricate thrust stack. However the clear ordering of the tectonostratigraphy from the oldest successions in the NW to the youngest in the SE, as demonstrated both in the Rhinns and throughout the Southern Uplands, imparts a distinct asymmetry to the imbrication unlike most thrust belts. This asymmetry is essentially as expected in an accretionary prism in which clastic input is from one margin only and deposition and deformation are synchronous and diachronous (Seely *et al* 1974). In the successor basin model (Murphy and Hutton 1986) climactic end-Caledonian thrusting would be expected to repeat the same stratigraphy, as in most thrust belts, it is presumptious of this model to propose that only the basal section of the sedimentary succession would be involved in the thrusting. The diachronous thrust deformation implicit in the marginal basin model (Stone *et al* 1987) is more suited to the stratigraphy encountered. However as the basin is symmetrical, at some stage it would be expected that the stratigraphic age of the imbricate blocks would start to increase southeastwards and this is not the case. More significantly, the foreland basin model (Stone *et al* 1987), in which it is proposed the Hawick Group (late Llandovery) and Wenlock rocks were deposited, is invalidated by its failure to account for the presence of Ashgill to Llandovery age Moffat Shales stratigraphically underlying the Hawick Group at Tieveshilly in the Ards Peninsula (see Anderson, and Fig. 5, in Barnes *et al* 1987, Anderson and Rickards - in prep.).

The petrographic studies carried out in the Rhinns (Chapter 3 - Section 3.2) prove somewhat ambiguous though in general they indicate a recycled orogen provenance with a subduction complex source. Two distinct clusters of clast composition were identified. In one subsidiary input was from a magmatic arc, while the other had a more mature input from a collision orogen or foreland uplift source. Two distinct source areas are inferred from these clusters. The petrography is compatible with all three tectonic models, though it is least suited to the successor basin model where more magmatic-arc detritus would be expected. In this model a progression from an undissected magmatic arc to a dissected magmatic arc with increasing subsidiary input of recycled orogen material should be evident with decreasing age. Similarly more magmatic arc detritus might be expected in the marginal basin model, though this model is attractive in supplying two contrasting source areas for the detritus. The relevant palaeocurrent directions in the Rhinns are axial, (i.e. NE-SW trending) and so fail to differentiate the relevant source localities. The foreland basin model, in which it is proposed the Hawick Group and Wenlock rocks were deposited, is also consistent with the observed petrography, the high detrital carbonate content and increased maturity being characteristic features of many foreland basins (see Dickinson and Suczek 1979). However the overall trend in the Rhinns and throughout the Southern Uplands, from a magmatic arc rich provenance in the NW to a more mature, quartzose, carbonate-rich provenance in the SE, can be accommodated in all three models and does not particularly favour any.

The facies analysis in Sections 3.4.2 and 3.7 of Chapter 3, indicates that extensive outboard pelagic sedimentation to the SE over a 35 million year period was catastrophically replaced inboard by a contemporaneous and highly proximal prograding turbidite sequence to the NW. This provides strong evidence that deposition took place in a trench environment above an active NW-dipping subduction zone. The unusual association of Facies D, G and E, so prevalent in the Rhinns, and the absence of significant clastic outer fan or basin plain deposits are characteristic features of axial channel deposition in a subduction zone trench (see Underwood and Bachman 1982). Both successor and marginal basins would be unlikely to provide sites for pelagic sedimentation to occur over a 35 million year period. A large oceanic basin remote from a clastic source is a much more likely setting. Similarly in both the successor and marginal basin models, deposition might be expected to take place in relatively large, unconfined submarine fans prograding across the basin floor and giving rise to extensive outer fan deposition above the pelagic, basin plain, Moffat Shale deposits. This progradational sequence is not found in the Southern Uplands. Even more significant is the failure of the marginal basin model to successfully account for the presence of outboard pelagic deposition contemporaneous with inboard clastic deposition in what is essentially a symmetrical basin. Sediment bypass is required on one margin and not the other. Only the Port Logan Formation and Mull of Galloway Formation in the Rhinns provide evidence of deposition in large, unconfined submarine fans. Such fans could only form above a subduction zone if the trench were overtopped.

The Rhinns palaeocurrent analyses (see Chapter 3 - Sections 3.5 and 3.7) in conjunction with palaeocurrent data from throughout the Southern Uplands indicate flow was dominantly axial from the NE or lateral from the NW. Until this study, southeasterly derived palaeocurrents were confined to a statistically small data set in the Northern Belt (see Morris 1987, Stone *et al* 1987, also Leggett 1987) and were virtually unknown from the Central and Southern Belts. The scant palaeocurrent evidence of symmetrical input into the basin of deposition is a major flaw in the marginal basin model (Northern Belt only) of Morris (1987) and the marginal basin and foreland basin model of Stone *et al* (1987). The aysmmetric input and axial flow indicated is as expected in a trench forearc environment and conceivably also fits the successor basin model of Murphy and Hutton (1986). A major new factor is the clear southeasterly derivation indicated by the two youngest (post-*M. sedgwicki* Zone) formations in the Rhinns, the Clanyard Bay Formation (uppermost Gala Group) and the Mull of Galloway Formation (Hawick Group). Apart from a few southeasterly derived palaeocurrents in the Wigtown Peninsula (see Rust 1965b) the along-strike equivalents of these formations have a dominant axial flow both from the NE and SW or are derived laterally from the NW (see Warren 1963). Interestingly the distinctive detrital carbonate-rich and mature composition of the Hawick Group remains unaffected by changes in flow direction suggesting derivation is from the same or similar source areas. In the Southern Belt (Kemp 1987) has demonstrated that palaeoflow remains either axial or lateral from the NW indicating that the southeasterly derivation evident in the Rhinns is a localised anomaly both in time and space (see later - Section 5.7).

The stratigraphic and sedimentological evidence presented above clearly lend most support to the accretionary prism model (McKerrow *et al* 1977, Leggett *et al* 1979). Major weaknesses are identified in both the successor basin model (Murphy and Hutton 1986) and to a greater degree the marginal basin/foreland basin model (Stone *et al* 1987). However the latter model is innovative in recognising the fundamental importance of the Gala Group/Hawick Group boundary and offering an explanation for the change in sedimentation across it.

The calc-alkaline lamprophyre dyke suite identified in the Rhinns (Chapter 4 - Section 4.5.1), and throughout the Southern Uplands, presents a number of paradoxes for the accretionary-prism-model (see Rock *et al* 1986). Chief among these are 'the dykes imply substantial extension at a high angle to the assumed (Iapetus) suture' and 'the lamprophyres are too K-rich, and of excessively deep mantle source, for their close proximity to the assumed suture trace' (Rock *et al, op. cit.*, p.505). No new evidence or explanation is offered here to account for these observations save to point out an important area of research, i.e. dyke emplacement, still to be undertaken in the Rhinns and Southern Uplands generally.

5.3 TECTONIC IMPLICATIONS OF THE STRUCTURE : OPPOSING THRUST GEOMETRY WITHIN THE SOUTHERN UPLANDS

The most important findings of this study pertain to the D_1 structure as described in Chapter 4. These findings are presented below and are summarized in McCurry and Anderson (in press). Four of the nine Silurian fault-defined blocks identified young internally to the SE and constitute a 12 km wide zone of thrust geometry opposite in sense of rotation to that dominant in the terrane as a whole (Fig. 5.1). D_1 major thrusts at the stratigraphic base and within each of the four blocks have movement indicators of NW overthrusting, consistent with extensive macroscopic development of NW-vergent F_1 chevron folding. This contrasts with the

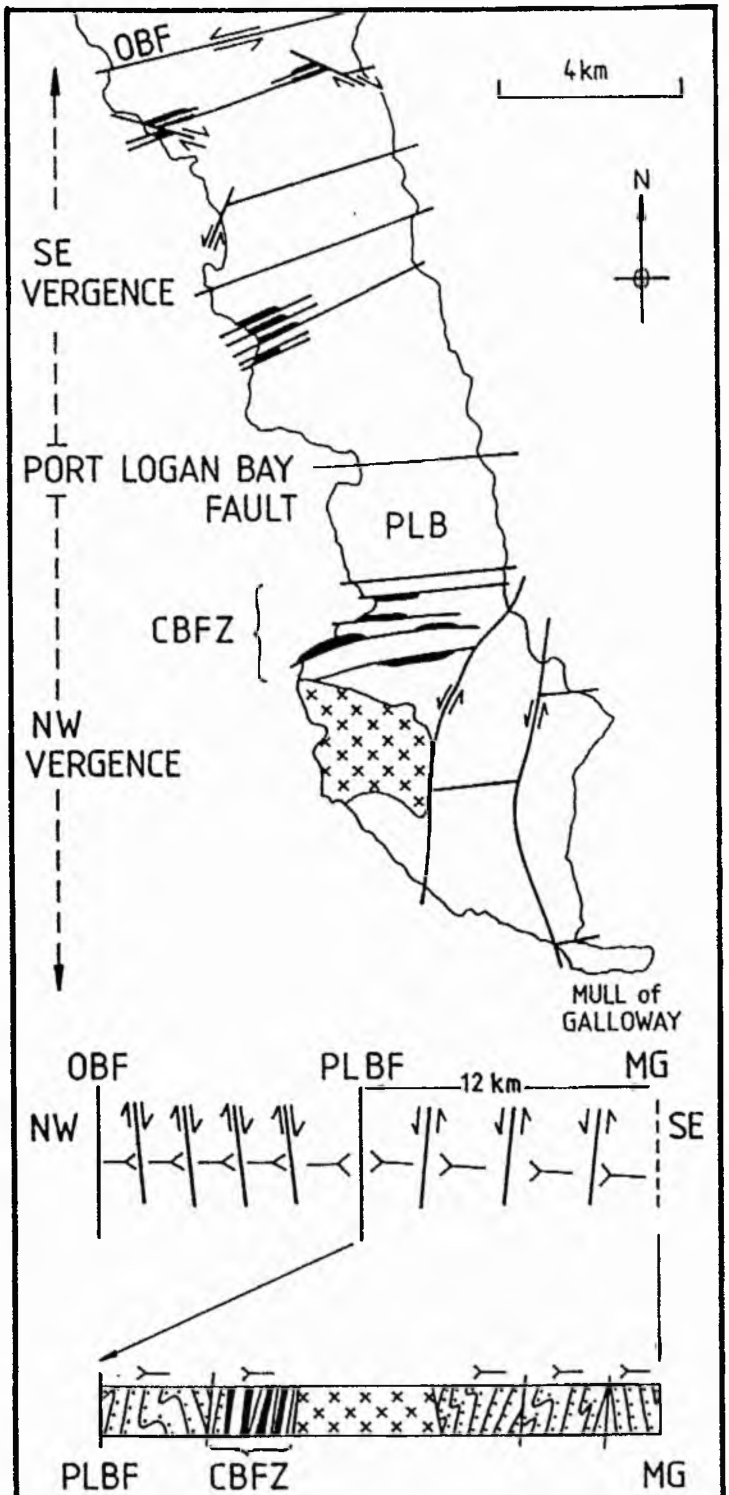


Fig 5.1: Outline map and NW-SE cross section of Rhinns of Galloway showing younging directions and vergence of major thrust zones. Black indicates Moffat Shale outcrops; cross pattern indicates granitic intrusion. CBFZ = Clanyard Bay Fault Zone, MG = Mull of Galloway, PLB = Port Logan Block, PLBF = Port Logan Bay Fault, OBF = Orlock Bridge Fault.

characteristic SE thrust vergence found elsewhere in the Southern Uplands. The Port Logan Bay Fault is best interpreted as a major NW-vergent thrust.

Evidence of large-scale NW-vergent structure exists elsewhere in the Southern Uplands (Fig. 5.2). Anomalous thrust geometry is strikingly displayed NE of Creetown (Cook and Weir 1979), where adjacent, well defined, thrust slices containing open, symmetric folds develop opposing facing directions NE along-strike. A 1.7 km wide belt of vertically dipping, SE-younging strata in the Portavogie Block of the Ards Peninsula (Anderson and Cameron 1979) is a probable product of NW-directed overthrusting. A recent attempt by Barnes, Anderson and McCurry (1987) - (Appendix 2) to effect stratigraphic and structural correlation between SW Scotland and NE Ireland established the presence of such structures in a strike-parallel belt. This is now (Fig. 5.2) recognised as having an along-strike extent of at least 100 km stretching from the Ards Peninsula to the Loch Ken Fault (extensive drift cover precludes its further definition). The structural relations are best displayed in the Rhinns with attenuation of the belt to the NE and SW.

A similar S-younging belt of strata is identified in the less well exposed Wenlock rocks of the Langholm/Hawick area (Fig. 5.2). Here tracts in which bedding youngs consistently SE for 3.2 km and 2.8 km have previously been interpreted as the 'SE-younging limbs of major synclines' (Kemp 1986, p. 244). These proposed folds, of apparent NW-vergence, seem impossibly large in the context of an imbricate thrust terrane involving the sequential imbrication of 0.8-1.2 km thick thrust pockets (Kemp 1986, p. 254). Localised northwesterly overthrusting seems a much more likely explanation.

These belts of NW-vergent thrusts constitute an important, previously unrecognised element in the Southern Uplands structure and require integration in any tectonic interpretation of the terrane.

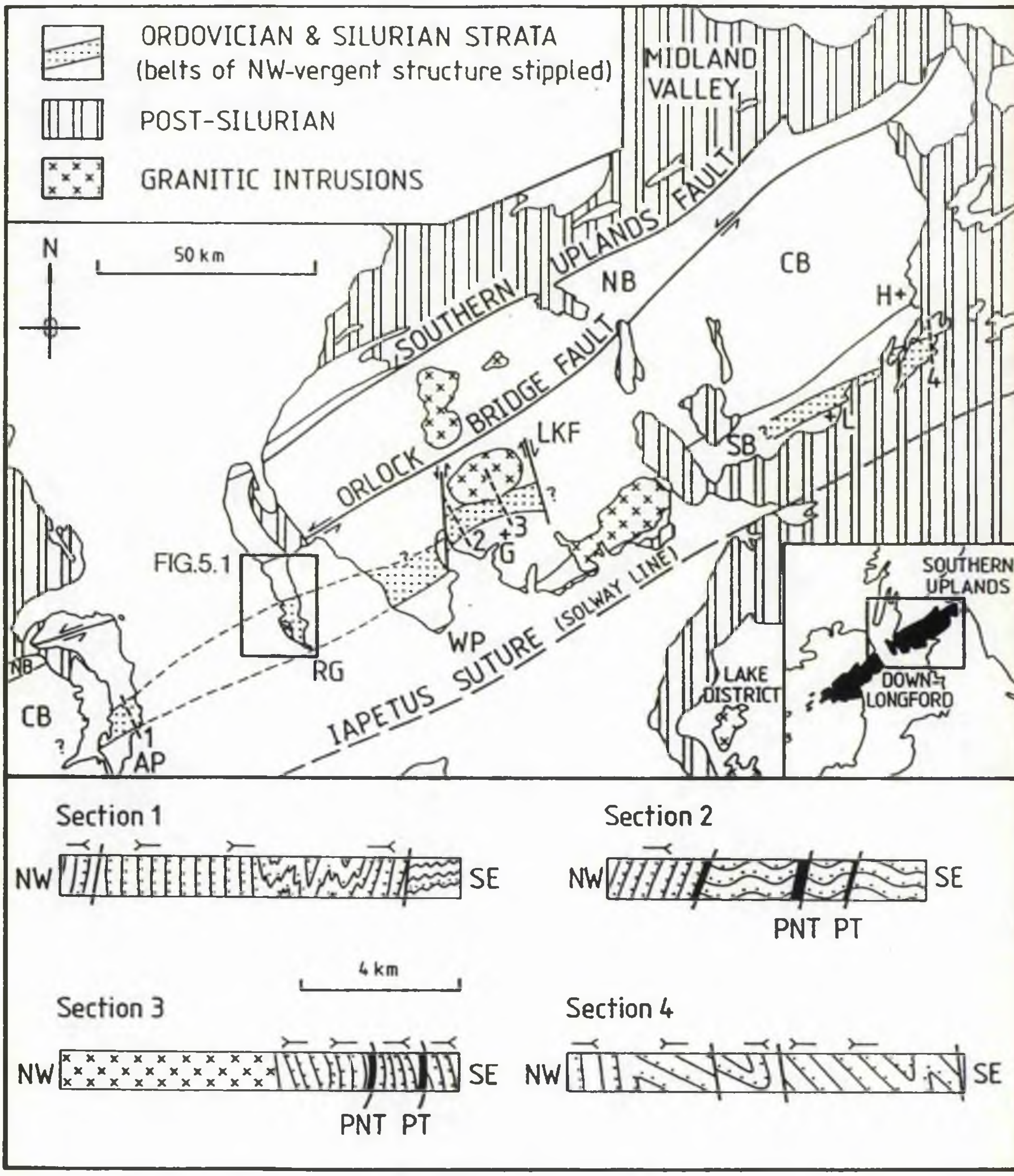


Fig 5.2: Map showing Ordovician Northern Belt (NB), Llandoverian and Ordovician Central Belt (CB) and Wenlockian Southern Belt (SB). Section 1 of Ards Peninsula, (AP) County Down is redrawn from Anderson and Cameron (1979), Sections 2 and 3, NW and NE of Gatehouse of Fleet (G) are from Cook and Weir (1979), and Section 4, SE of Hawick (H) is from Warren (1964). L = Langholm, LKF = Loch Ken Fault, PNT = Pool Ness Thrust. PT = Pibble Thrust, RG = Rhinns of Galloway, WP = Wigtown Peninsula.

5.4 THE WASHINGTON-OREGON MARGIN ANALOGUE

Seismic traverses across the Washington-Oregon continental margin (Fig. 5.3) indicate thrusts of opposing vergence above a subduction zone (Silver 1972). The possible reasons for this geometry have received detailed theoretical and model analogue analyses by Seely (1977). Suppression of the normally dominant, landward dipping, seaward verging thrusts is favoured by the presence of a basal layer of low shear strength, typically a water-retentive clay highly overpressured by the rapid deposition of overlying turbidite sands. The shear stress imposed by the subducting plate is dissipated within the basal layer (Fig. 5.4), so that conditions for pure shear deformation, rather than simple shear, obtain in the superincumbant sediments. This causes landward directed overthrusts to nucleate on any seaward-dipping anisotropy, typically bedding, in the sediment pile. Corresponding structures have since been identified in the eastern Aleutian trench slope (Moore and Allwardt 1980) (Fig. 5.3), Colombia margin (Lu and McMillen 1982) and Shimanto Belt of SW Japan (Byrne and Hibbard (1987).

The model prescribes two basic conditions for landward directed overthrusting to occur: (1) the presence within the sediment pile of a horizon capable of extreme overpressing; and (2) an increase in the sedimentation rate to produce that overpressuring. There is clear evidence that both requirements were met in the Southern Uplands in the late Llandovery.

5.5 SOUTHERN UPLANDS SEDIMENTATION IN THE LATE LLANDOVERY

The hemipelagic mudstones and pyroclastic bentonites (Cameron and Anderson 1980) of the Moffat Shales are recognised as a weak layer acting as a décollement horizon during thrust propagation in the Southern Uplands (Toghill 1970, Fyfe and Weir 1976). The characteristically low permeability and extremely small

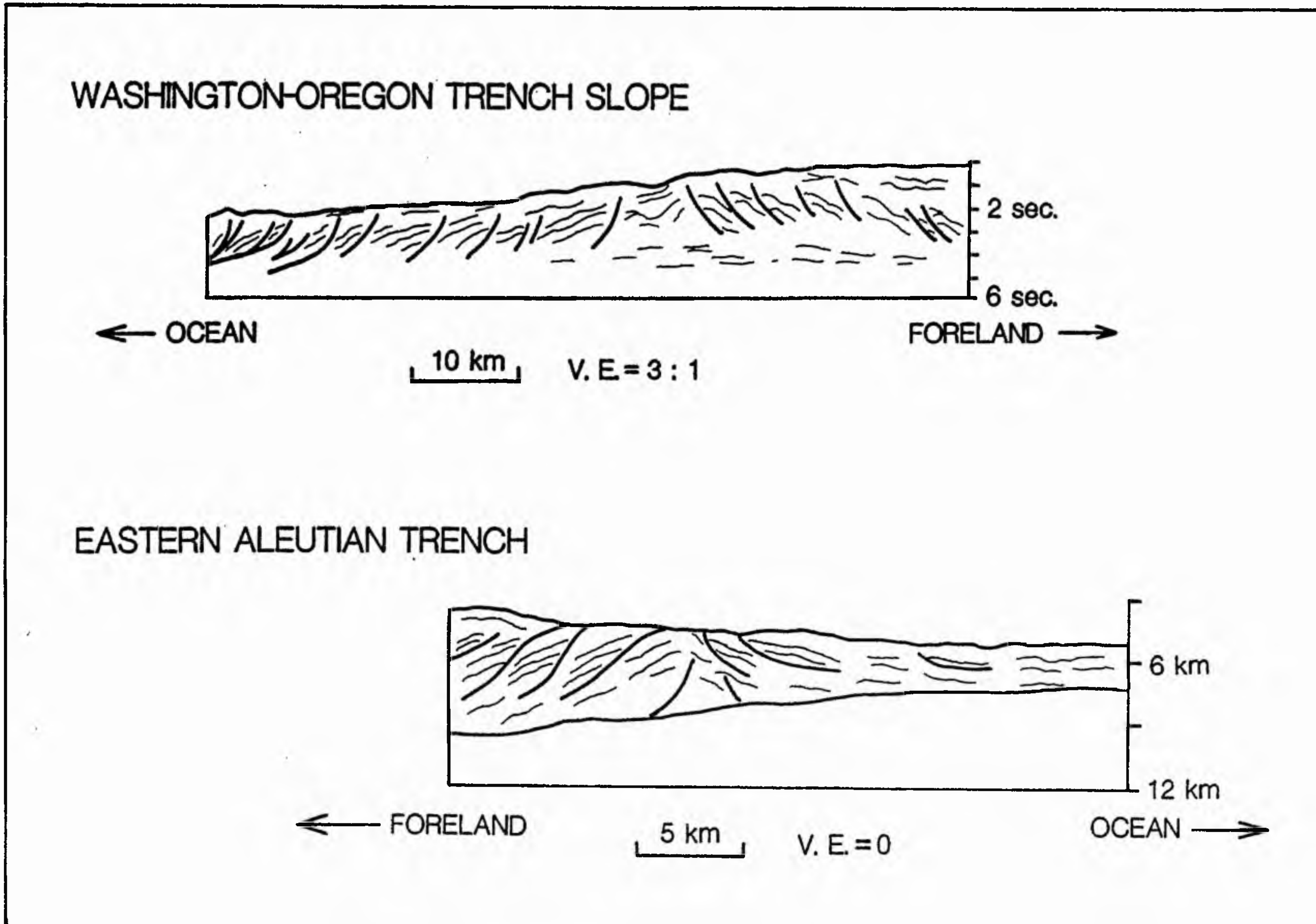


Fig 5.3: Seismic traverses across the Washington-Oregon and Eastern Aleutian margin showing both landward- and seaward-vergent thrusting (after Seely, 1977 - Figs 6 (A) and 12). V.E. - vertical exageration.

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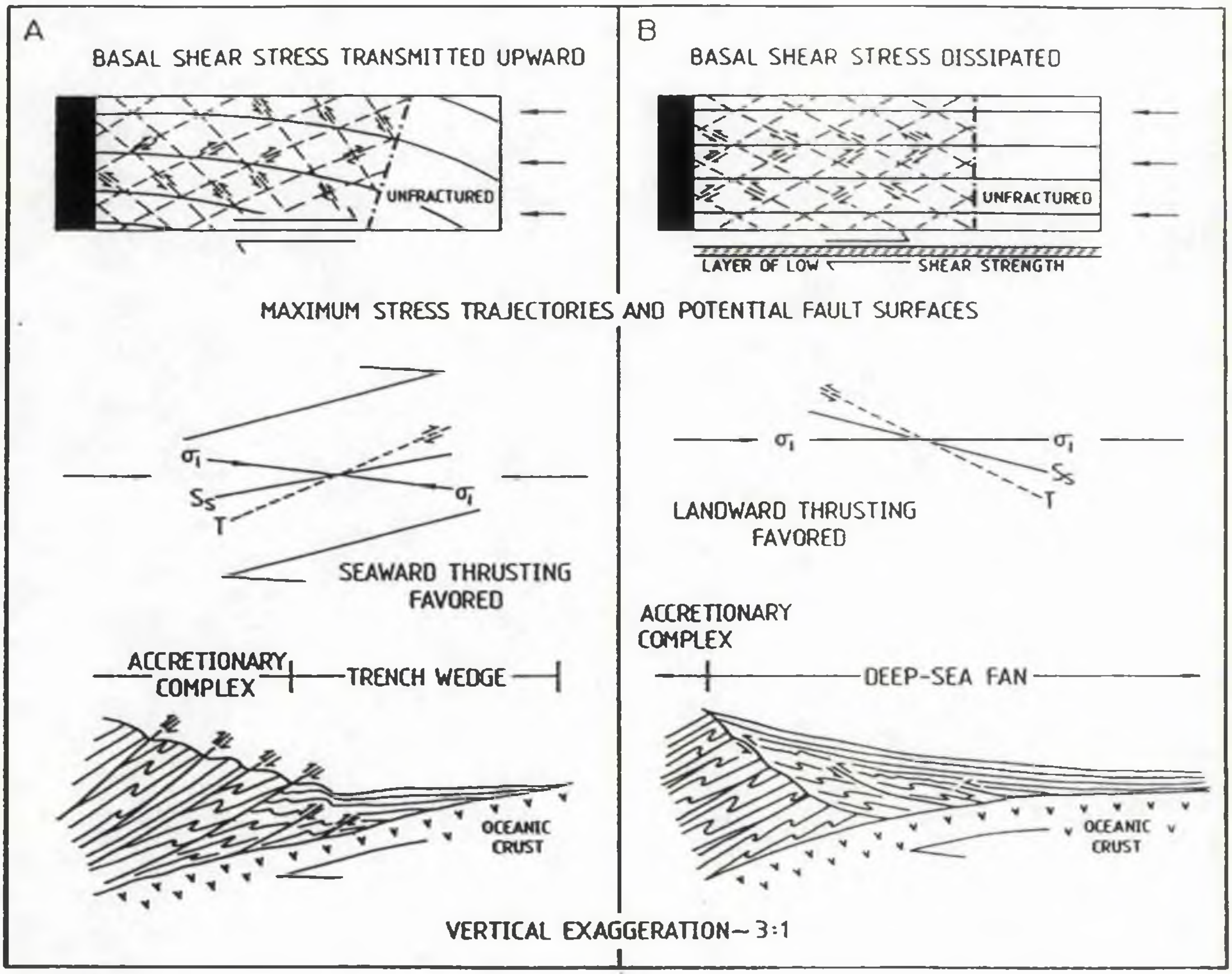

Fig 5.4: Effects of basal traction on geometry of initial thrusting within accretionary wedges (A), transmitted upward through the sedimentary pile (B), dissipated on a basal layer of negligible shear strength. Solid lines show maximum-stress trajectories; broken lines show potential thrust faults. Full arrows show compression direction; half arrows show traction. σ_1 = the maximum compressive stress, S_s = bedding, and T = thrust surface favoured. Based in part on Hafner (1951, Figs 6 and 7), Seely (1977, Figs 1 and 2).

grain size of the originally smectite-rich bentonites confer a capacity to trap large volumes of water (Rieke and Chilingarian 1974, p. 7-9) and enhance the attainable pore pressure. Thrusts are commonly observed to have preferentially nucleated and developed along the water retentive bentonite bands of the Moffat Shale sequence both in the Rhinns (see Plate 4.19) and in the classic localities around Moffat. NW-directed imbricate thrusting is well displayed in the four Moffat Shale inliers of the 1.5 km wide Clanyard Bay Fault Zone in the Rhinns (Fig. 5.1).

Both stratigraphic and sedimentological evidence support an increase in the sedimentation rate in the late Llandovery. Excellent stratigraphic control in the Wigtown Peninsula (Barnes *et al* 1987) indicates a threefold increase in across-strike 'accretion' rate from 2.5 km/graptolite zone in the Gala Group (early-mid Llandovery), to 7.2 km/graptolite zone in the Hawick Group (late Llandovery). This increase is a regional feature of the Southern Uplands terrane. Similarly the age of the base of the turbidites, overlying the Moffat Shales, decreases incrementally southeastwards, tract by tract (Leggett *et al* 1979). However the incremental slope of this phenomenon decreases markedly in the late Llandovery (see Leggett *et al* 1979- Fig. 2, Barnes *et al* 1987 - Fig. 5). This is most strikingly displayed in the Ards Peninsula (Fig. 5.5) where the turbidite base above the newly identified Moffat Shale inlier at Tieveshilly (see Chapter 2 - Section 2.4) is only one zone younger than at the Coalpit Bay inlier 30 km to the NW across-strike, despite the huge foreshortening implied by the presence of at least six major thrusts between the two. A major increase in sediment supply to the ocean floor is thus required in the late Llandovery.

Previous estimates of sedimentation rate suggest a maximum of 150-300 m/million years (Leggett and Casey 1982). The northwesterly overthrust Port Logan Block of the Rhinns (Fig. 5.1) possesses stratigraphic and structural controls which provide a rare opportunity to reliably estimate the sedimentation rate. The Port Logan Formation consists of three, lithologically distinct, hemipelagic members, each over,

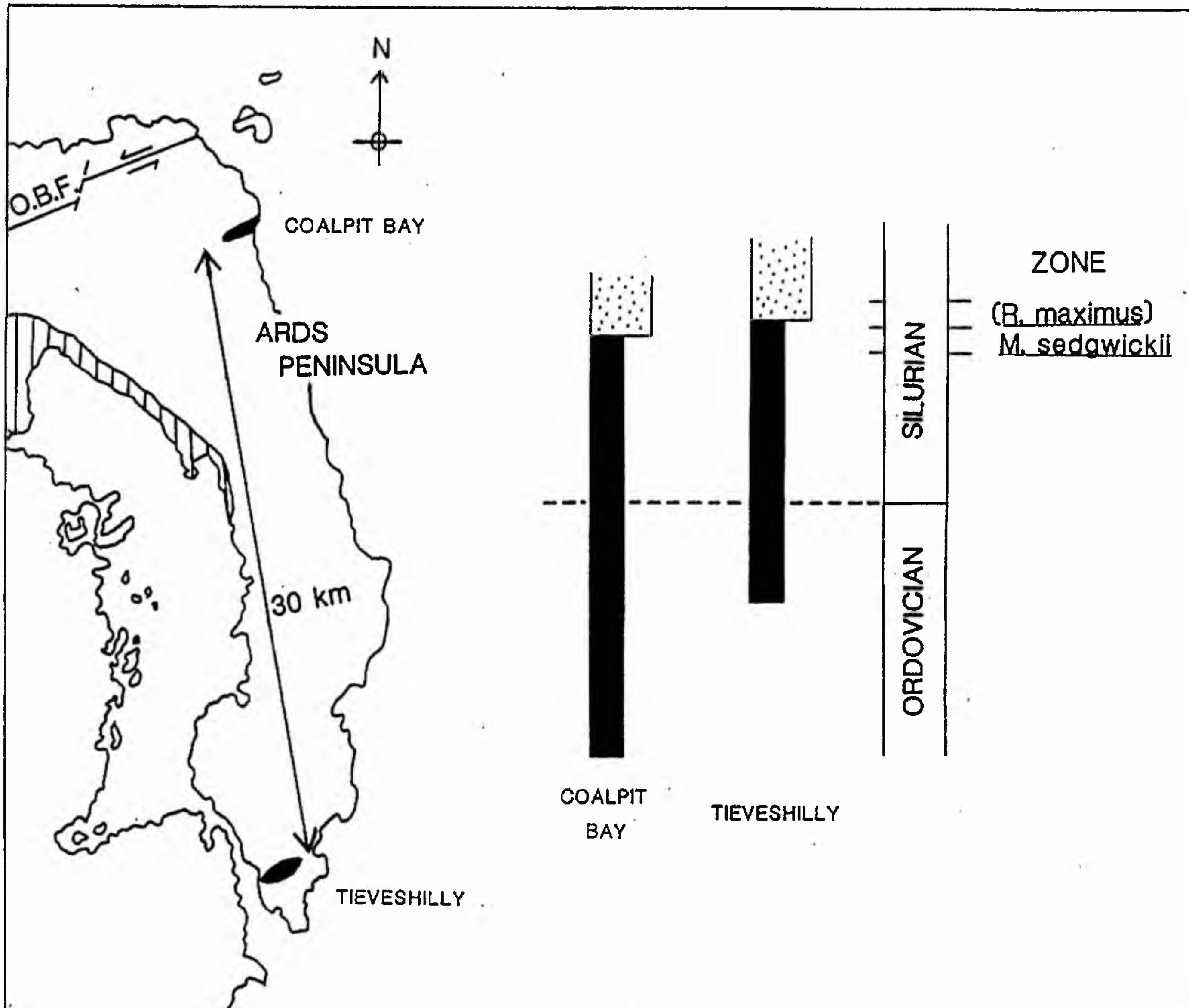

Fig 5.5: Age of the onset of turbidite sedimentation above Moffat Shales at Coalpit Bay (J595789) and Tieveshilly (J632496) in the Ards Peninsula (based upon Barnes et al 1987 - Fig 5). O.B.F. - Orlock Bridge Fault. Solid black - Moffat Shale Group; stipple - greywacke.

100 m thick interbedded with greywackes. The Slate Heugh Member is characterised by thin, carbonate-rich siltstones, the Green Saddle Member by grey chert bands, and the Strones Bay Member by dark, graptolite bearing laminae of *M. crispus* Zone age. This distinctive stratigraphy has enabled recognition of all major imbrication within the block and a minimum formation thickness of 700 m to be established. Graptolites collected from five horizons spaced through the formation all indicate a *M. turriculatus* (post-*R. maximus* sub-Zone) *M. crispus* Zone age.

Since the Llandovery has a duration of 10-12 million years (McKerrow *et al* 1985 - and references therein) spanning 10 to 14 graptolite zones the mean zone duration is between 0.7 and 1.2 million years (see Table 5.1). This fits with Rickards assessment (in Kemp 1987, p. 129) that Llandovery graptolite zones had an approximate duration of 0.5-2 million years. Assuming 25% compaction, although a much higher figure is probably as over half the sequence is hemipelagic (hemipelagic sediments have an initial porosity of *c.* 80% and undergo a total sediment volume loss of 50% when buried to a depth of 500 m - see Rieke and Chilingarian 1974, p. 7), the sedimentation rate for the Port Logan Formation is calculated at 390 - 660 m/million years. These values are remarkably similar to those of 410 - 690 m/million years recorded by Seely (1977) at the Washington-Oregon margin. Accompanying the increase in sedimentation rate bedding scale liquefaction and dewatering structures become increasingly important. Large-scale load structures, slumping and sand volcanoes which are virtually absent from the Silurian formations N of the Port Logan Bay Fault are abundant in the S-younging formations S of the fault.

5.6 OBDUCTION MODEL

These features all contribute to a refined model of Silurian accretion above an active, NW-dipping subduction zone (Fig. 5.6). An accretionary wedge of seaward vergent thrusts resulted from early-mid Llandovery simple shear deformation of trench

Estimated duration of Landovery graptolite zones:

	(minimum)	(maximum)
Duration of Llandovery[1-5]	10 million years	12 million years
Number of zones[6]	14	10
Graptolite zone duration (assumed equal)	0.71 million years	1.2 million years

Sedimentation rate in the Port Logan Formation:

Age range (maximum)	2 graptolite zones - *M. turriculatus?* and *M. crispus*
Thickness	700 m +
Porosity reduction (compaction)[7-9]	25%
Sedimentation rate	350 m/graptolite zone

		(minimum)	(maximum)
	=	350 m/1.2 million years	350 m/0.71 million years
	=	292 m/million years	493 m/million years
+ 25% compaction	=	389 m/million years	657 m/million years

∴ (minimum) sedimentation rate ~ 389-657 m/million years

[1] McKerrow *et al* (1985). [2] Snelling (1985). [3] Ross *et al* (1982). [4] Gale and Beckinsale (1983). [5] Harland *et al* (1982). [6] Strachan (personal communcation). [7] Nagtegaal (1978). [8] Galloway (1974). [9] Rieke and Chilingarian (1974).

TABLE 5.1 - CALCULATION OF THE SEDIMENTATION RATE IN THE PORT LOGAN FORMATION

wedge deposits (Fig. 5.4(A) and 5.6(A)) giving a ridged Sumatran morphology (Dickinson and Seely 1979). A decrease, or temporary cessation, in the subduction rate in the late Llandovery (with no evidence for a marine regression and subsequent increase in the sedimentation rate) caused rapid filling of the trench and progradation of deep-sea turbidite fans over the ocean floor (Fig. 5.6(B)). Increased overburden heightened overpressuring in the Moffat Shales, producing high, possibly lithostatic, pore-fluid pressures, as recorded in the smectite-rich muds at the toe of the Barbados accretionary complex (Moore *et al* 1982). Consequent loss of cohesive strength in the shale eliminated its ability to transmit shear stress, so initiating pure shear conditions in the overlying sequence and promoting symmetrical thrust development (Hafner 1951, Seely 1977, Chapple 1978). Obduction would clearly be favoured by the seaward dip of bedding in the fan in combination with the increased buoyancy of the fan deposits relative to the trench slope (Fig. 5.4(B) and 5.6(C)). Deformation initiated as a series of major, NW-vergent, asymmetric folds with thrusts forming in their short limbs. Rapid loss of pore-fluid pressure in the Moffat Shales caused by the opening of dewatering conduits along the thrust zones (Byrne and Hibbard 1987) allowed simple shear deformation of the thrust packets to proceed contemporaneous with thrusting, producing a series of NW-vergent F_1 chevron folds within each.

The decrease in the shear strength at the base of the accretionary complex caused a reduction in its seaward slope (Davis *et al* 1983) and an imbricate terrace built out over the ocean floor. Oceanward of the trench axis, overpressuring reduced in relation to the decreasing overburden, resulting in a reversion to underthrust accretion in the uppermost Llandovery, possibly initiated at irregularities in basement topography (*cf.* McCarthy and Scholl 1985 - Fig. 10). Shear resistance in the Moffat Shales now exceeded that in the rapidly deposited Hawick Group causing the décollement to step up into the turbidite succession. The extreme thickness of the succession in the Ards Peninsula, as noted earlier, suggests it was deposited near the apex of a large deep- sea fan.

Penecontemporaneous variations in subduction rate, fan geometry, basement topography and lithology along the margin throughout the late Llandovery and Wenlock are considered the important controls promoting the development of either landward or seaward vergent thrusting. As sub-horizontal compression at the margin continued, both sets of thrusts progressively steepened, rotating in opposite directions above a triangle zone on the site of the Port Logan Bay Fault. Individual thrusts steepened into sub-vertical attitudes until strain hardening caused locking and the subsequent development of SE-vergent D_2 thrusts. These thrusts are best displayed and effect a greater shortening in the domain of SE-younging, probably because bedding on the short limbs of the large-scale NW-vergent F_1 folds and D_2 thrust surfaces are sub-parallel. F_2 folds typically display a distinct SE-vergent asymmetry. However where D_1 is subparallel to bedding in the short limbs of major NW-vergent F_1 folds, symmetric, open folds develop, as described from Quarry Bay in the Port Logan Block and Inchnagour in the Clanyard Bay Block in Section 4.32 of Chapter 4 (see also Fig. 4.17 and Plates 4.13(A) and (B)). End-Caledonian continental collision caused final rotation of the thrust slices into their present attitudes (Fig. 5.6(D)).

In summary the structural and stratigraphic variation within the Southern Uplands terrane, including specifically the landward verging, seaward younging domains described above, accords best with interacting deposition and deformation in a steady-state trench (Helwig and Hall 1974, Moore 1979), with forearc morphology (Dickinson and Seely 1979) combining features of the ridged Sumatran and terraced Washington-Oregon margins.

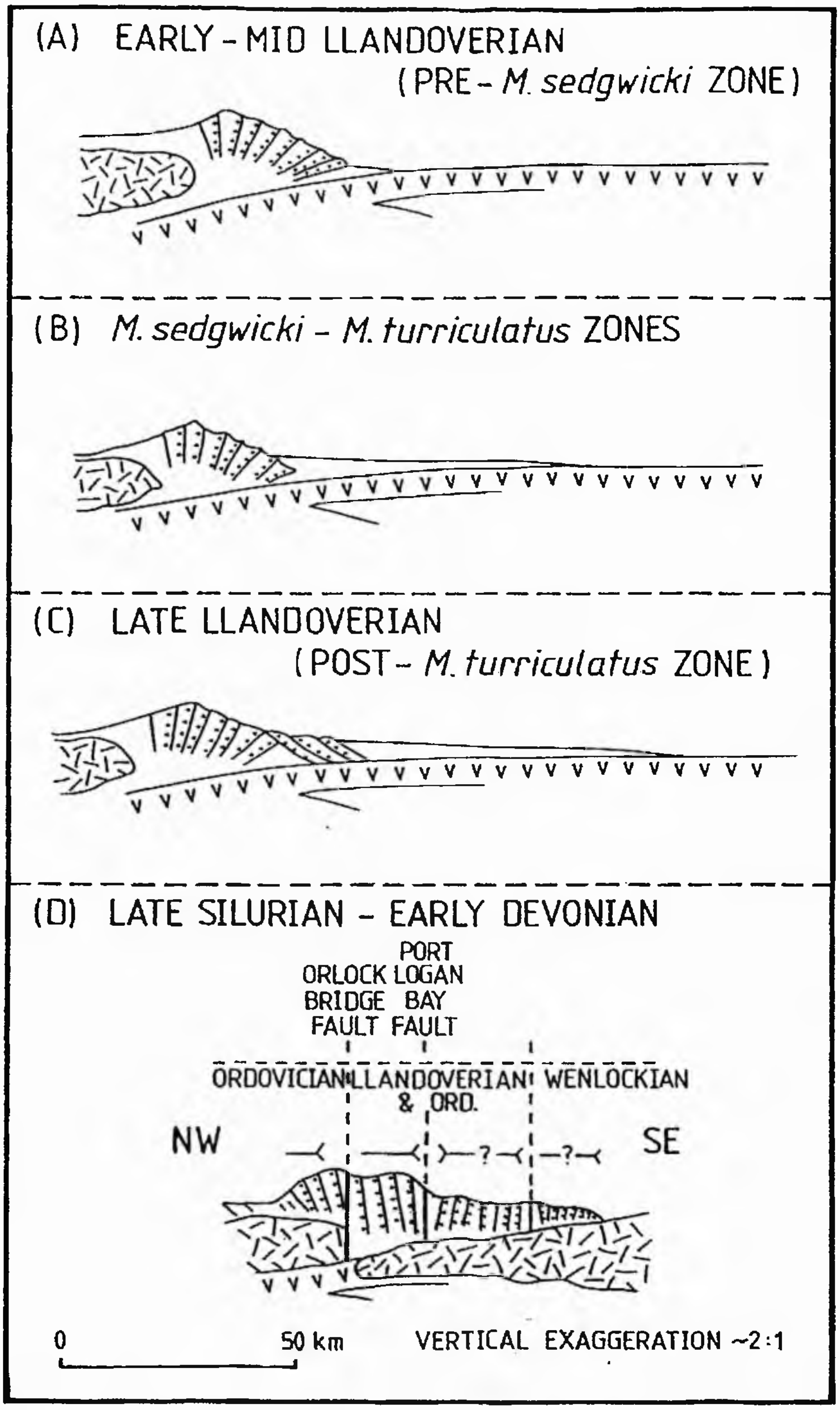

Fig 5.6: Obduction-accretion model for Silurian of Southern Uplands-Down-Longford. A: Accretionary complex of seaward vergent thrusts results from simple shear deformation. B: Decrease in subduction rate causes infilling of trench and progradation of deep-sea fan over ocean floor. C: Increase in overburden leads to overpressuring, causing reduction in basal traction, consequent pure shear deformation, and landward-vergent thrusting. Imbricate terrace builds out over the ocean floor. D: Thrust slices rotated into subvertical orientations they now occupy. Random-dash pattern indicates continental crust: V pattern is oceanic crust.

5.7 TECTONIC SUMMARY - SIGNIFICANCE OF SE-DERIVED PALAEOCURRENTS AND POST-D_2 NW-VERGENT RECUMBENT FOLDS AND THRUSTS

The model implies that NW-directed subduction of Iapetus oceanic crust beneath the southern Laurentian margin continued throughout the Silurian until climactic convergence with the Cadomian micro-continent in the late Silurian-early Devonian. The localised occurrence of southeasterly derived palaeocurrents in the Clanyard Bay Formation and Mull of Galloway Formation in the Rhinns suggests the Cadomian continental margin may have been so shaped (Fig. 5.7(A)) as to impinge earlier on the Laurentian margin in this area causing the early (late Llandovery) juxtaposition of sediment derived from both margins. However if this were the case it is perhaps surprising that the pelagic, black shale units intercalated in the Clanyard Bay Formation and distinctive carbonate-rich Hawick Group composition of the Mull of Galloway Formation are exact lithological matches of the NW or axially derived formations along-strike throughout the Southern Uplands (see Chapter 2 - Section 2.4). This suggests derivation from one rather than two sources. Leggett (1987) described a system in the Nankai Trough trench off Japan whereby sediment is tectonically constrained to flow back towards the margin from which it is derived. Although this may be applicable to axial channel deposition, it is much more difficult to envisage, though possible (Fig. 5.7(B)), in a major submarine fan system as prescribed for these sediments. A third alternative is that a sliver of the northwestern margin has sinistrally displaced adjacent to the margin along a transform fault (Fig.5.7(C)) in the manner proposed by Kelling *et al* (1987) for the Northern Belt, forming a localised tectonic basin with symmetrical input of the same composition A possible analogue of this is the Miocene Taupa-Hikurangi system in New Zealand (Cole and Lewis 1981).

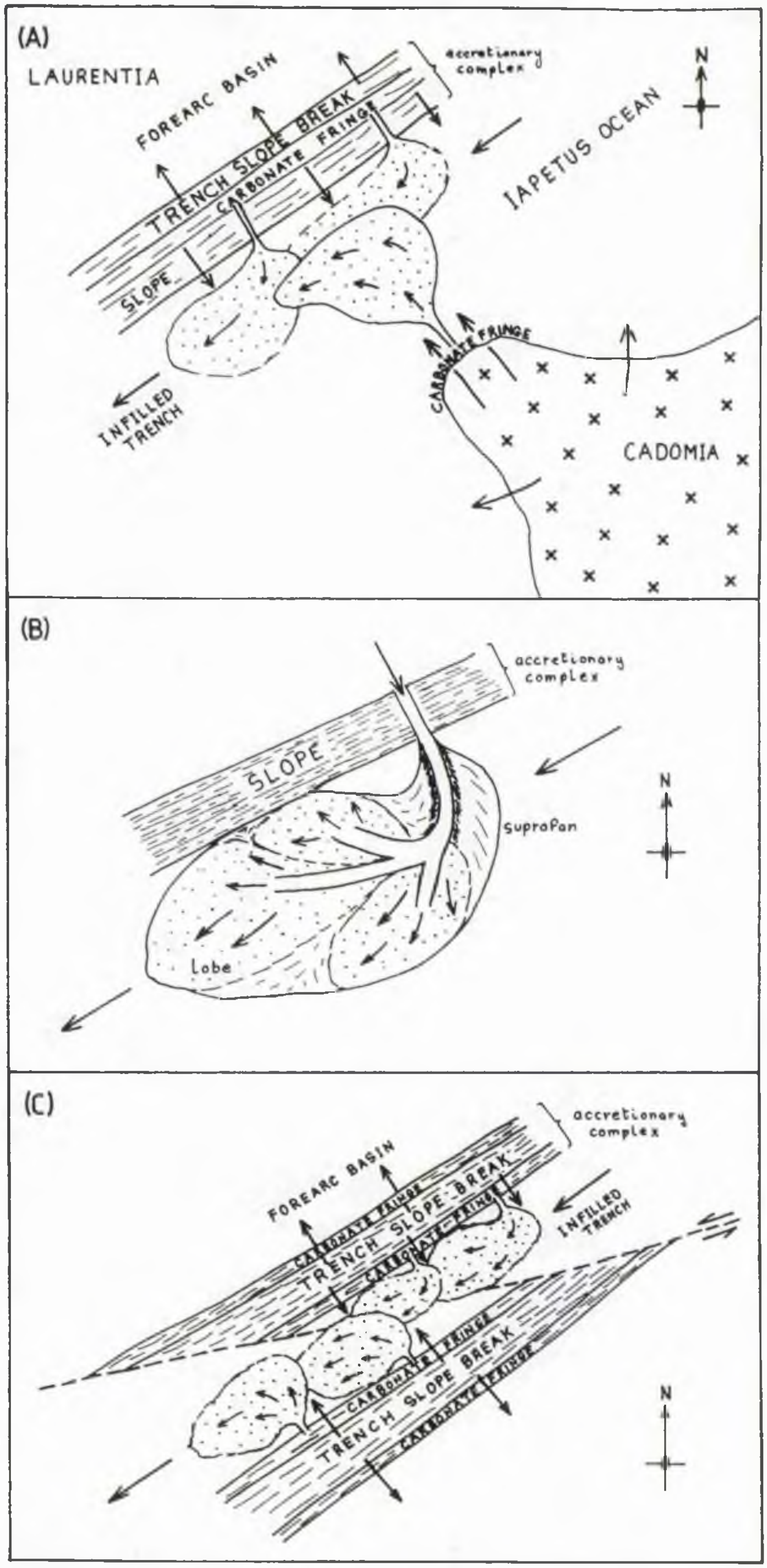

Fig 5.7: Alternative models explaining the southeasterly derivation of the Clanyard Bay and Mull of Galloway Formations (for full explanation see text). (A) sediment derived from early impinging Cadomian margin; (B) axial asymmetry of submarine fan causes some flowage back towards the margin; (C) sinistral displacement of margin along a possible transform causes the juxtaposition of fans of similar composition but opposing derivation.

The post-F_2 phase of minor, NW-vergent recumbent folding and thrusting (Chapter 4 - Sections 4.3.3 and 4.43) is found both N and S of the Orlock Bridge Fault in the Rhinns. Similar structures have been found throughout both Southern Upland terranes on either side of the Orlock Bridge Fault (Knipe and Needham 1985, Craig 1982-F_3, Cameron 1981-F_3, Rust 1965a-F_4, Weir 1968-F_4), and are attributed to the end-Caledonian collision event (Anderson and Cameron 1979, Needham and Knipe 1986). These folds and thrusts have important implications for the timing of movement along the margin. Assuming they are indeed collision related, the 400 km + sinistral strike-slip along the Orlock Bridge Fault (Anderson and Oliver 1986) must have been essentially completed prior to docking of the amalgamated terrane. The final stages of movement along the fault were broadly synchronous with, or later than, dyke intrusion (Anderson and Oliver 1986), dated at *c*. 425-395 million years (Rock *et al* 1986), but must have pre-dated deposition of the Great Conglomerate, a Lower Old Red Sandstone overlap sequence of *c*. 410-400 million years (Rock and Rundle 1986). Major sinistral strike-slip displacements were thus a feature of the margin in the late Silurian before terminal collision of Cadomia with Laurentia in the early Devonian.

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APPENDIX 1 - Graptolite specimens from the Rhinns with locality and age

The graptolitic specimens listed are from three sources:

(1) collections made by the author with identifications by Dr I. Strachan (AUTHOR);

(2) recent collections made by Dr A.W.A. Rushton and Dr D.E. White of BGS and contained in BGS reports PD86/160, PD87/46 and PD87/47 (BGS); and

(3) a recent re-examination of the Survey collections of last century (Irvine 1872, Geike and Irvine 1873, Peach and Horne 1899) by Dr I. Strachan and Dr A.W.A. Rushton and contained in BGS reports PD87/49 and PD876/50 (SURVEY).

Graptolites at one locality S of Float Bay (NX06404696) were collected by Mr P. Davies and identified by Dr B. Rickards. Localities are listed in the same N to S order as treated in the stratigraphy chapter (Chapter 2).

Moffat Shale Group of the Portayew Fault Zone

Portayew (NX03885029)

AUTHOR

Orthograptus sp. *(quadrimucranatus* type)

Age: Hartfell?

SURVEY

Climacograptus spiniferus Reudemann

Cryptograptus tricornis (Carruthers)

Dicranograptus furcatus minimus Lapworth

Didymograptus superstes Lapworth

Orthograptus whitfieldi (Hall)

O. amplexicoule (Hall)?

diplograptids indeterminate

leptograptid stipes

Age: *Nemograptus gracilis* or *Climacograptus peltifer* Zone

Moffat Shale Group of the Strandfoot Fault Zone

Strandfoot (NX05224810)

AUTHOR

Climacograptus sp.(*normalis* type)

Climacograptus sp.

Monograptus sp.

Orthograptus (?) sp.

Age: Lower Birkhill

BGS

Atavograptus atavus (Jones)

Climacograptus miserabilis Elles and Wood

Dimorphograptus erectus Elles and Wood

D. cf. longissimus (Kurck) proximal end

Age: *Cystograptus vesiculosus* or *Cornograptus cyphus* Zone

Float Bay Formation

100 m NW of Island Buoy (NX06404696)

P. DAVIES

Monograptus revolutus Kurck group

Rhaptiidograptus toernquisti (Elles and Wood)

Climacograptus cf. rectangularis (McCoy)

Glyptograptus sp.

Dimorphograptus sp

Age: *C. vesiculosus* or *C. cyphus* Zone

South side of Float Bay (NX06514722)

BGS

Climacograptus normalis Lapworth

monograptid, possibly *Coronograptus cyphus* (Lapworth)

Age: possibly *C. vesiculosus* or *C. cyphus* Zone

North side of Float Bay (NX06264728)

AUTHOR

Monograptus spp.

Age: *C. cyphus* Zone??

70 m NW of Goodwifes Cave (NX05264805)

BGS

Climacograptus normalis Lapworth

Monograptus, triangulate species

Age: *Coronograptus gregarius* Zone

'Stinking Bight beds'

Gully 100 m NW of Hackle Rock (NX06834455)

BGS

Discinocaris giganea Woodward?

Coronograptus gregarius (Lapworth)

Glyptograptus cf. incertus Elles and Wood

Monograptus difformis Toernquist

M. revolutus Kurck Group

M. triangulatus (Harkness) group

Orthograptus cyperoides Toernquist?

O. insectiformis (Nicholson)

Rastrites sp. (fragments)

Age: near the boundary of *C. cyphus* and *C. gregarius* Zones

Moffat Shale Group of the Drumbreddan Bay Fault Zone

Southeastern side of peninsula in Drumbreddan Bay (NX07764359)

SURVEY

Glyptograptus incertus Elles and Wood

Monograptus convolutus (Hisinger)

M. decipiens Toernquist

M. 'gemmatus' of Elles and Wood

M. triangulatus (Harkness) group

Petalograptus palmeus (Barrande)

Pribylograptus leptotheca (Lapworth)?

Rastrites sp.

Age: *Monograptus convolutus*

Southeastern side of Grennan Point (NX07734376)

AUTHOR

Coronograptus gregarius (Lapworth)

C. cf. cyphus (Lapworth)

Monograptus cf. sandersoni Lapworth

Monograptus sp. (*triangulatus* type)

Monograptus spp.

Climacograptus spp.

Pseudoclimacograptus (?) sp.

Age: *C. gregarius* Zone and possibly also *C. cyphus* Zone

BGS

Coronograptus gregarius (Lapworth)

Monograptus triangulatus (Harkness) group S.L.

Climacograptus sp.

Age: *C. gregarius* Zone

SURVEY

Rastrites longispinus Perner

Monograptus limatulus Toernquist

Age: *M. convolutus* Zone

Grennan Bay:-

15 m NW of the southeastern boundary of the inlier (NX0744378)

AUTHOR

Rhaphidograptus cf. toernquisti (Elles and Wood)

R. cf. extenuatus (Elles and Wood)

Climacograptus cf. normalis Lapworth

Climacograptus sp.

Age: *C. vesiculosus* Zone

40 m NW of the southeastern boundary of the inlier (NX07484380)

AUTHOR

Rhaphidograptus extenuatus (Elles and Wood)

Climacograptus (Normalis type)

Climacograptus spp.

Age: *C. vesiculosus* Zone

20 m SE of the northwestern boundary of the inlier (NX07524387)

AUTHOR

Climacograptus cf. medius Toernquist

C. cf. normalis Lapworth

Glyptograptus spp.

Orthograptus (?) sp.

Age: Lower Birkhill

Grennan Bay (NX07504380)

SURVEY

Dicranograptus ramosus (Hall)

Rastrites peregrinus Barrande

Age: *Climacograptus wilsoni* or *Dicranograptus clingani* Zone

Mull of Logan Formation

80 m N of Cairnie Finnart (NX08834146)

BGS

Monograptus proteus (Barrande)

Diversograptus runcinatus (Lapworth)?

Age: suggest *Monograptus turriculatus* Zone

Port Logan Formation

Quarry Bay (NX09214031)

AUTHOR

Monograptus sp. *(priodon* type)

Age: *M. turriculatus* (post-*Rastrites maximus* sub-Zone) or

Monograptus crispus Zone

100 m SW of Scrangie (NX09054008)

AUTHOR

Monograptus sp.

Age: *M . turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

Kettle Mouth (NX09223961)

AUTHOR

Monograptus sp. *(priodon* type)

Age: *M . turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

70 m S of Strones Bay (NX09563862)

AUTHOR

Monograptus aff. *nudus* (Lapworth)

Age: *M . turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

Strones Bay (NX09583872)

AUTHOR

Monograptus sp. (*marri* type)

Monograptus sp. (*sedgwicki* type)

Monograptus spp.

Age: *M . turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

BGS

Monograptus marri (Perner)

M. priodon (Bonn)

hooked monograptid fragments

Age: *M . turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

Grennan Slate Quaries:-

Quarry 1 (NX12673943)

BGS

Monograptus crispus Lapworth - several

M. marri (Perner) - several

M. priodon (Bronn) - several

M. veles (Richter)

M. exiguus (Nicholson)

M. proteus (Barrande)

Age: *M. crispus* Zone

Quarry 2 (NX12583932)

BGS

Monograptus crispus Lapworth

M. exiguus (Nicholson) - abundant

M. priodon (Bronn)

M. cf. marri (Perner)

Grennan Slate Quarries (NX12603940)

SURVEY

Monograptus nodifer Toernquist

Monograptus sp. (*sedgwicki* type)

Age: *M . turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

Moffat Shale Group of the Clanyard Bay Fault Zone

Northern end of Clanyard Bay (NX10103810):-

AUTHOR (6 localities below)

Centre of the synclinal core of Birkhill Shale exposed 30 m S of the 7 m wide felsite dyke within the inlier (NX10113807)

Diplograptus cf. magnus H. Lapworth

Climacograptus cf. scalaris (Hisinger)

Pristiograptus sp.

Age: possible *C. gregarius* Zone

Within the same synclinal core of Birkhill Shale about 1.5 m from the northern fault boundary with the Barren Mudstones (NX10103808)

Cystograptus vesiculosus (Nicholson)

Coronogratpus cyphus (Lapworth)

Pristiograptus cf. argutus Lapworth

Climacograptus cf. rectangularis (McCoy)

Climacograptus sp.

Age: *C. vesiculosus* Zone

7 m N of the 7 m wide felsite dyke (NX10073811)

Cystograptus vesiculosus (Nicholson)

Climacograptus cf. rectangularis (McCoy)

C. cf. medius Toernquist - 6 specimens

Coronograptus cyphus (Lapworth) (type)

Monograptus spp.

Age: *C. cyphus* or *C. vesiculosus* Zone

15 m N of the 7 m wide felsite dyke (NX10063812)

Atavograptus strachani (Hutt and Rickards)

Cystograptus vesiculosus (Nicholson)

Climacograptus rectangularis (McCoy)

Coronograptus cyphus (Lapworth)

C. cf. gregarius (Lapworth)

Age: *C. cyphus* Zone

12 m S of the northern boundary of the inlier (NX10053812)

Monograptus convolutus (Hisinger)

Coronograptus gregarius (Lapworth)

Rhapidograptus sp. (*toernquisti* type)

Diplograptus cf. magnus H. Lapworth

cf. Glyptograptus tamariscus (Nicholson)

Age: *M. convolutus* Zone or possibly *C. gregarius* Zone

5 m S of the northern boundary of the inlier (NX10053813)

Metoclimacograptus undulatus (Elles and Wood)

Monograptus sp. (*regularis* type)

Monograptus sp. (*lobiferous* type)

Age: *M. convolutus* or *Monograptus sedgwicki* Zone

BGS (6 unspecified localities below)

Locality A

Glyptograptus incertus Elles and Wood

Monograptus sedgwicki (Portlock)

Monograptus sp. (triangulate)

Petalograptus tenuis (Barrande)

Petalograptus tenuis (Barrande)

Pseudoplegmatograptus? sp.

Age: *M. sedgwicki* Zone

Locality B

Coronograptus cyphus (Lapworth)

C. gregarius (Lapworth)

Dimorphograptus cf. longissimus (Kurck) distal part

Glyptograptus sinuatus (Nicholson)

Monograptus difformis Toernquist

Monograptus sp. triangulate proximal end

Age: near the boundary of *C. cyphus* and *C. gregarius* Zones

Locliaty C

Atavograptus atavus (Jones)

Climacograptus normalis Lapworth?

Coronograptus cyphus (Lapworth)

Cystograptus vesiculosus (Nicholson)

Dimorphograptus physophora (Nicholson)

Monograptus austerus Toernquist?

M. revolutus Kurck (group)

Orthograptus cyperoides Toernquist?

O. insectiformis (Nicholson)

Pribylograptus sandersoni (Lapworth)

Rhapidograptus toernquisti (Elles and Wood)

Age: *C. cyphus* Zone

Locality D

Climacograptus medius Toernquist

C. normalis Lapworth

Diplograptus modestus Lapworth

Age: probably *C. vesiculosus* Zone

Locality E

Climacograptus medius Toernquist

C. miserabilis Elles and Wood

Cystograptus vesiculosus (Nicholson)

Diplograptus modestus Lapworth

Age: *C. vesiculosus* Zone

Locality F

Climacograptus medius Toernquist

C. normalis Lapworth

Cystograptus vesiculosus (Nicholson)

Dimorphograptus elongatus Lapworth

Rhapidograptus extenuatus Elles and Wood

Age: *C. vesiculosus* Zone

SURVEY (3 unspecified localities below)

Locality 1

Atavograptus sp.

Climacograptus medius Toernquist

C. normalis Lapworth

C. rectangularis (McCoy)

Cystograptus vesiculosus (Nicholson)

Lagarograptus acinaces (Toernquist)

Age: *C. vesiculosus* Zone

Locality 2

Monograptus convolutus (Hisinger)

M. lobiferus (McCoy)

M. limatulus Toernquist

Glyptograptus serratus Elles and Wood

Orothograptus bellulus Toernquist

Age: *M. convolutus* Zone

Locality 3

Dicellograptus sp

Age: Ordovician (possibly *Dicellograptus anceps* Zone).

Southern end of Clanyard Bay (NX09803770)

AUTHOR

Monograptus attenuatus (Rickards)

M. cf. clingani (Carruthers)

Monograptus sp. (*denticulatus* type)

Monograptus sp. (*lobiferus* type)

Climacograptus sp. (*rectangularis* type)

cf. Climacograptus spp.

Age: *M. convolutus* Zone

SURVEY

Monograptus lobiferus (McCoy)

Monograptus sp. (*convolutus type*)

Age: *M. convolutus* Zone

Breddock Bay (NX09153720)

AUTHOR

Diversograptus rectus (Hopkinson)

Climacograptus cf. miserabilis Elles and Wood

C. cf. medius Toernquist

Diplograptus cf. modestus Lapworth

Coronograptus cf. cyphus (Lapworth)

Cystograptus cf. vesiculosus (Nicholson)

Monograptus cf. fragilis Rickards

Monograptus sp.

Orthograptus sp.

Age: *C. cyphus* Zone and possible *C. vesiculosus* Zone

Cave of the Saddle (NX08553675)

AUTHOR

cf. Diplograptus magnus H. Lapworth

Diplograptus spp.

Climacograptus sp.

Age: possibly *C. gregarius* Zone

SURVEY

Climacograptus rectangularis (McCoy)

Coronograptus cyphus (Lapworth)

Glyptograptus cf. tamariscus (Nicholson)

Orthograptus mutabilis Elles and Wood

Age: suggest *C. cyphus* Zone

Clanyard Bay Formation

Dunbuck (NX09583851)

AUTHOR

Monograptus exiguus (Nicholson) - abundant

M. cf. nodifer Toernquist

M. cf. planus (Barrande)

Monograptus sp. (*runcinatus* type)

Monograptus sp.

cf. Petalograptus sp.

Age: *M. turriculatus* (post-*R. maximus* sub-Zone) or *M. crispus* Zone

BGS

Monograptus exiguus (Nicholson) - several

M. exiguus towards *primulus* Boucek and Pribyl

M. marri Perner

M. cf. planus (Barrande)

M. cf. priodon (Bronn)

M. proteus (Barrande)

M. pseudobecki? Boucek and Pribyl - one fragment

Petalograptus altissimus? Elles and Wood

Age: *M. crispus* Zone

APPENDIX 2 - Along-strike variation in the stratigraphical and structural profile of the Southern Uplands Central Belt in Galloway and Down - BARNES, R.P., ANDERSON, T.B. and McCURRY J.A. (1987).

(SEE INSIDE BACK COVER)

APPENDIX 3 - Sandstone point count data (500 points/specimen)

SPECIMEN NO	FORMATION	Q	Q_m	Q_p	F	F_p	F_k	A	B	S	M_t	F_m	M	M_{nc}	M_c	GRID REFERENCE
PF1	PYF	24.7	21.3	3.4	10.4	6.4	4.0	13.3	3.4	0.4	4.3	-	43.8	2.4	41.4	NX03755040
CF5	PYF	22.6	19.3	3.3	8.6	5.7	2.9	12.3	2.9	0.4	7.8	-	45.7	3.3	42.4	NX03955013
CF4A	PYF	27.5	22.6	4.9	12.4	9.7	2.7	10.5	9.8	1.2	7.2	-	31.6	8.8	22.8	NX03965002
Mean		25.0	21.1	3.9	10.5	7.3	3.2	12.0	5.4	0.7	6.4	-	40.3	4.8	35.5	
CL2	MHF	28.3	20.0	8.3	9.9	7.1	2.8	17.4	12.3	7.1	11.3	-	13.5	9.5	4.0	NX04574883
CL3	MHF	36.7	28.3	8.4	9.4	7.4	2.0	15.8	11.2	3.6	10.0	0.2	13.2	11.2	2.0	NX04514868
MH2	MHF	24.8	19.8	5.0	14.8	12.4	2.4	20.0	9.6	2.0	3.6	4.2	21.0	16.6	4.4	NX04524838
MH4	MHF	30.0	26.0	4.0	10.6	6.2	4.4	14.0	15.8	3.8	3.0	2.2	20.6	18.4	2.2	NX04874830
JMcC6	MHF	29.8	25.4	4.4	10.0	6.0	4.0	8.4	6.2	4.6	9.8	-	31.2	16.2	15.0	NX05024818
Mean		29.9	23.9	6.0	10.9	7.8	3.1	15.1	11.0	4.2	7.5	1.3	19.9	14.4	5.5	
SF2	FBF	42.3	38.3	4.0	14.9	12.5	2.4	6.0	2.0	-	2.6	-	32.4	29.6	2.8	NX05334790
SF4	FBF	41.1	36.5	4.6	13.8	10.4	3.4	10.2	6.4	0.2	6.8	-	21.6	16.4	5.2	NX05694762
SF7	FBF	42.5	37.6	4.9	15.7	7.8	7.9	7.9	12.2	0.4	3.4	-	18.1	17.2	0.9	NX05884731
FB2	FBF	45.8	40.2	5.6	10.6	9.0	1.6	9.0	5.4	-	3.0	-	26.3	21.7	4.6	NX06374710
FB5	FBF	43.3	38.5	4.8	7.0	5.4	1.6	8.4	8.8	1.0	3.4	-	28.2	17.0	11.2	NX06474689
HS1	FBF	37.7	32.5	5.2	7.6	7.0	0.6	11.2	11.4	0.8	2.4	-	28.9	27.1	1.8	NX06654670
HS4	FBF	39.4	34.8	4.6	9.4	6.6	2.8	8.0	7.2	0.6	2.4	-	33.2	18.1	15.1	NX06884630
Mean		41.7	36.9	4.8	11.3	8.4	2.9	8.7	7.6	0.4	3.0	-	26.9	21.0	5.9	
AN1	'SBb'	42.4	37.0	5.4	6.8	5.4	1.4	7.6	6.6	2.0	3.4	-	31.2	19.0	12.2	NX07054596
AN3	'SBb'	47.7	43.7	4.0	8.6	6.0	2.6	7.6	6.4	1.2	4.8	-	24.0	23.2	0.8	NX07124539
HO1	'SBb'	42.2	36.4	5.8	13.4	10.6	2.8	8.4	8.0	0.2	2.6	-	25.2	24.4	0.8	NX06654470
Mean		44.1	39.0	5.1	9.6	7.3	2.3	7.9	7.0	1.1	3.6	-	26.8	22.2	4.6	
GP1	GPF	39.1	33.7	5.4	11.2	9.8	1.4	9.2	10.0	0.4	4.2	0.2	25.9	23.7	2.2	NX06804441
GP3	GPF	43.8	38.4	5.4	10.2	7.0	3.2	8.2	4.8	2.0	2.8	-	28.3	18.5	9.8	NX07034401
GP5	GPF	39.8	35.6	4.2	11.2	7.8	3.4	9.8	8.2	1.4	5.2	-	24.4	17.6	6.8	NX07524367
Mean		40.9	35.9	5.0	10.9	8.2	2.7	9.1	7.7	1.3	4.1	0.1	26.2	19.9	6.3	

[APPENDIX 3 - continued]

SPECIMEN NO	FORMATION	Q	Q_m	Q_p	F	F_p	F_k	A	B	S	M_t	F_m	M	M_{nc}	M_c	GRID REFERENCE
PP2	MLF^{TC}	3 2	24.1	8.1	9.9	6.1	3.8	13.2	11.9	2.2	10.7	1.6	18.4	16.8	1.6	NX07674308
PP4	MLF^{TC}	25.7	18.5	5.2	19.9	13.5	6.4	22.1	8.6	1.6	9.2	0.2	14.7	14.7	-	NX07744284
PP5	MLF^{TC}	22.6	16.3	6.3	11.6	9.2	2.4	19.4	17.9	1.8	6.5	3.3	16.9	16.3	0.6	NX07614262
DF1	MLF^{DH}	13.4	12.0	1.4	2.4	2.0	0.4	11.6	8.8	8.3	9.2	0.6	45.5	44.9	0.6	NX07604246
DF3	MLF^{DH}	27.3	23.9	3.4	20.5	16.6	3.9	20.5	5.9	3.4	11.5	1.2	9.9	9.1	0.8	NX07594227
L161	MLF^{DH}	30.6	27.0	3.6	20.6	17.4	3.2	10.4	10.0	5.4	7.2	1.0	14.8	14.2	0.6	NX07574216
L164	MLF^{DH}	28.1	25.4	2.7	9.8	7.2	2.6	6.4	13.9	4.1	4.5	2.4	30.8	28.1	2.7	NX07434199
L166	MLF^{DP}	27.6	22.6	5.0	13.2	10.4	2.8	16.2	13.6	-	8.8	0.4	19.8	19.8	-	NX07684168
L168	MLF^{CF}	38.4	35.4	3.0	8.4	7.6	0.8	7.2	4.2	-	-0.6	-	41.2	29.4	11.8	NX08544156
L171	MLF^{CF}	43.6	39.8	3.8	8.4	7.8	0.6	7.2	4.8	0.2	2.4	0.2	33.2	26.2	7.0	NX09154130
Mean	MLF^{TC}	26.1	19.6	6.5	13.8	9.6	4.2	18.2	12.8	1.9	8.8	1.7	16.6	15.9	0.7	
Mean	MLF^{DH}	24.9	22.1	2.8	13.3	10.8	2.5	12.2	9.7	5.3	8.1	1.3	25.3	24.1	1.2	
Mean	MLF^{CF}	41.0	37.6	3.4	8.4	7.7	0.7	7.2	4.5	0.1	1.5	0.1	37.2	27.8	9.4	
Mean		28.8	24.5	4.3	12.5	9.8	2.7	13.4	10.0	2.7	7.1	1.1	23.9	22.0	1.9	
L174	PLF	54.2	43.4	10.8	4.2	3.8	0.4	2.8	1.0	0.8	7.6	0.4	29	23.8	5.2	NX09274039
L177	PLF	51.5	42.7	8.8	7.8	6.4	1.4	3.8	1.8	0.4	3.6	0.2	30.9	28.9	2.0	NX09063989
L179	PLF	56.0	43.3	9.7	1.6	1.4	0.2	4.2	3.2	3.2	30.0	-	28.6	28.4	0.2	NX09303933
L181	PLF	56.7	40.9	15.8	10.4	8.0	2.4	5.2	0.4	0.4	2	-	25.0	33.0	2.0	NX09493876
Mean		54.6	43.3	11.3	6.0	4.9	1.1	4.0	1.6	1.2	4.1	0.2	28.4	26.0	2.4	
L184	CBF^{a}	32.1	30.3	1.8	7.1	6.7	0.4	9.9	4.6	1.2	2.4	-	42.8	23	19.8	NX09653844
L186	CBF^{a}	32.6	29.8	2.8	6.6	6.2	0.4	6.2	1.8	0.6	1.8	0.2	50.2	31.6	18.6	NX09973814
L7	CBF^{a}	37.0	34.8	2.2	7.7	7.6	1.0	5.0	3.4	1.4	3.2	-	41.4	36.4	5.0	NX09763767
L65	CBF^{PM}	50.1	32.9	17.2	4.8	4.2	0.6	2.6	4.2	1.0	9.8	-	27.9	27.9	-	NX10693235
L68	CBF^{PM}	55.8	34.6	21.2	4.8	3.6	1.2	3.0	2.2	0.6	7.6	-	26.2	24.0	2.2	NX10853211
Mean	CBF^{a}	33.9	31.6	2.3	7.4	6.8	0.6	7.0	3.3	1.1	2.5	0.1	44.8	30.3	14.5	
Mean	CBF^{PM}	53.0	33.8	19.2	4.8	3.9	0.9	2.8	3.2	0.8	8.7	-	27.1	2.6	1.1	
Mean		41.5	32.5	9.0	6.4	5.7	0.7	5.3	3.2	1.0	5.0	0.1	37.7	28.6	9.1	

[APPENDIX 3 - continued]

SPECIMEN NO	FORMATION	Q	Q_m	Q_p	F	F_p	F_k	A	B	S	M_t	F_m	M	M_{nc}	M_c	GRID REFERENCE
L70	MGF^a	32.8	29.2	3.6	8.6	7.2	1.4	7.6	2.6	0.4	1.6	-	46.5	21.5	25.0	NX11233182
L86	MGF^a	33.3	30.9	2.4	6.0	4.8	1.2	7.0	3.0	-	2.8	-	47.9	12.0	35.9	NX11673152
L91	MGF^{LC}	33.9	32.5	1.4	8.6	7.4	1.2	7.8	3.2	1.2	4.2	-	41.3	12.4	28.9	NX12203143
L94	MGF^{LC}	33.9	32.3	1.6	7.2	6.0	1.2	8.6	3.8	0.2	3.8	-	42.5	15.0	27.5	NX12523135
L97	MGF^{LC}	28.1	25.7	2.4	7.4	6.2	1.2	11.6	8.0	1.6	7.0	-	46.4	13.8	22.6	NX12833109
L100	MGF^{LC}	25.2	23.4	1.8	6.0	4.0	2.0	7.4	5.2	1.4	5.0	-	49.9	17.0	32.9	NX13213096
L102	MGF^{LC}	36.9	34.1	2.8	8.0	6.4	1.6	9.6	3.4	0.6	3.0	-	38.7	14.1	24.6	NX13453090
L105	MGF^{LC}	34.9	31.3	3.6	9.7	6.3	3.4	11.1	1.4	0.4	6.2	-	36.3	9.5	26.8	NX14003098
L109	MFG^b	29.2	27.0	2.2	5.6	4.6	1.0	5.4	-	0.4	5.6	-	53.8	52.2	1.6	NX14093064
L111	MGF^b	39.4	35.8	3.6	6.8	6.2	0.6	12.1	1.8	-	2.0	-	38.0	23.7	14.3	NX14523028
L113	MGF^b	37.6	36.0	1.6	6.8	5.2	1.6	9.0	1.2	-	3.2	-	42.2	10.0	32.2	NX15803029
Mean	MGF^a	33.1	30.1	3.0	7.3	6.0	1.3	7.3	2.8	0.2	2.2	-	47.3	16.8	30.5	
Mean	MGF^{LC}	32.2	29.9	2.3	7.9	6.1	1.8	9.4	4.2	0.9	4.9	-	40.8	13.6	27.2	
Mean	MGF^b	35.4	32.9	2.5	6.4	5.3	1.1	8.8	1.0	0.1	3.6	-	44.6	28.6	16.0	
Mean		33.2	30.7	2.5	6.8	5.3	1.5	8.9	3.1	0.6	4.0	-	43.1	18.3	24.8	

Stratigraphic divisions:

PYF- Portayew Formation; MHF - Money Head Formation; FBF - Float Bay Formation; 'SBb' 'Stinking Bight beds'; GPF - Grennan Point Formation; MLF - Mull of Logan Formation (MLF^{TC} - The Chair Member; MLF^{DH} Duniehinnie Member; MLF^{DP} - Daw Point Member; MLF^{CF} - Carinie Finnart Member): PLF - Port Logan Formation; CBF - Clanyard Bay Formation (CBF^a - lower division; CBF^{PM} - Port Mona Member); MGF - Mull of Galloway Formation (MGF^a - lower division; MGF^{LC} - Leucarron Member; MGF^b - upper division).

Compositional classes:

Q_m - monocrystalline quartz; P_p - polycrystalline quartz; F_p - plagioclase feldspar; F_k - alkali-feldspar; A - acid igneous fragments; B - basic and intermediate igneous fragments; S - sedimentary rock fragments; M_t - metamorphic rock fragments; F_m - ferromagnesian minerals; M_{nc} - non-carbonate matrix; M_c - carbonate matrix. Q - total quartz; F - total feldspar; M - total matrix.

APPENDIX 4 - Ternary plot percentage compositions of sandstone point count data

SPECIMEN NO	FORMATION	M	Q	F + RF	Q	F	L	Q_m	F	L_t	Q_p	L_v	L_s	Q_m	F_p	F_k	Q	M	F
PF1	PYF	44	25	31	44	18	38	38	18	44	13	68	19	67	20	13	42	44	14
CF5	PYF	48	23	29	42	16	43	35	126	49	12	57	31	69	20	10	42	46	12
CF4A	PYF	32	28	40	40	18	42	33	18	49	15	60	25	64	28	8	45	33	22
Mean		41	25	33	42	17	41	35	17	47	13	62	25	67	23	10	43	41	16
CL2	MHF	14	28	58	33	12	56	23	12	66	15	53	33	67	24	9	57	21	22
CL3	MHF	13	37	50	42	11	47	33	11	57	17	55	28	75	20	5	62	17	21
MH2	MHF	21	25	54	33	20	47	27	20	54	13	73	14	57	36	7	48	23	29
MH4	MHF	21	30	49	39	14	47	34	14	52	10	73	17	71	17	12	47	28	29
J McC6	MHF	31	30	39	43	15	42	37	15	48	13	44	43	72	17	11	48	36	16
Mean		20	30	50	38	14	48	31	14	55	14	60	27	68	23	9	52	25	23
SF2	FBF	32	42	26	63	22	16	57	22	22	27	55	18	72	24	4	51	32	17
SF4	FBF	22	41	37	53	18	30	47	18	36	16	59	25	73	21	7	58	22	20
SF7	FBF	18	43	39	52	19	29	46	19	35	17	70	13	71	14	15	54	18	28
FB2	FBF	26	46	28	62	14	24	55	14	32	25	63	13	79	18	3	58	26	16
FB5	FBF	28	43	29	60	10	30	54	10	37	18	65	17	85	12	4	55	29	16
HS1	FBF	29	38	33	53	11	36	46	11	43	17	73	10	81	18	2	51	30	19
HS4	FBF	33	39	28	59	14	27	52	14	34	20	67	13	79	15	61	50	34	17
Mean		27	42	31	57	15	27	51	15	34	20	65	16	77	17	6	54	27	19
AN1	'SBb'	24	42	27	62	10	29	54	10	37	21	57	22	85	12	3	53	33	13
AN3	'SBb'	24	48	28	63	11	26	57	11	31	17	58	25	84	11	5	60	25	15
HO1	'SBb'	25	42	33	57	18	26	49	18	34	23	66	11	73	21	6	53	25	21
Mean		27	44	29	61	13	27	53	13	34	20	60	19	81	15	5	55	28	16

[Appendix 4 - continued]

SPECIMEN NO	FORMATION	M	Q	F + RF	Q	F	L	Q_m	F	L_t	Q_p	L_v	L_s	Q_m	F_p	F_k	Q	M	F
GP1	GPF	26	39	35	53	15	32	46	15	39	19	66	16	75	22	3	52	26	21
GP3	GPF	28	44	28	61	14	25	54	14	33	23	56	21	79	14	7	55	30	15
GP5	GPF	24	40	36	53	15	33	47	15	39	15	63	23	76	17	7	55	26	19
Mean		26	41	33	56	15	30	49	15	37	19	62	20	77	18	6	54	27	18
PP2	MLF^{TC}	18	32	50	40	12	47	30	12	57	18	55	28	71	18	9	56	21	23
PP4	MLF^{TC}	15	14	61	28	23	49	22	23	55	11	66	23	48	35	17	55	16	29
PP5	MLF^{TC}	17	23	60	28	14	57	20	14	65	12	72	16	58	33	8	51	19	30
DF1	MLF^{DH}	46	13	41	25	3	71	22	3	74	4	52	45	83	14	3	34	54	12
DF3	MLF^{DH}	10	27	63	31	23	46	27	23	50	8	59	33	54	37	9	53	13	34
L161	MLF^{DH}	15	31	54	36	25	39	32	25	43	10	56	34	57	37	7	48	20	32
L164	MLF^{DH}	31	28	41	42	15	43	38	15	47	9	64	27	72	21	7	39	35	26
L166	MLF^{DP}	20	28	52	35	17	48	28	17	54	11	68	20	62	30	8	53	20	28
L168	MLF^{CF}	41	38	21	65	14	20	60	14	25	20	76	4	81	17	2	46	41	13
L171	MLF^{CF}	33	44	23	65	13	22	60	13	28	21	65	14	83	16	1	53	33	13
Mean	MLF^{TC}	17	26	57	32	16	51	24	16	59	14	64	22	59	29	11	54	19	27
Mean	MLF^{DH}	26	25	50	34	17	50	30	17	54	8	58	35	67	27	7	44	31	26
Mean	MLF^{CF}	37	41	22	65	14	21	60	14	27	21	71	9	82	17	2	50	37	13
Mean		25	29	47	40	16	44	37	16	50	12	63	24	67	26	7	49	27	24
L174	PLF	29	54	17	81	6	17	65	6	33	49	17	34	91	8	1	64	29	7
L177	PLF	31	52	17	75	11	14	62	11	27	48	30	22	85	13	3	59	31	10
L179	PLF	29	56	15	78	3	19	65	3	32	42	32	26	96	3	1	63	32	5
L181	PLF	25	57	18	76	14	11	55	14	32	66	24	10	80	15	5	64	25	11
Mean		29	55	17	78	8	15	62	8	31	52	26	23	88	10	3	63	29	8

[Appendix 4 - continued]

SPECIMEN NO	FORMATION	M	Q	F + RF	Q	F	L	Q_m	F	L_t	Q_p	L_v	L_s	Q_m	F_p	F_k	Q	M	F
L184	CBF^{a}	43	32	25	56	12	31	53	12	34	9	73	18	81	18	1	44	44	12
L186	CBF^{a}	50	33	17	66	13	21	60	13	27	21	61	18	82	18	1	41	51	9
L7	CBF^{a}	41	37	22	63	15	22	59	15	26	14	55	30	80	18	2	45	43	12
L65	CBF^{PM}	28	50	22	71	7	22	47	7	46	52	15	33	87	11	2	61	30	9
L68	CBF^{PM}	26	56	18	75	7	18	47	7	47	61	15	24	88	9	3	66	27	7
Mean	CBF^{a}	45	34	21	62	13	25	47	13	29	15	63	22	812	18	1	43	46	11
Mean	CBF^{PM}	27	53	20	73	7	20	47	7	47	57	15	29	88	10	3	64	29	8
Mean		38	42	21	66	11	23	53	11	36	31	44	25	84	15	2	51	39	10
L70	MGF^{a}	47	33	20	61	16	23	55	16	30	23	65	13	77	19	4	42	47	11
L86	MGF^{a}	48	33	19	64	12	25	59	12	30	16	66	18	81	6	13	43	48	9
L91	MGF^{LC}	41	34	25	58	15	28	55	15	30	8	62	30	79	18	3	46	42	19
L94	MGF^{LC}	43	34	23	59	12	28	56	12	31	9	69	22	82	15	3	46	43	11
L97	MGF^{LC}	36	28	36	44	12	44	40	12	48	8	64	28	78	19	4	47	38	15
L100	MGF^{LC}	50	25	25	50	12	38	47	12	42	9	61	31	80	14	7	38	51	11
L102	MGF^{LC}	39	37	24	60	13	27	56	13	32	14	67	19	81	15	4	49	39	11
L105	MGF^{LC}	36	35	29	55	15	30	49	15	36	16	55	29	76	15	8	52	37	11
L109	MGF^{b}	54	29	17	63	12	256	58	12	30	127	39	44	83	14	3	40	54	6
L111	MGF^{b}	38	39	23	64	11	26	58	11	32	18	71	10	84	14	1	53	38	9
L113	MGF^{b}	42	38	20	65	12	23	62	12	26	11	68	21	84	12	4	50	42	8
Mean	MGF^{a}	48	33	20	63	14	24	57	14	30	20	66	16	79	13	9	43	48	10
Mean	MGF^{LC}	41	32	27	54	13	33	51	13	37	11	63	27	79	16	5	46	42	12
Mean	MGF^{b}	45	35	20	64	12	25	59	12	29	15	59	25	84	13	3	48	45	8
Mean		43	33	24	58	13	29	54	13	31	14	62	24	80	15	5	46	45	10

For stratigraphic divisions and compositional classes (excepting the Q-M-F plot) see Appendix 3, plus: $F + RF = F + A + B + S + M_t + F_m$; $L = A + B + S + M_t$; $L_t = L + Q_p$; $L_v = A + B$; and $L_s = S$. (For Q-M-F plot only: $Q = Q + A + M_t$; $M = M + S$; and $F = F + B + F_m$.)

APPENDIX 5 - The derivation, biostratigraphy and palaeobiogeographic significance of corals from Silurian deep-sea turbidite facies in the south-west Southern Uplands - SCRUTTON, C.T. and McCURRY, J.A. (1987).

(SEE INSIDE BACK COVER)

Declaration:-

(a) I, John A. McCurry, hereby certify that this thesis has been composed by myself, that it is a record of my own work, and that it has not been accepted in partial or complete fulfilment of any other degree or professional qualification.

Signed John A. McCurry Date 5th April 1989

(b) I was admitted to the Faculty of Science of the University of St. Andrews under Ordinance General No. 12 as a candidate for the degree of Ph.D. in October 1983.

Signed John A. McCurry Date 5th April 1989

(c) I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate to the Degree of Ph.D.

Supervisor's signature J.C. Walton Date 5 April 1989.

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The derivation, biostratigraphy and palaeobiogeographic significance of corals from Silurian deep-sea turbidite facies in the south-west Southern Uplands

COLIN T. SCRUTTON[1] and JOHN A. MCCURRY[2]
[1]*Department of Geology, The University, Newcastle upon Tyne, NE1 7RU*
[2]*Department of Geology, The University, St. Andrews, Fife, KY16 9ST*

SYNOPSIS

Two new records are described and one previous record reviewed of isolated coral colonies from Llandovery turbidites in the south-west Southern Uplands. Criteria allowing the distinction between modes of origin of such specimens by floatation, bedload transportation and/or reworking are discussed. Two of the specimens, the tabulate corals *Propora exigua* and *P. edwardsi*, are interpreted as derived from contemporaneous shelf environments and transported by floatation and sinking to their points of interment. The third, a rugose coral *Ceriaster* sp., was probably transported in the same way initially, but may have reached its final locus of deposition as part of a turbidite bedload. All three corals are of biostratigraphic or palaeobiogeographic interest. *Propora exigua* is characteristic of the Telychian whilst *P. edwardsi sensu stricto* has only been recorded previously from earlier Llandovery rocks near Girvan. The geographical range of the genus *Ceriaster* was hitherto restricted to Asia.

INTRODUCTION

Corals are only rarely encountered in sequences of turbiditic sediments. Although there are a few solitary rugose corals that were adapted to life in soft muddy deep-water environments (see Kullman 1975 for example), other scattered records are of coralla from shelf environments that were transported on or after death into basins with turbidite input. Such allochthonous coralla have been recorded previously from the greywacke sequences of the Southern Uplands and Longford-Down areas (Peach and Horne 1899; Griffith 1961; Rust 1965b). We describe here two new finds made by one of us (J.A.M.) and the opportunity is taken to revise the record of Rust (1965b).

Records of such material have been treated as curiosities in the past and accorded little attention. We wish to show that a careful analysis of these specimens and their mode of occurence can help to deduce their manner of derivation, which in turn may allow them to yield valuable biostratigraphic and/or palaeobiogeographic information.

Scott. J. Geol. **23**, (1), 49–64, 1987

Stratigraphy and field occurrence

Poorly fossiliferous Silurian greywackes crop out across the Central and Southern belts of the Southern Uplands. These rocks have usually been subdivided into four lithostratigraphic units considered to form a younging stratigraphic sequence, the Gala Group, Hawick Rocks, Riccarton Beds and Raeberry Castle Beds (Peach and Horne 1899; Cocks *et al.* 1971). However, there has been considerable uncertainty as to the spatial relationships and ages of these units. Recognition of the Southern Uplands as a thrust dominated terrane and its subsequent interpretation as an ancient accretionary prism (McKerrow *et al.* 1977, Leggett *et al.* 1979) have highlighted the continuity of deposition and contemporaneous deformation within the accreting sediment pile. This has modified, but not significantly changed stratigraphic interpretation and recently, attempts have been made to impose a more rigid, regionally applicable lithostratigraphy upon local tectonostratigraphic units (Barnes *et al.* 1987; Kemp 1986). A three-fold stratigraphic subdivision is now envisaged for the Central Belt (Fig. 1) with the Caradoc to Llandovery Moffat Shale Group of ocean floor hemipelagic sediments overlain by the Llandovery trench and deep-sea fan turbidite facies of the Gala and Hawick groups. The succeeding Wenlock turbidites and associated facies of the Southern Belt have been redefined as the Riccarton Group (Kemp 1986).

Rust (1963, 1965a,b) revised the stratigraphy of the Hawick Rocks in south-east Wigtownshire (now the Wigtown Peninsula of Dumfries and Galloway). He recorded an isolated colonial coral as *Heliolites* cf. *megastoma* Edwards and Haime from a red mudstone in his Carghidown beds, which on structural grounds he considered to be the lower of two divisions of the Hawick Rocks and dated late Llandovery in age. Barnes (in press) has reassessed the structural evidence and reverses Rust's stratigraphy, raising this division to formation status as the highest unit of the Hawick Group. On the basis of graptolite evidence from the subjacent and superjacent stratigraphic units, he suggests the Carghidown Formation to be of latest Llandovery (Telychian) *crenulata* Zone age. Rust's specimen, from the cliffs south of Morrach Farm [G.R. NX 468 348] (Fig. 1), is reidentified here as *Propora edwardsi* Nicholson and Etheridge. It is a corallum $70 \times 70 \times 100$ mm in size, which was found in growth orientation, showing no signs of pre-depositional erosion and no evidence of matrix other than the enclosing red mudstone. Apart from the coral, the maximum clast size in rocks of the area is <3 mm. Rust (1965b, p. 235) also recorded "... irregular elongate impressions suggestive of algal stipes, ..." in the red mudstones containing the coral. These have been re-examined and prove to be indeterminate simple exogene and possibly also endogene trace fossils.

Two isoloated colonial corals have been found in a recent resurvey of the Silurian sequence in the Rhinns of Galloway. Both specimens are also Llandovery

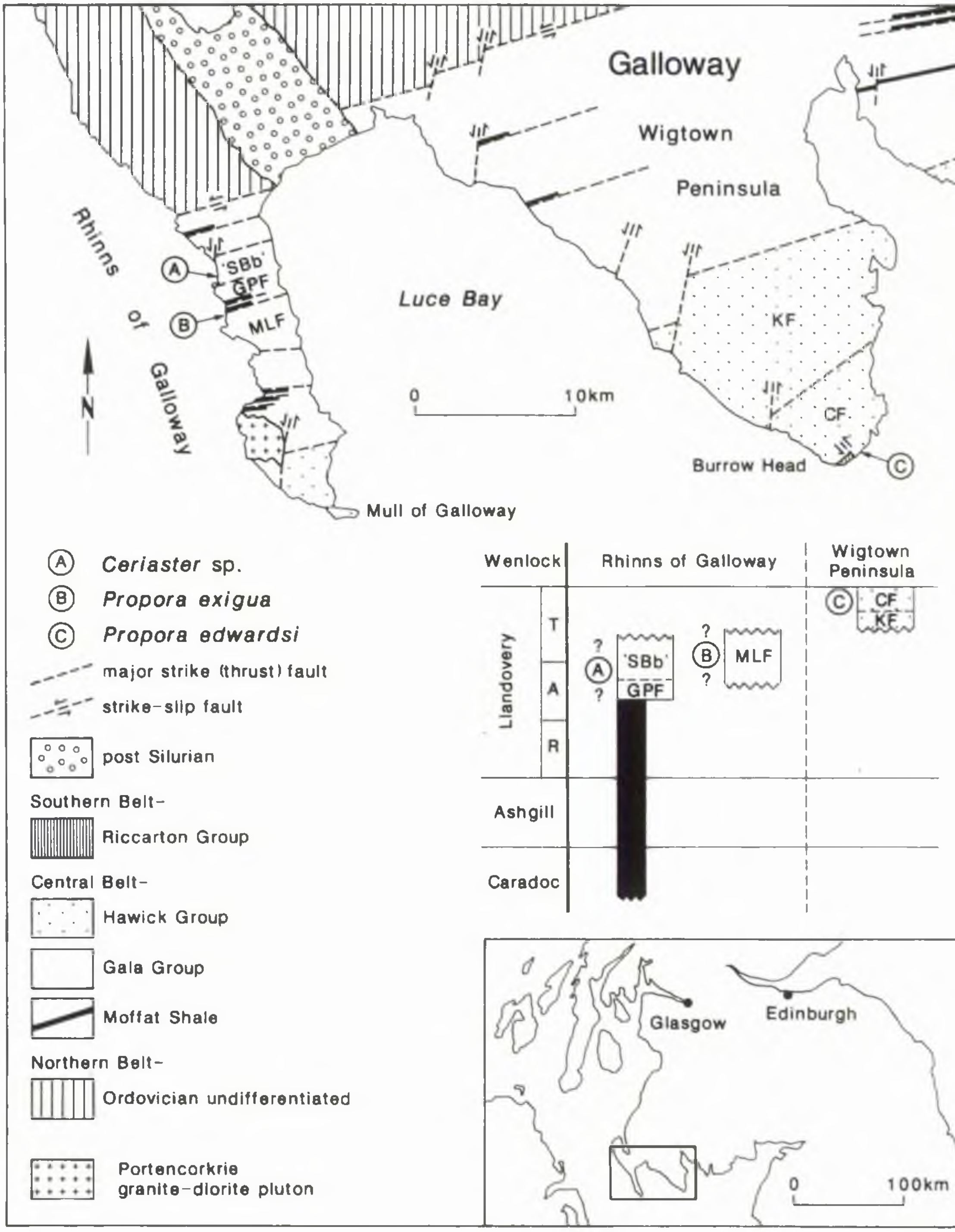

Fig. 1. Geological map of south-western Dumfries and Galloway indicating localities mentioned in the text and their stratigraphic relationships. Location of main map outlined in inset. Moffat Shale not differentiated in Northern Belt. Abbreviations: Llandovery stages—T, Telychian; A, Aeronian; R, Rhuddanian. Lithostratigraphic units—'SBb', 'Stinking Bight beds'; CF, Carghidown Formation; GPF. Grennan Point Formation; KF, Kirkmaiden Formation; MLF, Mull of Logan Formation. Based in part on Barnes *et al.* 1987.

in age (Gala Group lithology), although they can only be indirectly dated. The first, *Ceriaster* sp., was found 250 m north of Ardwell Bay [G.R. NX 0714 4551] (Fig. 1), in a 100 m thick sequence of massive (<2 m thick) granule to medium sand grade greywacke beds with thin interbedded mudstones. The succession here is referred to the informal 'Stinking Bight beds', a unit of unknown age but probably bracketed within a mid to late Llandovery, *cyphus* to *crispus* Zone range. It is tentatively ascribed an Aeronian *sedgwicki* Zone age. The well-preserved 30 × 15 × 10 mm fragment was found 150 mm above the sole of a 1 m thick coarse-tail graded T_{ae} turbidite forming a gritty matrix with granules <3 mm in size. Numerous moderately rounded mudstone rip-up clasts with cross sectional dimensions <40 × 30 mm were concentrated in, though not exclusive to, the basal part of the turbidite. The coral specimen was the only bioclast present in the bed and lacks any sign of exotic matrix.

The second specimen, identified as *Propora exigua* (Billings), is from the Chair Member, a sub-unit of the Mull of Logan Formation (Fig. 1). The exact age of the formation is unknown but evidence from adjacent tectonic units suggests that it lies within a mid to late Llandovery *sedgwicki* to *crispus* Zone range, with a latest Aeronian *sedgwicki* Zone or earliest Telychian *turriculatus* Zone age most likely. The specimen was found at Back Port [G.R. NX 0772 4285] in a 15 m wide zone of sheared mudstones and siltstones which contain a *ca* 3 m sequence dominated by greywacke beds. The mudstones and siltstones are predominantly light grey or green in colour, though red, brown and pale varieties are also present. They are well laminated, forming beds <35 mm thick, the thicker and coarser of which possess a distinct cross-lamination. The greywackes are coarse-tail graded coarse to fine sand grade turbidites which have undergone bedding-parallel ductile and brittle extension producing pinch and swell bedding, lenticular boudins and shear-bounded lozenges. The coral specimen was found upside-down in a small shear-bounded mudstone lens within the greywacke dominated sequence. It is a hemispherical corallum 140 × 110 × 45 mm in size with no associated exotic matrix, and although well-preserved has had part of its base removed by pressure-solution.

Source of coral material

General considerations

These three coral specimens are all colonial forms that are normally found in shelf carbonate or fine-grained clastic sediments. They were not adapted to life in basinal environments receiving turbiditic sedimentation. Their occurrence in these Llandovery greywacke sequences, interpreted as deep sea trench and ocean floor deposits, is the result, therefore, of one or a combination of two processes. Either the material was introduced as clasts in the transport loads of sediment gravity flows, particularly turbidity currents, or the coralla were transported by currents whilst floating in the water mass before becoming water logged and sinking. In the case of derivation in a turbidity flow, a further possibility is that a specimen could be reworked from older sediments.

It may be possible to distinguish among these options through the field occurrence, condition and petrography of the specimen. The important clues to reworking from pre-existing sediments would be the presence in or around a specimen of a matrix foreign to the final enclosing sediment (see, for example Sutherland 1970), or a clear discrepancy in age between the known stratigraphical distribution of the species represented and the dating of the sequence into which it was transported. The former in itself would not necessarily imply any significant difference in age between the origin of the specimen and its final resting place. The latter may involve degrees of uncertainty depending on the magnitude of the age discrepancy and the quality of the distributional data. However, none of the specimens described here has any sign of a pre-existing matrix and none can be demonstrated to show any significant discrepancy between its known range elsewhere (considered inadequately known in the case of *Propora edwardsi*) and the age of the sediments from which it was collected.

Material carried from a shelf environment by slump initiated turbidity flow might be expected to contain, if any, a variety of bioclasts and to be associated with the basal part of the resulting turbidite. One excellent example of such an association is described by Tucker (1969) from the Marble Cliff Beds in the Devonian basinal sequence of North Cornwall. Allochthonous blocks of the rugose coral *Phillipsastrea hennahi hennahi* (Lonsdale) up to 450 × 400 × 100 mm are concentrated at the base of a coarse, 400 mm limestone turbidite together with fragments of other corals, both solitary and colonial, stromatoporoids, ostracods, calcareous algae and indeterminate thick shell fragments. The records of shelly fossils from Lower Palaeozoic greywackes in Co. Down, on strike from the Southern Uplands, reported by Griffith (1961), appear to be mainly, if not wholly, of this type. Bioclasts might become more widely scattered in cases where population density in the source area was low and the distance of transport great. Even so, the petrography of the matrix might still provide evidence as to whether or not a bedload origin was likely for such bioclasts.

On the other hand, coral colonies transported by floatation before sinking though the water mass to be incorporated in bottom sediments are likely to be totally isolated bioclasts. Kornicker and Squires (1962) demonstrated experimentally how Recent coral heads may float for up to 8 months by virtue of air entrapped in the cellular skeleton following beaching and drying after death. They mention coralla ranging from complete and unworn, occasionally still with dried polypal tissues adhering, to worn and fragmentary coralla observed as transported in this way. Calculations by Abbott (1973) suggest that Palaeozoic colonial coral skeletons had densities of the same order as those of comparable Recent scleractinian coralla. Depending on ocean currents, such material could have had an extremely wide post-mortem distribution. Various shells capable of trapping air may be similarly distributed (see for example House 1973), but solid skeletal material could only be transported in a similar way through another agency providing bouyancy. Also it seems less likely that many solitary corals could entrap enough air to float for any length of time. Wells (1967) coined the term necroplotic for material transported post-mortem by floatation, although his particular specimen was later shown to be part of a local benthonic community by Sorauf (1977, 1978). This example suggests a cautious approach to interpretations based on isolation alone.

In the case of basinal environments, like those of the Llandovery in the Southern Uplands, when such material finally settles into bottom sediment, it is statistically most likely to be incorporated into slowly deposited fine grained sediments rather than the very rapidly deposited basal units of turbidites. Thus a large corallum or corallum fragment may become associated with a sedimentary regime suggesting current activity too weak to have moved the corallum by traction. The chance sinking of a specimen into an active turbidite must be a possibility, however, in which case a clue to its true origin might be the total lack of any other bioclasts. Although the recognition of such a specimen may be uncertain, the occurrence of an isolated, substantial, colonial corallum in basinal mud-grade sediments is a strong indication of derivation by floatation. As by its very nature, a specimen introduced in this way must be geologically contemporaneous in origin, it could yield important biostratigraphic information in otherwise unfossiliferous sediments. Although specimens transported by turbiditic flow may be similarly utilised, the possibility of unrecognised reworking from older sediments may lessen their value.

Southern Uplands corals

Of the three specimens considered here, the two tabulate corals, *Propora edwardsi* and *P. exigua*, both occur as isolated large coralla in mudstone units. Rust (1963, p. 14) initially concluded that his specimen had been *in situ*, and citing the presence of algal stipes in the red mudstone as supportive evidence, tentatively proposed a shallow water depositional environment for the Hawick Rocks. Both derivation by sediment transport and floatation were rejected, the former because the weak current strengths within a hemipelagic depositional environment would be inadequate to transport the corallum, the latter through lack of evidence of a sufficiently bouyant medium on which the specimen could have floated. Later Rust rejected this interpretation as incompatible with the general environment of sedimentation and on account of the unique character of the coral specimen. Instead, he advocated (1965b, p. 235) floatation on or within an algal mat to explain both the presence of the coral and his supposed algal stipes in the mudstone. Although his evidence for associated algal material has been discounted, a secondary bouyancy agency is not considered necessary to a necroplotic interpretation. We regard the evidence available strongly to favour transportation by floatation followed by sinking to the site of deposition for this specimen.

The specimen of *P. exigua*, although found within a thick mudstone unit and in a mudstone matrix, was associated with a band of sheared greywackes. The possibility that the coral could have sunk through liquifaction of the subjacent muds from the base of a turbidite is discounted. There are no structures in the sediments to support such an interpretation, although ductile shear could have obliterated the evidence. Neither is there any greywacke matrix associated with the coral. In any case, maximum clast size within the greywackes is 2 mm, with no other bioclasts present, so that transportation of this large corallum as part of a bed load is highly unlikely. The evidence again supports a derivation by floatation followed by sinking for the coral specimen.

The rugose coral *Ceriaster* sp. is a much smaller colonial fragment collected from near the base of a granule to medium sand grade greywacke. Numerous mudstone rip-up clasts present within the bed, commonly with dimensions much larger than those of the coral fragment, are evidence of the strong erosive nature of the turbidity current responsible for their deposition. The moderately rounded shape of the clasts and rarity of erosive sole markings within the sequence indicate that they have undergone significant transportation after incorporation. Their addition to the bedload probably inhibited further erosion from taking place along the base of the flow. Although the rip-up clasts are more concentrated towards the base of the bed, they do not form a distinct basal layer and are also found at higher levels. This distribution of the clasts within the bed suggests they formed part of the bedload and were transported by a combination of saltation, dispersive pressure and suspension. Clasts <3 mm were probably transported by both suspension and dispersive pressure. The coral fragment was clearly capable of being transported as a bioclast within such a high concentration flow in a manner similar to the rip-up clasts.

However, direct derivation from its location of growth through the sole agency of turbidity current transport is considered highly unlikely in the absence of any other bioclasts within the wholly siliciclastic greywacke. In addition, the possibility of reworking from earlier sediments either at the source of the turbidity current or along its path is not supported by the presence of any exotic matrix on or in the coral. Reworking from unconsolidated sediments cannot be discounted but still requires the introduction of a unique bioclast into the source environment before it could be incorporated into the current. We conclude that derivation by floatation is likely to have been a factor in the introduction of this specimen into the depositional basin, with or without significant subsequent transport in a turbidity current. The coral was therefore penecontemporaneous in life with the sediments in which it was found.

Biostratigraphic and palaeobiogeographic significance of the corals

Propora edwardsi

This species was first described by Nicholson and Etheridge (1880) from the Lower Llandovery (Rhuddanian) Woodland Formation of *cyphus* Zone age on the coast at Woodland Point, 3 km south of Girvan (see Cocks and Toghill 1973), in what are considered to be fore-arc basin deposits (Bluck *et al.* 1980; Leggett 1980). Although clearly defined, the species seems not to have been recorded outside Scotland. It is, however, closely related to and a possible synonym of the Upper Ordovician to Upper Silurian cosmopolitan species *P. conferta* Edwards and Haime. Specimens of this species approaching the *P. edwardsi* morphology are known from the late Ordovician through at least to the mid Llandovery. The specimen collected by Rust from the Wigtown Peninsula could have been beached and floated in from the nearest shelf environment on the north-western margin of the Iapetus Ocean (using present day orientation), although due allowance must be made for postulated major sinistral strike-slip movement along this margin (Dewey and Shackleton 1984; Soper and Hutton 1984). For example, Elders 1987 considers the Southern Uplands area to have been SE of Newfoundland in the late Ordovician on the basis of an analysis of derived granitic clasts. Rust's specimen was also reported as collected from sediments considerably younger than those at the type locality. The implication is that it might have been derived from either eastern Canada, or perhaps less likely northern Europe, rather than from the Girvan area. *P. conferta sensu lato* is relatively abundant in both areas, although no late Llandovery examples with the *P. edwardsi* morphology appear yet to have been recorded. The alternative, that the Carghidown Formation is somewhat older than currently suggested, is less favoured, both on the evidence of associated graptolite faunas (Barnes in press) and the very sparse data on *P. edwardsi*.

Propora exigua

Up until now, this species has been moderately widely reported from North America but only doubtfully recorded from Europe. Its European occurrence is confirmed here with a new record of *in situ* material from the later Llandovery Hughley Shales of the Welsh Borderland. In North America, *P. exigua* appears to be of mid to late Llandovery age although there is some uncertainty concerning its precise range, and particularly any pre-Telychian record. The European records are both latest Llandovery (late Telychian) in age. The floated-in specimen from the Southern Uplands, which is thought to be of latest Aeronian or earliest Telychian age, would therefore appear more likely to have been derived from the Scoto-North American shelf and to confirm at least early Telychian if not pre-Telychian records there. Alternatively, as the precise age of the Southern

Uplands specimen is uncertain, the biostratigraphic evidence of the coral could be taken as favouring a slightly younger age for the host rock.

Ceriaster sp.

This record is by far the most intriguing of all. Although *Ceriaster* is not a particularly common coral, it is certainly distinctive. To date it has been recorded only from the Llandovery of Asiatic Russia (Tadzhikistan) and China, He's (1980) younger Chinese records being erroneously dated (Rong Jia-yu, pers. com. 1986). No records of the genus, or even of its close relative *Stauria*, are known from North America. The Southern Uplands occurrence is thus of great interest. Whatever reconstruction of Silurian continental distributions is favoured, derivation from the known sources of *Ceriaster* would require floatation of considerable duration with favourable ocean currents (see for example Scotese *et al.* 1979). The oceanic circulation postulated by Ziegler *et al.* (1977, fig. 5) for the Silurian does include an appropriate edquatorial westerly current but suggests a separation at low latitudes of *ca* 100° longitude between a possible source area for the coral and the Iapetus Ocean! The alternative is that *Ceriaster* remains to be discovered in Llandovery shelf sediments of much greater proximity and probably on the Scoto-American side of Iapetus. The Southern Uplands specimen is considered not to match any of the described species of *Ceriaster*, which could be taken to favour the second alternative. From general considerations this also seems the more likely explanation and hopefully future records will confirm this conclusion.

Systematic palaeontology

This section sets out the evidence for the identification of the three corals under consideration as this is crucial to the paper. No broader systematic revisions are made, however, as they are considered inappropriate here. Classification and terminology follows the recent revisions of Hill (1981). The material is deposited in the Royal Museum of Scotland (RMS) and the Grant Institute of Geology, Edinburgh University (EDNCM).

Subclass Rugosa Edwards and Haime, 1850
Order Stauriida Verril, 1865
Suborder Stauriina Verril, 1865
Family Stauriidae Edwards and Haime, 1850
Genus Ceriaster Lindström, 1883

Remarks. He (1980) has established three new genera for the *Stauria–Ceriaster*

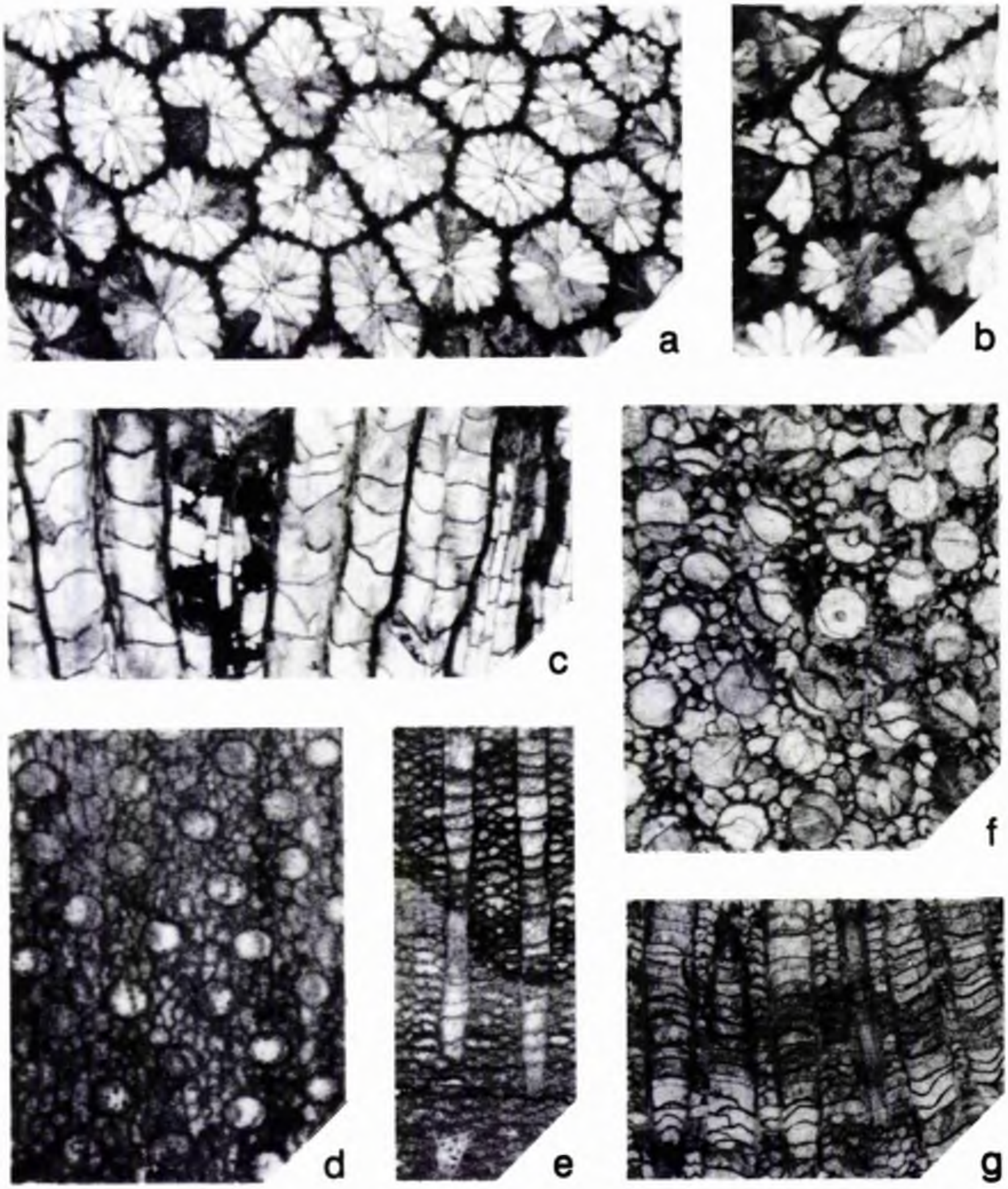

FIG. 2. a–c. *Ceriaster* sp. RMS 1986.24.1. Silurian, Llandovery, 'Stinking Bight beds', latest Rhuddanian–Telychian (*cyphus* to *crispus* Zone, tentatively considered most probably *sedgwicki* Zone). 250 m N of Ardwell Bay, Dumfries and Galloway [NX 0714 4551]. a, Cross-section; c, Longitudinal section, both ×8. b, Cross-section of corallite showing early stages of axial increase, ×10. d–e. *Propora exigua*. RMS 1986.24.2. Silurian, Llandovery, Mull of Logan Formation, latest Aeronian or earliest Telychian (*sedgwicki* to *crispus* Zone, most probably *sedgwicki* or *turriculatus* Zone). Back Port, Dumfries and Galloway [NX 0772 4285]. d, Cross-section; e, Longitudinal section, both ×6. f–g. *Propora edwardsi*. EDNCM 47,557. Silurian, Llandovery, Carghidown Formation (Hawick Group), late Telychian (*crenulata* Zone). Cliffs south of Morrach Farm, Wigtown Peninsula, Dumfries and Galloway [NX 468 348]. f, Cross-section; g, Longitudinal section, both ×6.

group. Not only are the discriminating features apparently rather minor but He appears to have introduced nomenclatorial problems. For the moment, the simple division into two genera, *Stauria* and *Ceriaster*, as defined by Hill (1981) is retained here. *Ceriaster* is recorded from the Llandovery of Asiatic Russia and from China where it is characteristic of latest Aeronian and Telychian (Rong Jia-yu, pers. com. 1986 *contra* He 1980)

Ceriaster sp.

(Figs. 2a–c)

Material. RMS 1986.24.1. Silurian, Llandovery, 'Stinking Bight beds', latest Rhuddanian–Telychian (*cyphus* to *crispus* Zone, tentatively considered most probably *sedgwicki* Zone). 250 m N of Ardwell Bay, Dumfries and Galloway [NX 0714 4551].

Description. Massive, cerioid corallum with mean corallite area 2·49 mm^2 (equivalent mean "diameter" 1·78 mm) and 10–12 major septa. Corallites prismatic. Major septa narrowly tapering, meet in axis except in juveniles. Minor septa a quarter to a half radius in length. Expanding septal bases merge into moderately thick wall with clear, straight to zigzag axial plate. Tabulae thin, spaced, flat, gently dished or shallowly inclined upwards to axial zone of septal intercepts. Mean spacing 0·67 mm. Subsidiary tabulae very rare. No dissepiments. Increase axial, parricidal, producing ?4 offsets; initiated at corallite areas of *ca.* 4 mm^2 (equivalent "diameter" 2·26 mm).

Remarks. This specimen is closest in general morphology and dimensions to *C. guanyinqiaoensis* He from the late Llandovery of China. The Chinese species has slightly larger corallites (4·07 $mm^2 \equiv$ 2·28 mm "diameter") with more major septa, fewer of which meet in the axis. Its tabulae are also much closer spaced. The type species, *C. calamites* Lindström (1883, p. 61, pl. 5, figs. 2–5) has similar tabulae but has even larger corallites with marginally fewer septa than the present specimen. Although the Scottish material appears not to belong to an existing species, it is considered inappropriate to erect a new species on a single, derived specimen.

Subclass TABULATA Edwards and Haime, 1850
Order HELIOLITIDA Frech, 1897
Superfamily PROPORICAE Sokolov, 1949
Family PROPORIDAE Sokolov, 1949
Genus PROPORA Edwards and Haime, 1849

Remarks. For the species of *Propora*, use is made of the average cross-sectional tabularial area as a percentage of the total cross-sectional area, a parameter introduced by Dixon (1974) and a more useful expression of tabularial density than tabularial spacing. Other measurements are standard.

Propora edwardsi Nicholson and Etheridge, 1880

(Figs. 2f–g)

1880 *Propora edwardsi* Nicholson and Etheridge, p. 270, pl. 17, figs. 3, 3a, b.

Material. EDNCM 47,557. Silurian, Llandovery, Carghidown Formation (Hawick Group), late Telychian (*crenulata* Zone). Cliffs south of Morrach Farm, Wigtown Peninsula, Dumfries and Galloway [NX 468 348].

Description. Propora with tabularia generally circular, smooth, lacking any signs of internal septa, but rarely with up to 12 trabecular swellings in a thickened wall and weak scalloping. Mean diameter 1·06 mm. Thin septa often extend from tabularia a short distance into the coenenchyme, occasionally forming an incomplete aureole of tubuli. Tabularia close spaced to rarely touching, occupying 41% of surface area. Coenenchyme regularly vesicular with short vertical trabecular spines sparsely scattered on small, uniformly sized dissepiments. Tabularia with flat to arched, rarely dished, moderately spaced tabulae 0·28 mm apart, mainly complete.

Remarks. This specimen is almost identical to the type specimen from Woodland Point, near Girvan. The species is very close, however, to the long ranging, cosmopolitan *P. conferta* Edwards and Haime as revised by Dixon (1974). *P. edwardsi* has a considerably smaller mean tabularium diameter than that reported in the type material of *P. conferta*; the enlargement of Lindström's figures (1899, pl. 8, figs. 32, 38) of the types can be confirmed as correctly stated from an examination of the original sections (see discussion in Dixon 1979, pp. 577–8). Nevertheless the Scottish species is very close to such species as *P. affinis* (Billings) and *P. cancellata* Lindstöm, placed in synonymy with *P. conferta* by Dixon (1974), as well as with Dixon's late Ordovician sample from Anticosti Island. It is distinguished by even stronger exothecal septal development than figured as the extreme in *P. conferta* by Dixon (1974, pl. 1, figs. 7–9). Although large samples are clearly very variable, there may be some justification in retaining *P. edwardsi* as a distinct species for the moment until the variation in related Llandovery populations is better understood.

Propora exigua (Billings, 1865)

(Figs. 2d–e)

1865 *Heliolites exiguus* Billings, p. 428.
1866 *Heliolites exiguus* Billings, p. 31, fig. 14.
1899 *Propora conferta* var. *minima* Lindström, p. 95, pl. 9, figs. 24–26.
1984 *Propora exigua* (Billings), Noble and Young, p. 869, figs. 4A, B, 5A, 6. (*cum syn.*)

Material. RMS 1986.24.2. Silurian, Llandovery, Mull of Logan Formation, latest Aeronian or earliest Telychian (*sedgwicki* to *crispus* Zone, most probably *sedwicki* or *turriculatus* Zone). Back Port, Dumfries and Galloway [NX 0772 4285].

Description. Propora with small aseptate tabularia mainly smoothly circular but sometimes gently scalloped with 12 segments. Mean diameter 0·70 mm. Tabularia distantly and evenly spaced in cross-section, separated by irregular intersects of vesicular coenenchymal tissue. Tabularial area averages 18% of cross-sectional area. In longitudinal section, vesicles of coenenchyme small and regularly developed, occasionally with zones of short, vertical, thin trabecular spines. Tabulae complete, gently dished, well but irregularly spaced, on average 0·39 mm apart.

Remarks. P. exigua is a distinctive species, well represented in the late Llandovery of eastern North America. Although the type specimen had been reported to come from the late Ordovician Ellis Bay Formation of Anticosti Island, it is clear from Dixon (1974, p. 579) that it was most probably originally from the late Llandovery (Telychian) Jupiter Formation. The species is also reported by Laub (1979, p. 343) from the Brassfield Formation of Indiana. Although the Brassfield Formation is generally of mid Llandovery age, it diachronously youngs to the north where the only locality to yield *P. exigua* is not independently dated and could be younger, although definitely pre-Wenlock in age. To these records can be added that in the late Llandovery of Gotland (Lindström 1899), and one of us (C.T.S.) has recovered several specimens from the late Llandovery Hughley Shales of Shropshire. Thus this species, apart from the doubt surrounding the date of the Brassfield specimen, appears to be reasonable indicator of a late Llandovery (Telychian) age.

Acknowledgements

We are most grateful to Ken Walton (University of St Andrews) for helpful comments on the manuscript and to Bernard Anderson (Queen's University, Belfast) who first spotted the specimen of *Ceriaster* in the field. We thank both Bill Baird (Royal Museum of Scotland) and Peder Aspen (University of Edinburgh) for curatorial help, and Christine Jeans and Brian Richardson (both University of Newcastle upon Tyne) for drafting Fig. 1 and preparing the thin sections respectively. C.T.S. gratefully acknowledges support from N.A.T.O. Research Grant no. 439/84 which has contributed to this project. J.A.M. completed this study during tenure of a research studentship from the Department of Education for Northern Ireland.

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Note added in proof

Whilst this paper was in press, new biostratigraphical information has been made available to us by Dr A. W. A. Rushton (British Geological Survey) as a result of his recent collecting for graptolite faunas in the Rhinns of Galloway.

Material from the 'Stinking Bight beds' indicates a *gregarius* Zone age. This implies that the fault separating these beds from the Grennan Point Formation is a major thrust juxtaposing two discrete structural blocks. The 'Stinking Bight beds' must be largely older than the Grennan Point Formation although possibly of equivalent age in their upper part in contrast to the sequence shown in Fig. 1. The specimen of *Ceriaster* sp. from the 'Stinking Bight beds' is thus of *cyphus* to *sedgwicki*, most probably *gregarius* Zone age and therefore possibly older than any of the previous records of this genus. This lends support to the suggestion that the specimen was not derived from any of the currently known areas of occurrence of the genus.

Graptolites from the Mull of Logan Formation indicate a probable *turriculatus* Zone age. The specimen of *Propora exigua* is most likely to be of *turriculatus* or *crispus* Zone age and thus more closely in agreement with the more securely dated Telychian range of this species established elsewhere. This vindicates the suggestion of a younger age for the Mull of Logan Formation tentatively proposed on the evidence of this coral.

We are grateful to Dr Rushton for allowing us to quote this information.

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Along-strike variation in the stratigraphical and structural profile of the Southern Uplands Central Belt in Galloway and Down

R. P. BARNES[1], T. B. ANDERSON[2] & J. A. McCURRY[3]

[1] *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK,*

[2] *Department of Geology, The Queen's University of Belfast, Belfast BT7 1NN, UK*

[3] *Department of Geology, The University of St. Andrews, St. Andrews, Fife KY16 9ST, UK*

Abstract: The modern interpretation of the Southern Uplands depends on the recognition of laterally extensive, linear, fault-bounded tracts of northward-younging Lower Palaeozoic sediments with rare volcanics. The tracts become progressively younger southwards and are thought to have been sequentially accreted by northward underthrusting above a subduction zone.

Detailed mapping and tentative correlation of three, well-exposed, coastal profiles through the Central Belt in SW Scotland and NE Ireland offers a new test of the Southern Uplands model. Comparison of the northern parts of each section indicates the presence of strike-parallel tracts with model structure. Moffat Shale outcrops associated with the tract-defining faults demonstrate a diachronous, incremental, southerly decrease in the age of the base of the overlying turbidites, essentially as in the Northern Belt. Southward this becomes markedly less pronounced, particularly in Down where the Central Belt is much wider than in Galloway. Distinctive Hawick Group lithologies permit the correlation of the southern parts of the sections. Large areas of predominantly southward-younging occur in each section, especially in Galloway where the southward-younging area is 12 km across. Here northerly-verging D_1 fold pairs are consistent with observed fault movement opposite in sense to the northerly underthrusting of the model. Back thrusting, in the style of the Pleistocene Cascadia Basin, is invoked to account for the landward-verging structure of these areas and to explain the narrowing of the Central Belt in Galloway.

The structure of the Central Belt thus differs significantly from that of the Northern Belt and the accretionary prism model.

The Southern Uplands were sub-divided into three strike-parallel 'belts' (Fig. 1), for the "sake of convenience of description" by Peach & Horne (1899). Simply termed the Northern, Central and Southern Belts, they are composed of Ordovician, mainly Llandovery and Wenlock strata, respectively. These divisions have since proved to be fundamental in the interpretation of Southern Uplands geology, each belt having distinctive characteristics.

The Northern Belt is divided into a number of strike-parallel tracts of greywacke by discontinuous narrow outcrops of fossiliferous black mudstone and chert (Moffat Shale), rarely including basic lavas. The thin Moffat Shale successions are clearly the imbricated repetitions of a pelagic sequence which forms the base of the stratigraphical sequence in each tract. The overlying greywackes young very consistently NNW although a few southward-younging short limbs of south-easterly-verging F_1 folds do occur. The base of the greywacke sequence becomes progressively younger southwards in successive tracts and the sandstone in each is compositionally distinct (e.g. Floyd 1982). The published maps (e.g. Leggett *et al.* 1979, fig. 2, 1982, fig. 3) show tracts of remarkably consistent width, typically about 5 km, persistent for at least 30 km, and commonly over 100 km, along strike. These Northern Belt stratigraphical and structural relationships are the essential basis of the accretionary prism model for the Southern Uplands as a whole. The model was conceived in the Northern Belt and is still largely substantiated by observations made in that area.

The distinctive Northern Belt pattern is generally assumed to continue southwards into the Central Belt but the basis of this assumption is weakened by the evidence of major sinistral displacement on the Orlock Bridge Fault separating the two belts (Anderson & Oliver 1986). The relatively small amount of detail published from the Central Belt pre-dates the accretionary prism model, with the exception of Cook & Weir (1979, 1980), Stringer & Treagus (1980, 1981) and Webb (1983) in Scotland, and Anderson (1978), Anderson & Cameron (1979) and Cameron (1981) in NE Ireland. The Central Belt has two distinct parts. The northern part is characterized by the proximal turbidite facies of the Gala Group, in which the sandstone is usually quartzose in composition although locally pyroxenous. Moffat Shale inliers occur but are much less continuous than those farther north, defining relatively indistinct tracts. The southern part of the Central Belt is composed of an extremely uniform, relatively distal turbidite facies (the Hawick Group), in which the sandstone is compositionally distinct from Gala Group sandstone by virtue of its high content of primary carbonate detritus.

Recent work in three well-exposed coastal sections of SW Scotland and NE Ireland (Fig. 1) allows detailed cross-strike and along-strike analyses of the Central Belt (see below).

The Southern Belt is composed of Wenlock greywackes of varied facies, unique in the Southern Uplands in that they can be precisely dated by the common occurrence of fossiliferous, argillaceous siltstone beds. As in the Northern Belt, a number of strike-parallel fault-bounded tracts become younger southwards (e.g. Kemp & White 1985), although important areas of southward-younging strata (e.g.

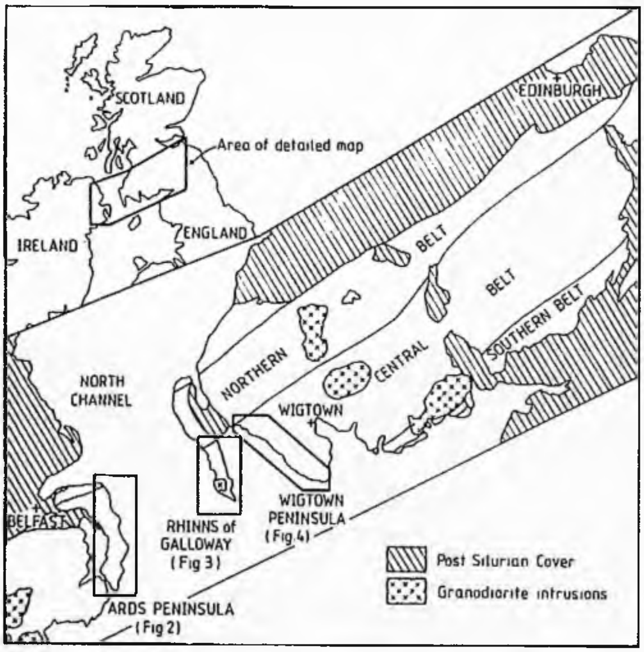

Fig. 1. The locations of the three study areas with respect to the broad subdivisions of the Southern Uplands of Scotland and NE Ireland.

Warren 1964) suggest possible similarities of Central Belt structures (see below).

The Central Belt in Down and Galloway

A brief summary of the stratigraphical and structural characteristics of each area is given, supported by maps, including structural detail (Figs 2–4), and biostratigraphical detail (Fig. 5). In each of the three areas strike-parallel faults separate a number of structural 'blocks' with distinctive lithostratigraphies. In the northern parts of the areas these faults are marked by outcrops of Moffat Shale. Otherwise the blocks comprise turbidite sequences described below with reference to the classification of turbidite facies (A to G) described by Walker & Mutti (1973).

Ards Peninsula (*Fig.* 2)

The Northern and Central Belts are separated by the major Orlock Bridge Fault, described in detail by Anderson and Oliver (1986). Aspects of the stratigraphy and structure of the Central Belt in County Down have been recorded by Anderson (1962, 1969, 1978), Anderson and Cameron (1979), Cameron (1981) and Griffith and Wilson (1982). Reynolds (1931) described the numerous minor intrusions.

The northernmost (Donaghadee) Block is a composite of several structural slices with three repetitions of Moffat Shale and an infaulted wedge of Ashgillian strata (the Portavoe Formation). The Moffat Shales range up to the *Monograptus cyphus* Zones and are conformably succeeded by turbidites, of variable but predominantly coarse clast size (facies C, Walker & Mutti 1973), including rare conglomerates of intrabasinal origin (A_2). Interstratified silty mudstone beds are generally less than 0.2 m thick. Laminated shale (G), in units up to 10 m thick, crops out locally within the turbidites. The narrow Coalpit Bay Block exposes the best-preserved Moffat Shale sequence in Ireland, overlain in the *M. sedgwickii* Zone by some 20 m of thickly bedded, coarse-grained greywacke (C). Massive coarse sandstone ($C(B_2)$) in beds up to 4 m thick with very well developed sole markings, dominates the Millisle Block, although a distinctive 40 m unit of siltstone and red mudstone is also present. Thickly bedded, massive sandstone (C), with interbedded bentonite bands (Anderson and Cameron 1979), crops out at the base of the succession in the Ballywhiskin Block. The greywacke sequence fines upward into siltstone and shale (D) with some red mudstone bands. A few monograptids have been obtained from shales (G) near the top of the succession. The siltstone (D) composing the northern part of the Ballywalter Block has abundant carbonate concretions and some thin limestone beds. The succession again includes thin red mudstone beds. In the southern part of the block more normal, quartz-rich, thinly bedded, fine sandstone and siltstone (D) crop out. The Wallace's Rocks Block comprises a variable sequence of coarse- to fine-grained greywacke ($C(A_4)$ and D). Two formations, predominantly of sandstone, crop out in the Portavogie Block. The Rowreagh Formation is medium- to coarse-grained (C) with interbedded black graptolitic shales demonstrating *M. crispus* Zone age. The succeeding Portavogie Formation is generally finer grained (C(D)) and unfossiliferous. Thin red mudstone bands occur in interbedded siltstone units. Both sandstones and siltstones show evidence of extensive intra-bed slumping and soft-sediment deformation. In the Portaferry Block there is extensive coastal outcrop of a succession of well-defined stratigraphical units. Coarse greywackes of the Tara Formation (C) include some thin but persistent bands of black shale with a *M. crispus* Zone fauna. These are overlain by some 100 m of dark siltstone and mudstone (D(G)) with numerous thin red mudstone beds at the base of the thick (>500 m) Kearney Formation. The Kearney Formation consists largely of thinly bedded, carbonate-rich siltstone and shale (C) with a few beds of coarse pebbly greywacke (A_4). Inland drainage work has recently produced a temporary section in Moffat Shales at the hinge of an anticline in the Tara Sandstones. The shales range in age from late Ordovician up to *Rastrites maximus* Subzone and are apparently sliced and repeated by faulting. The Ballyquintin Formation (D), which composes the most southerly fault block, closely resembles the carbonate-rich Kearney Formation described above.

Throughout the peninsula the sandstone is monotonously quartz-rich. No petrographical equivalent of the pyroxene-bearing greywacke of the Central Belt in SW Scotland has been recognized. Thin bentonite bands, though rare and difficult to recognize in the coarse sandstone formations, crop out in each of the nine blocks.

The structure of the northern blocks is characterized by strata dipping steeply south but younging north (Fig. 2), although major and minor F_1 fold pairs obviously produce significant southerly-younging tracts, particularly in the Millisle and Ballywalter Blocks. The Portavogie Block is dominated by the vertical, 1.7 km thick, southward-younging, northern limb of the Castle Hill–Portavogie Syncline. The siltstones of the two most southerly blocks are intensely folded with the sheet dip typically sub-horizonal or inclined gently to the north. F_1 fold axes plunge gently or moderately eastwards throughout the Peninsula except in the northern parts of the Ballywalter Block and in outcrops on the SW coast of the Portavogie Block, where steep to

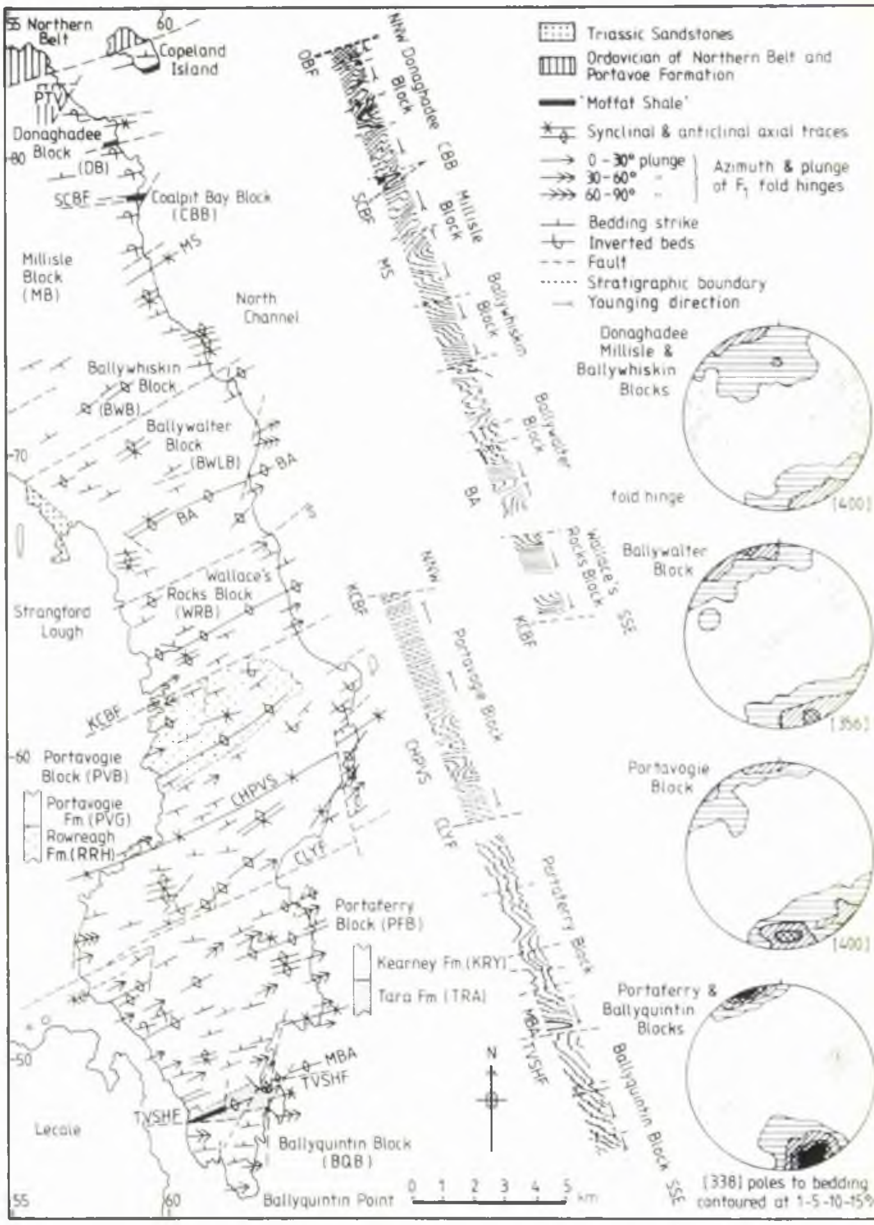

Fig. 2. Geological map of the Ards Peninsula, County Down. BA, Ballywalter Anticline; CHPVS, Castle Hill–Portavogie Syncline; CLYF, Cloughy Fault; KCBF, Kircubbin Fault; MBA, Millin Bay Anticline; MS, Millisle Syncline; OBF, Orlock Bridge Fault; PTV, Portavoe Formation; SCBF, Southern Coalpit Bay Fault; TVSHF, Tieveshilly Fault.

vertically plunging F_1 folds are common. The S_1 cleavage is either parallel to the axial surfaces of F_1 folds, as it is throughout the Ballyquintin Block, or transects them clockwise at an angle of some 10–20°, as it does throughout the Portaferry Block (see Anderson this issue). Later folds are only developed in the two most southerly blocks, where open, southward-verging F_2 folds have gently inclined axial surfaces and are associated with a well-developed crenulation cleavage (Anderson and Cameron 1979).

Lamprophyre dykes occur throughout the peninsula but are common only in the three most southerly blocks. The 'Older Series' of Reynolds (1931) is typically composed of bed-parallel mica-lamprophyres carrying a tectonic foliation continuous with the S_1 cleavage in the intruded sediments of the Portaferry and Ballyquintin Blocks. Unfoliated dykes of the 'Newer Series' crop out in all nine blocks but are common only in the Portavogie Block.

Rhinns of Galloway (*Fig.* 3)

Despite the excellent coastal sections, the recent work is the first since this area was mapped by the Geological Survey (Irvine 1872).

The northernmost unit, the Money Head Block, consists of massive, coarse-grained greywacke (facies $A_4B_2(C)$) in beds varying from 1 to 10 m in thickness, with subordinate thinly bedded siltstone and fine-grained greywacke (F), overlying an intensely imbricated Moffat Shale sequence. The greywackes include a 400 m wide tract which is petrographically distinct, being markedly pyroxenous. The Float Bay block consists of 1 m thick greywacke beds (C) interdigitated with units of silty mudstone (G(E)) which vary from 2 to 100 m in thickness. Thickly bedded, medium- to coarse-grained turbidites ($C(A_4B_2)$) dominate the Ardwell Point Block, although interbedded silty mudstone

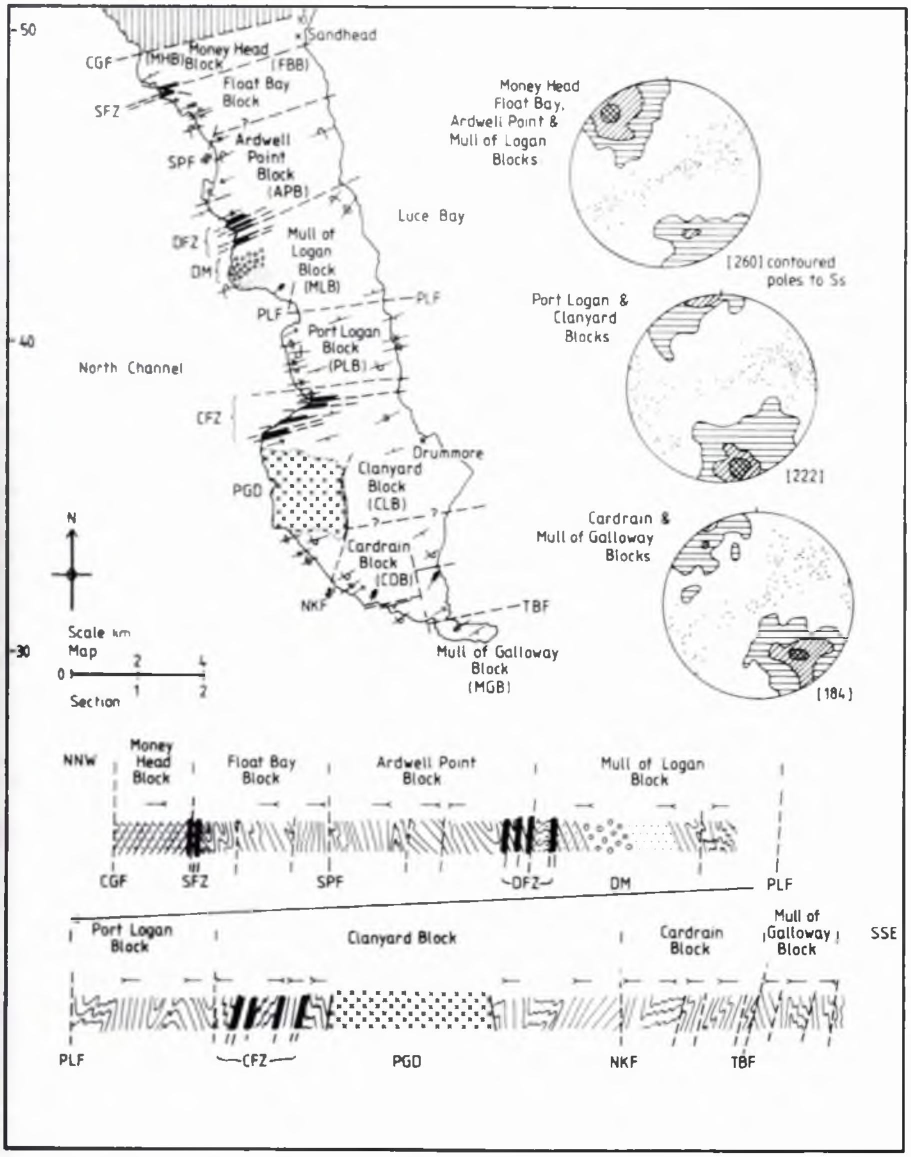

Fig. 3. Geological map of the southern part of the Rhinns of Galloway. CFZ, Clanyard Bay Fault Zone; CGF, Cairngarroch Fault; DFZ, Drumbredan Bay Fault Zone; DM, Duniehinnie Member; NKF, Nick of Kindram Fault; PGD, Portencorkrie Granodiorite; PLF, Port Logan Bay Fault; SFZ, Strandfoot Fault Zone; SPF, Salt Pans Bay Fault; TBF, Tarbet Fault. Other symbols as for Fig. 2.

units with red mudstone beds occur near the base of the succession. The Mull of Logan Block has a distinctive lithostratigraphy. Medium- to coarse-grained greywacke in beds less than 1 m thick (C(E)) is overlain by a sequence of coarse-grained massive sandstone (A_3A_4) and a 500 m thick conglomerate unit (F) (the Duniehinnie Member). The latter member consists of well-rounded, poorly organized intrabasinal clasts with more angular blocks (up to tens of metres in diameter) of greywacke and siltstone occurring near the northern margin. In the Port Logan Block medium- to coarse-grained greywacke (C), forming both fining and coarsening upward sequences, includes units of laminated silty mudstone (E & G) up to 120 m thick. The structurally repeated Moffat Shale inliers at the northern margin of the Clanyard Block are overlain by medium- to coarse-grained, thickly bedded greywacke (C(BD)) with interbedded thin black shale bands and thick (up to 40 m) silty mudstone units (G(E)). South-west of the Nick of Kindram Fault, fine-grained, calcareous greywacke beds less than 60 cm thick are separated by green-grey silty mudstone with thin red mudstone beds (C & D). Coarser grained channelized greywacke beds occur locally in units up to 5 m thick.

The structure of the Rhinns of Galloway broadly conforms to a major anticlinorium with its axial region centred on the Port Logan Bay Fault. North of this fault strata are dominantly northward-younging, and bedding and S_1 cleavage dip steeply to the south. South of the fault strata are dominantly southward-younging with bedding and cleavage inclined at a steep to moderate dip to the north. The sheet dip in these two areas descends steeply to the north and south, respectively, although locally becoming more gently dipping. Major faults north of the Port Logan Bay Fault have a southerly downthrow whereas south of this fault their movement direction is more variable although most throw down to the north. F_1 folds are typically close to isoclinal with angular hinges plunging gently to moderately NE or SW. In large areas adjacent to the faults fold hinges may plunge steeply, becoming locally downward-facing as a result of rotation by post-S_1 shearing. A penetrative slaty or pressure-solution cleavage developed through the area usually transects fold axial surfaces.

Post-F_1 folds form open to close and intermediate scale structures. Southerly-verging F_2 folds become increasingly common southwards and are associated with a crenulation cleavage (S_2). Later northerly-verging folds and associated thrusts occur most commonly in the southernmost two blocks. A system of late conjugate faults affects the whole area although N–S sinistral fractures generally predominate.

Lamprophyre and felsic dykes are abundant in the Rhinns of Galloway (e.g. Read 1926). Hornblende lamprophyres occur throughout the peninsula but biotite lamprophyres are restricted to its southern tip.

Wigtown Peninsula (*Fig.* 4)

In Wigtownshire a thick drape of boulder clay obscures much of the coastline. Inland exposure compensates for this to some extent although a broad, strike-parallel belt between Mochrum and Monreith is generally very poorly exposed. Gordon (1962) described the northern part of this area in detail and the southern part has been described by Rust (1965) and Barnes in press. Detail or the minor intrusions has recently been given by Barnes *et al.* (1986).

The northernmost three blocks, separated by Moffat Shale outcrops, are dominated by thickly bedded, massive or poorly graded, fine- to coarse-grained greywacke (facies B_2). In the Kilfillan Block, very thickly bedded, massive greywacke units (up to 100 m thick) are separated by units of relatively thinly bedded greywacke and sparsely fossiliferous silty mudstone (C); several slumped sequences also occur. The contact with the Moffat Shale at the southern edge of this block (exposed in Gillespie Burn, NX 257 539) is gradational. The first 50 m of the greywacke sequence includes fossiliferous mudstone beds which young northwards from *Alcdographis acuminatus* to *Coronographis cyphus* zones. Graptolites representative of these zones also occur in a few thin mudstone beds in the 5 km long coastal section. However, here they become younger southwards, suggesting that a number of structural slices must be present. Moffat Shale exposed in the south of the Garheugh Block is intensely deformed and only provides a maximum age for the base of the turbidite sequence. In the Garheugh coast section 500 m of relatively thinly bedded (0.5–1 m) greywacke (C) incorporates 10 m of laminated siltstone and silty mudstone with red mudstone bands (D) and two bentonite bands. Towards the northern edge of this block a single pebbly arenite/rudite bed (30 m thick) and a few metres of 'blocky arenite' are exposed. Blocky arenite (F) (massive fine- to coarse-grained sandstone packed with angular siltstone and greywacke blocks up to 0.5 m diameter) is well developed in the northern part of the Corwall Block where it occurs towards the top and base of a 700 m thick unit of medium- to very coarse-grained massive sandstone. This is overlain by fine-grained greywacke and sparsely fossiliferous laminated siltstone (C). To the south,

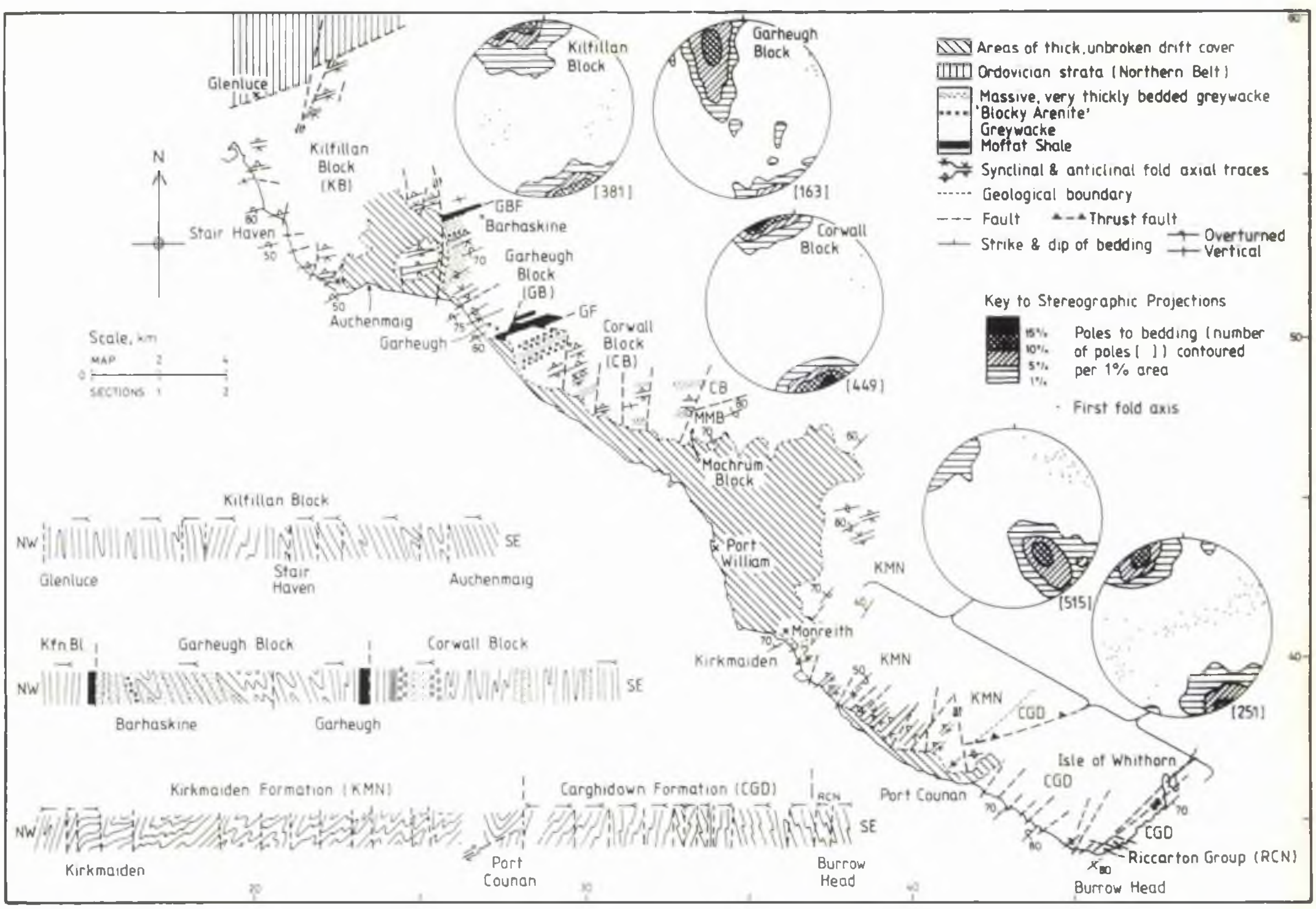

Fig. 4. Geological map of the western coastal area of the Wigtown Peninsula. GBF, Gillespie Burn Fault; GF, Garheugh Fault. Other symbols as for Fig. 2.

fine-grained, thin- to medium-bedded greywacke and interbedded silty mudstone (C) (locally yielding sparse *M. turriculatus* Zone faunas) include thick, massive sandstone sequences ($(A_4)B_2$). Near Mochrum, a few exposures of fine-grained greywacke beds (up to 1 m thick), with well-developed sole marks, in a relatively high proportion (*c.* 40%) of laminated silty mudstone are tentatively separated as the Mochrum Block.

From Monreith to Burrow Head a very uniform sequence comprises interdigitating units of fine-grained, medium to thinly bedded (less than 0.6 m) greywacke, with silty mudstone partings thin or absent (C), and laminated silty mudstone with very thin beds of fine-grained greywacke or siltstone (D). Rare thicker beds of poorly graded or massive greywacke (B_2) range from fine- to coarse-grained and are often channelized. These strata are subdivided into the Carghidown Formation, in which red mudstone beds become thinner and less common northwards, grading into the Kirkmaiden Formation without red mudstone. At Burrow Head fossiliferous (*M. centrifugus* to *M. riccartonensis* Zones), carbonaceous laminated siltstone beds indicate that the greywacke sequence is part of the Riccarton Group (Southern Belt). A few thin black mudstone laminae, which occur in the greywacke sequence at Kirkmaiden, yield a *M. griestoniensis* Zone fauna. The only evidence for the age of the Carghidown Formation is that it may be stratigraphically overlain by the Riccarton Group strata at Burrow Head (Barnes in press).

The structure of the well-exposed parts of the Wigtown peninsula is dominated by steeply dipping, northward-younging strata with the notable exception of the Kirkmaiden Formation outcrop which is intensely folded. In detail different sectors, corresponding in the north of the area with individual blocks, are structurally distinct (see stereograms, Fig. 4). The limited outcrop in the area between Mochrum and Monreith is dominantly southward-younging. Farther south, faults defining structural blocks cannot be identified. Minor reverse faulting is common locally and varies from D_1 to D_2 in age. Major folding is rare south of Port Counan, the only large southward-younging fold limb being that which includes the Carghidown Formation–Riccarton Group Boundary. The widely variable plunge of F_1 folds in this sector is due both to strongly curved folded hinges, locally downward facing, and to the common occurrence of steeply plunging sinistral fold pairs. The latter also occur in a narrow strike-parallel belt which crops out on the shore at Monreith.

Post-D_1 structures are best developed in the area SE of Monreith where open to close, steeply inclined D_2 folds are locally well developed. These occur together with a conjugate set of recumbent, open D_2 folds at Kirkmaiden. Rare, northward-verging, open folds occur in the Carghidown Formation and also in the Garheugh Block. Conjugate N–S and NW–SE wrench faults are locally well developed.

Dykes occur through the Wigtown peninsula and include widespread hornblende lamprophyres and a range of felsic types. Biotite lamprophyres are restricted to the Hawick and Riccarton Group outcrops where they are abundant. All dykes post-date F_1 and S_1 but their complex relationships with D_2 folds and the conjugate wrench faults indicate an alternation of extensional and compressional events (Barnes *et al.* 1986).

Correlation

Comparing the results of the three studies it is immediately evident that correlation is difficult because of the limited lithostratigraphical variation and the lack of other distinctive characteristics.

The successful use of greywacke composition as the principal means of correlation in the Northern Belt cannot be extended into the Central Belt because of the very much more uniform composition of the sandstones. However, correlation in the Central Belt is possible in two ways: (1) by comparing the lithostratigraphy of each block, constrained by the limited biostratigraphical evidence, and (2) by comparing the structure (principally D_1) of the different areas. These criteria are quite distinct and are considered separately below. One important change along strike, immediately apparent from Fig. 1, is a widening of the Central Belt from 30 km in Wigtownshire to a minimum (no Southern Belt Strata being exposed) of 45 km in NE Ireland. Although the apparent width in Wigtownshire is reduced by N–S sinistral wrench faulting, this cannot entirely account for the increase in width to the west, which is reflected in the greater number of blocks recognized in the Ards Peninsula.

Stratigraphical correlation

The three areas are broadly comparable in the predominance of proximal, medium- to coarse-grained turbidite facies (Gala Group) in the north as distinct from the relatively distal, fine-grained, carbonate-rich greywacke and silty mudstone facies (Hawick Group) seen in the south. Strata attributable to the Hawick Group (Fig. 6) are of very similar lithology in all three areas and are also of similar age (Fig. 5). The northern boundary of the Hawick Group in the Ards Peninsula is the strike-parallel Cloughy fault. Southwards the succession in the Portaferry Block is unique in that the Kearney Formation of the Hawick Group stratigraphically overlies the Tara Formation, of Gala Group lithology and age, and this in turn rests on Moffat Shale.

Three Gala Group blocks recognized in the northern part of the Wigtown area correlate readily with the northern blocks in the Rhinns of Galloway on the basis of distinctive lithological elements. The 'blocky arenite' exposed in the Corwall Block is seen in a more proximal form (the Duniehinnie Member) in the Mull of Logan Block. Moffat Shale is exposed at the base of the Garheugh and Ardwell Point blocks, with turbidite sedimentation from about *C. gregarius* Zone or lower *M. convolutus* Zone in both. Units of silty mudstone and siltstone with red mudstone beds occur in the lower part of a dominantly massive sandstone sequence in both areas. The composite Kilfillan Block is probably equivalent to the Money Head and Float Bay blocks of the Rhinns of Galloway; the turbidite successions in the Float Bay and Kilfillan blocks are very similar, being characterized by massive sandstone sequences separated by greywacke and silty mudstone. Poorly fossiliferous mudstone beds in the Float Bay Block are of similar age (*C. cyphus*) to strata in the Kilfillan Block. The poorly exposed Mochrum Block has some sedimentological characteristics in common with the Port Logan Block. No equivalent of the Clanyard Block is recognized in Wigtownshire, possibly because of faulting and poor exposure in the vicinity of Port William.

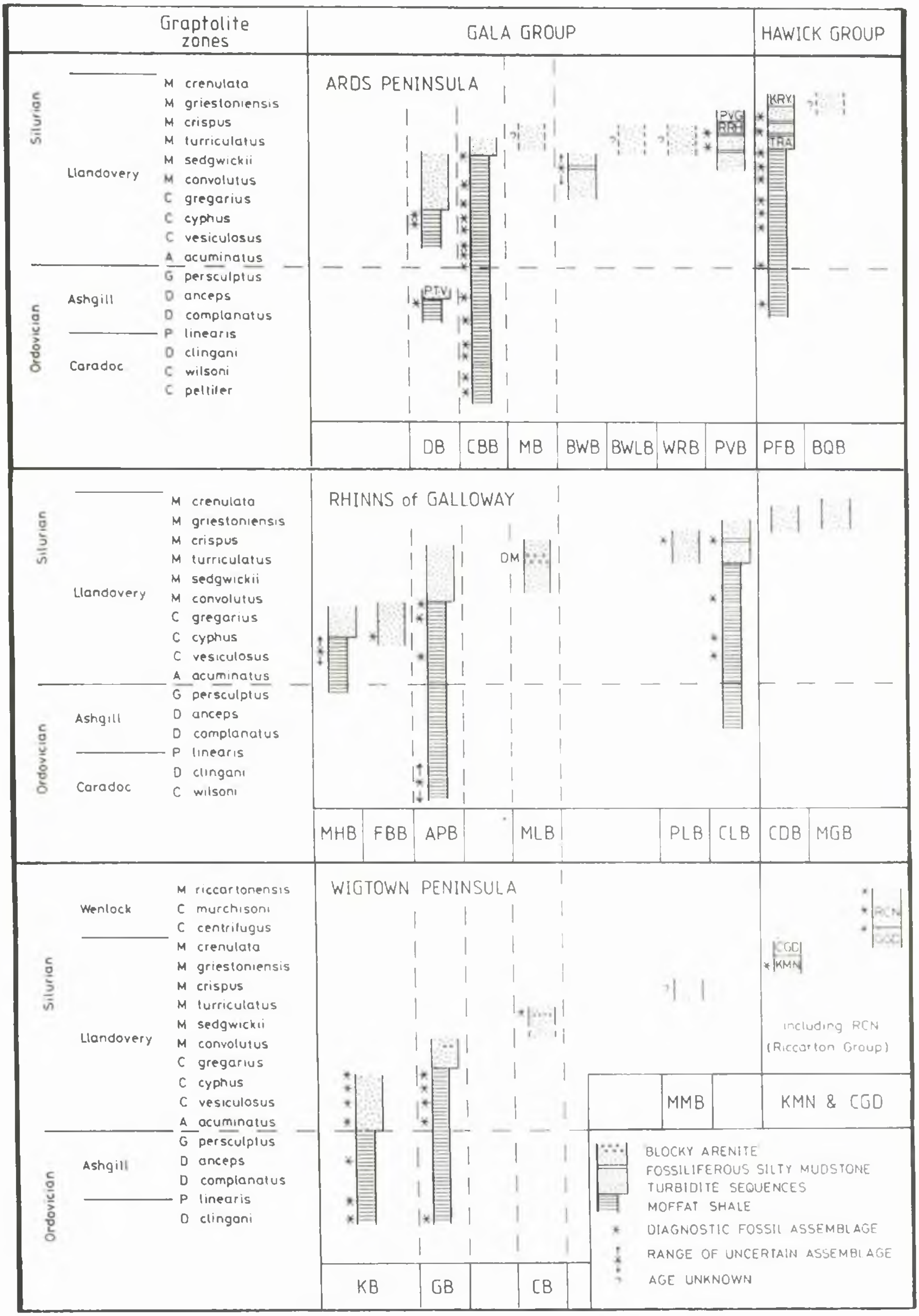

Fig. 5. Time–stratigraphic diagrams of the three study areas. Tectonic blocks are arranged according to the correlation detailed in the text and shown under the headings Gala Group or Hawick Group according to the predominant age and lithological affinities of the greywackes. Where no evidence is available about the age of the stratigraphic sequence in a tectonic block it is placed in relation to its neighbours assuming a progressive southerly decrease in age. Abbreviations of formation names are as on Figs 2, 3 and 4.

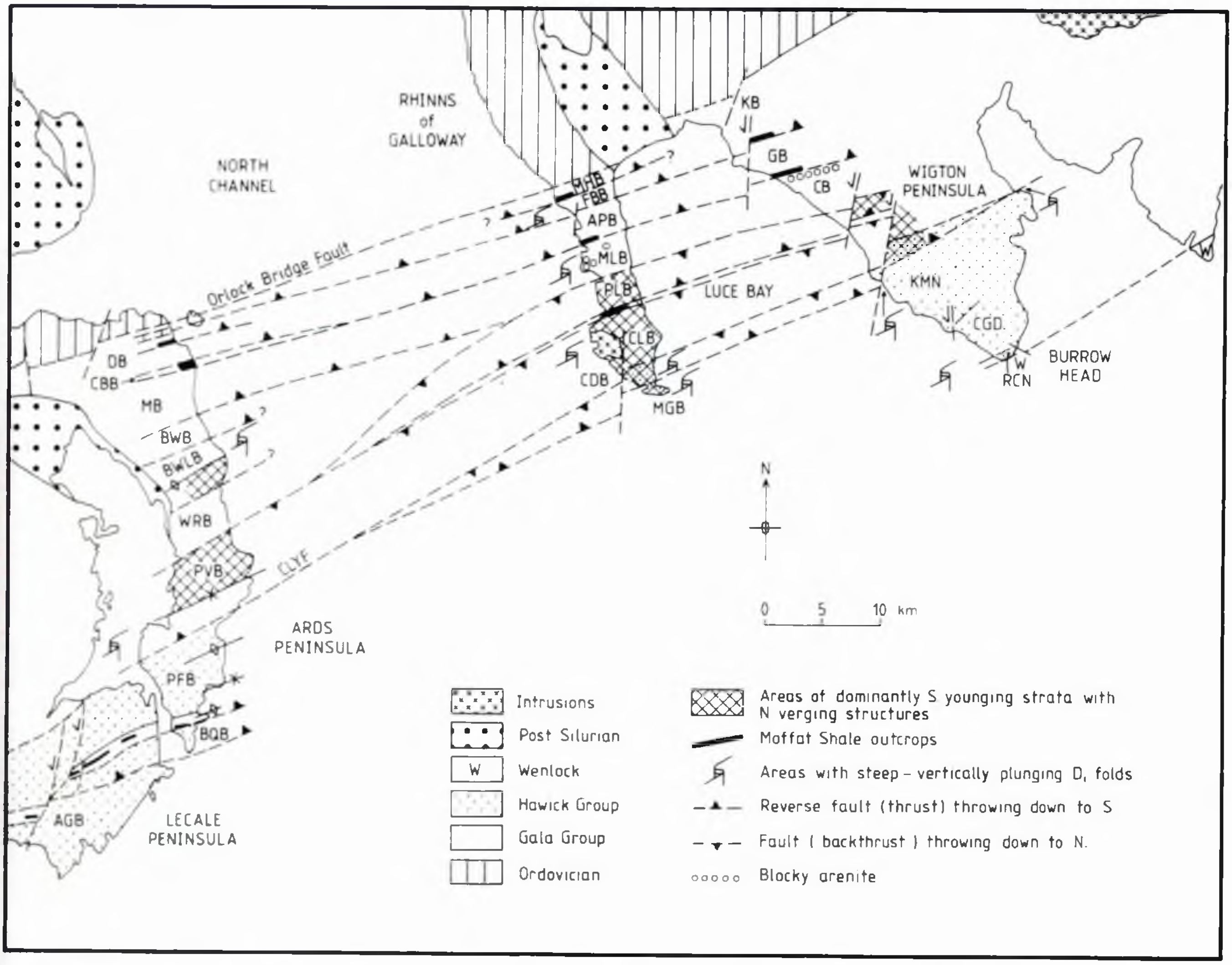

Fig. 6. Geological map of Galloway and east Down illustrating the correlations effected in the text. The Lecale Peninsula is based on Cameron (1981). AGB, Ardglass Block. Other abbreviations as for Figs 2, 3 and 4.

Correlation of the northern blocks in the Ards peninsula with SW Scotland is less clear. In the Donaghadee Block, the Moffat Shale ranges up to *C. cyphus* Zone in age, suggesting that much of this block is equivalent to the Ardwell Point and Garheugh blocks. Therefore the northernmost tract in Scotland must either be represented by the northern part of the Donaghadee Block or it fails to reach NE Ireland. No equivalent of the narrow Coalpit Bay Block is seen in SW Scotland. Very thickly bedded, massive sandstone in the Millisle Block may be correlated with the massive sandstone and blocky arenite sequences exposed in the Mull of Logan and Corwall blocks. The blocky arenites, representing a series of amalgamated debris-flow deposits which probably resulted from massive slumping within the basin, are unlikely to have a considerable lateral extent; hence their absence from the Millisle Block is not significant. None of the blocks from Ballywhiskin to the Hawick Group boundary can clearly be correlated with the Galloway succession. The calcareous strata forming the northern part of the Ballywalter Block are not seen in SW Scotland but the southern part of this block and the Wallace's Rocks Block are both superficially similar to the Port Logan Block. Thickly bedded, massive sandstone is dominant in both the Portavogie and Clanyard blocks, which may be correlated on this basis.

The northern and southern parts of the three areas can be correlated reasonably well using stratigraphical criteria. On this basis the widening of the Central Belt to the south-west is due to the presence of at least two extra blocks in the Ards Peninsula compared with SW Scotland (Fig. 6). The time–stratigraphical diagrams (Fig. 5) show that the base of the greywacke sequence becomes progressively younger southwards; abruptly so across the northern tracts in all areas, but markedly less so to the south in SW Scotland. In the Ards Peninsula and the graptolite evidence, although limited to three of the most southerly seven blocks, suggests little change in the age of turbidite sediments exposed south of Coalpit Bay.

Structural correlation

The overall tectonic style of the northern tracts is comparable with the overall Northern Belt structure. A few southward-verging folds occur in dominantly steeply dipping, often overturned strata, the sheet dip inclining steeply northwards. These blocks become progressively younger southwards (Fig. 5), requiring major reverse faults between the blocks (*cf.* Craig & Walton 1959). Steeply plunging folds adjacent to these faults are common in the Rhinns of Galloway but are not seen in the northern parts of the other two areas.

Central and southern parts of the three areas differ markedly from this pattern. The sheet dip is very variable, often being gently inclined or horizontal in intensely folded areas and dipping steeply southwards in large areas of southward-younging strata with northward-verging structures. The latter style is particularly well developed in the Rhinns of Galloway, south of the Port Logan Fault (Fig. 3) where strata are dominantly overturned, dipping steeply to the north. Extensive belts of steeply dipping, southward-younging strata occur in the Ards Peninsula, as a result of a major fold in the Portavogie Block (Fig. 2), and in the poorly exposed central part of the Wigtown area.

The Kirkmaiden Formation outcrop in the Wigtown Peninsula has a very similar structure to the Portaferry and Ballyquintin Blocks in the Ards Peninsula. In both areas the Hawick Group strata are intensely folded such that the sheet dip is inclined gently northward. A more complete section through the Hawick Group in NE Ireland, exposed in the Lecale area (Anderson & Cameron 1979, fig. 2; Cameron 1981, fig. 3) shows a strikingly similar structure to the Wigtown peninsula section.

The first folds in all three areas generally plunge gently or moderately to the NE or SW, but steep to vertically plunging, sometimes downward-facing, folds are abundant locally (Fig. 6), commonly forming minor- to intermediate-scale, sinistral pairs. Only one zone of steeply plunging structures, near the northern margin of the Hawick Group, occurs in all three areas: others are of only local extent. One pervasive fabric (S_1) occurs throughout the three areas and is congruous with the D_1 structures. In the Ards Peninsula it varies from parallel to fold axial surfaces to transecting, typically 20° clockwise. In SW Scotland cleavage is usually clockwise transecting, although by a variable amount. Models to account for transecting cleavage (e.g. Borradaile 1978; Sanderson *et al.* 1980, 1985; Stringer & Treagus 1980; Murphy 1985) invoke shear, usually sinistral, as the principal cause. Evidence for syn-D_1 sinistral shear is also seen in the zones of steeply plunging folds. Since neither these folds nor transecting cleavage are always developed continuously along strike in individual structural blocks, there must have been significant variations in strain within each thrust sheet if the blocks are indeed such.

Second phase (D_2) structures, usually open to close, southward-verging minor- to intermediate-scale folds, are only well developed in the Hawick Group outcrops in the three areas. Minor intrusions in all three areas increase in abundance southwards, with an intense zone of biotite lamprophyres coincident with the Hawick Group outcrop in Scotland but extending into the Portavogie Block in Ireland. These dykes have a range of ages, the earliest being pre-S_1 (but post-D_1 folding) in Ireland but post-S_1 although still pre-D_2 in Wigtownshire, and were intruded throughout a series of compressional and extensional events (Anderson 1969; Barnes *et al.* 1986).

Interpretation

As shown above the northern and southern parts of the three areas can be correlated, indicating some strike-parallel continuity, albeit with some uncertainty, especially across the North Channel. However, aspects of the central parts are unusual compared with the general picture of the Southern Uplands. The widening to the west is associated with an increase in the number of structural blocks and a flattening out of the trend of successive blocks to become younger southwards.

Major tracts of southward-younging strata, including northward-verging structures, suggest overthrusting towards the north rather than the northerly directed under-thrusting required by the Southern Uplands accretionary prism model. In the southern part of the Rhinns of Galloway major faults throw down to the south, and the overall structural configuration is consistent with northerly directed over-thrusting. This is also the case in the Ards Peninsula where the structure of the Portavogie Block can be interpreted in terms of a northward-directed, landward thrust rising from and transporting material in the opposite direction to the southerly directed Cloughy Fault. It is important to recognize that whatever mechanism is proposed for development of the southerly younging/northward-verging areas, it must be an integral part of the D_1 deformation since all of the major structures observed are of this age. Post-D_1, northerly directed thrusting would not generate wide areas of southward-younging strata, and any related, northward-verging structures would fold S_1. The development of major back thrusts as an integral part of the main thrusting event (D_1), effectively shortening the over-riding thrust sheet(s), meets this criterion and is proposed as an explanation for the Central Belt structures. These could not otherwise be accommodated in the accepted tectonic model for the Southern Uplands. Back-thrusting also explains the narrowing of the Central Belt eastwards with the loss of certain blocks but would allow correlatives of these to reappear farther east.

Landward fold vergence and overthrusting have been described from the Pleistocene tectonic accretion of the Cascadia Basin on the continental slope off Washington and north-western Oregon (Silver 1972). The possible reasons for this geometry have received detailed theoretical and model analogue analyses by Seely (1977). In the Cascadia Basin, landward vergence developed on a lower-slope terrace, contemporaneously with seaward vergence on the outer part of the continental shelf, in the early Pleistocene (Seely 1977, p. 191). The suppression of the normally dominant, landward-dipping, seaward-verging thrusts is favoured by the presence of a basal layer of low shear strength, typically a water-retentive clay overpressured by the rapid deposition of overlying turbidite sands (Roberts 1972; Seely 1977). Seaward-dipping anisotropy in the sediments, or in the underlying oceanic floor, and gentle topographic slopes are other possible favourable factors. At least the first of these factors probably obtained in the Southern Uplands Central Belt, with rapid deposition and growth of Upper Llandovery turbidite fans across the fine silts, shales and mixed-layer clay bentonites (Cameron & Anderson 1980) of the Moffat Shale sequence. South of the northerly verging structures, the return to predominantly southerly, seaward vergence in the Hawick Group of the Ards and Wigtown Peninsula and throughout the Southern Belt may reflect different turbidite sedimentation rates, a change in the nature of the underlying Moffat Shales, or simply that the main décollement horizon has climbed above the Moffat Shales.

Conclusions

Although some tracts can be tentatively correlated across the three study areas, it is evident that strike-parallel continuity of the character and width of the greywacke tracts, so remarkably demonstrated in the Northern Belt, is difficult to define in the Central Belt of Galloway and Down. Whilst some changes along strike, particularly across the North Channel, may be a reflection of original, sedimentary variation in the profiles of the turbidite fans, tectonic repetition and excision also appear to be important.

The large areas of northward fold vergence and southward-younging strata described in this paper represent a significant deviation from the current model of Southern Uplands structure. We are not aware of any proposed mechanism whereby packets of strata several kilometres thick could be underthrust and accreted in an essentially inverted position. Major areas of dominantly southward-younging strata strongly suggest overthrusting to the north. We recommend that the existing model be modified, in at least this south-western part of the Southern Uplands, to include such overthrusting or back thrusting, generating the northward-vergence we describe, penecontemporaneously with sequential northward under-thrusting.

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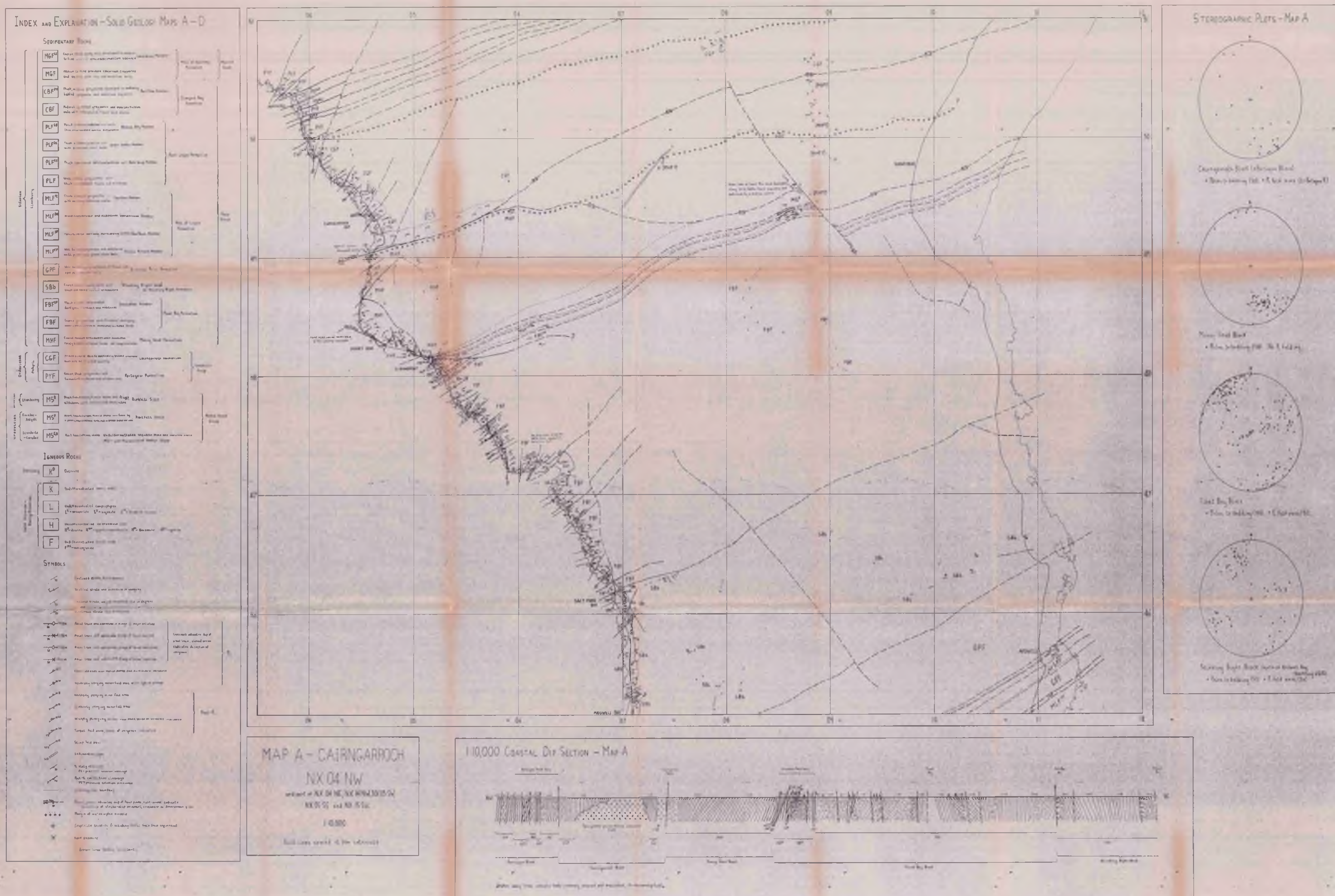
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Sedimentary Rocks
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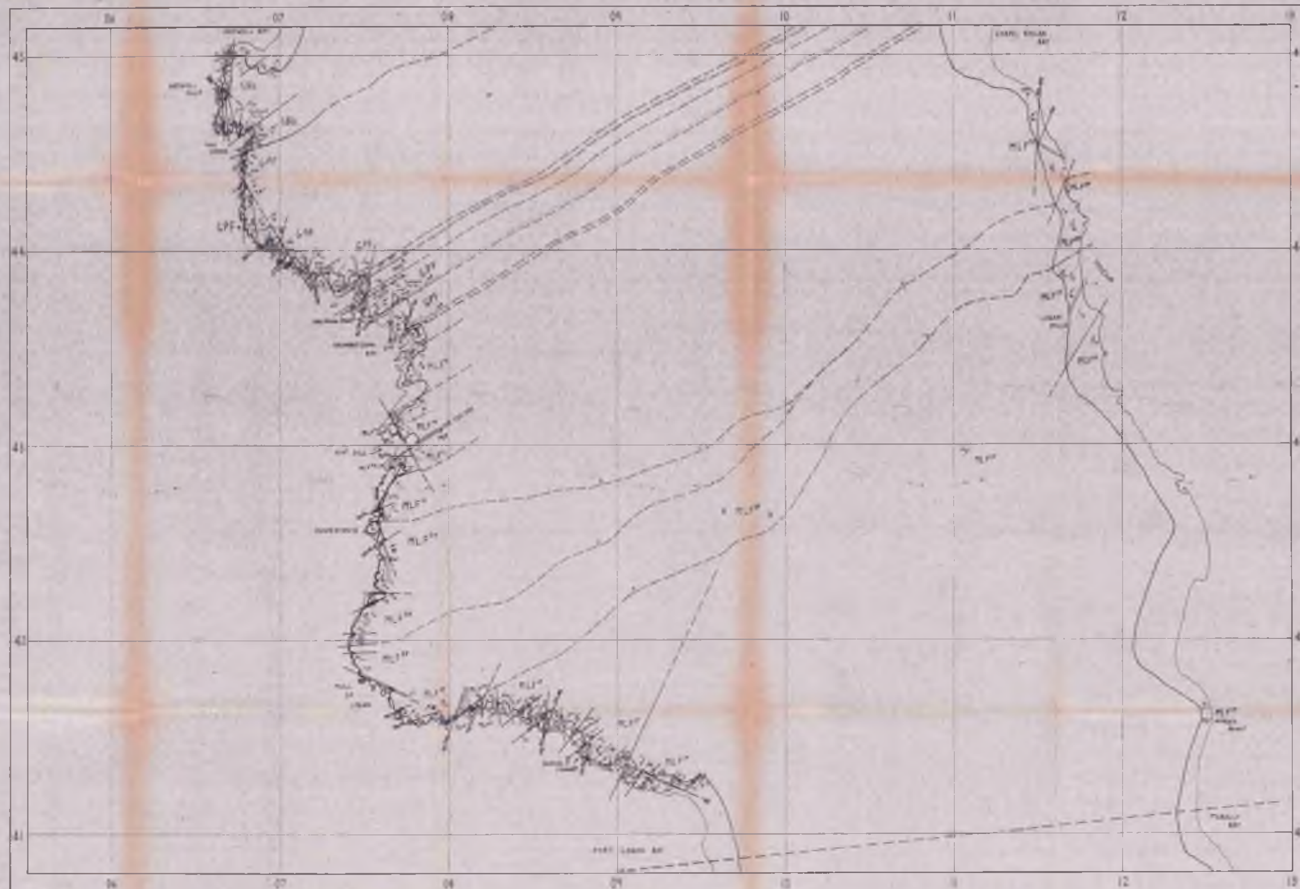
Stereographic Plots – Map A
MAP A – CAIRNGARROCH
NX 04 NW
1:10,000
1:10,000 Coastal Dip Section – Map A

MAP A
CAIRNGARROCH

MAP B
DRUMBREDDAN

Index and Explanation – Solid Geology Maps A – D



MAP B – DRUMBREDDAN

Parts of NX 04 SE, NX 14 SW, NX 04 NE and NX 14 NW

1:10,000

Grid lines spaced at 1Km intervals

(Index and Explanation – see Map A)

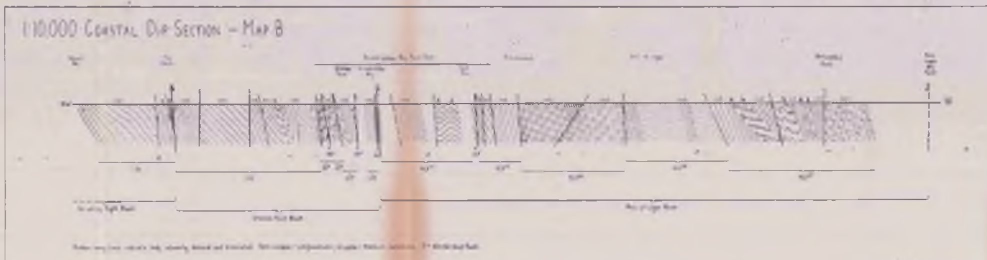
Stereographic Plots – Map B

Stinking Bight Block (south of Ardwell Bay – Northing 4515)
• Poles to bedding (23). × F_1 fold axes (16)

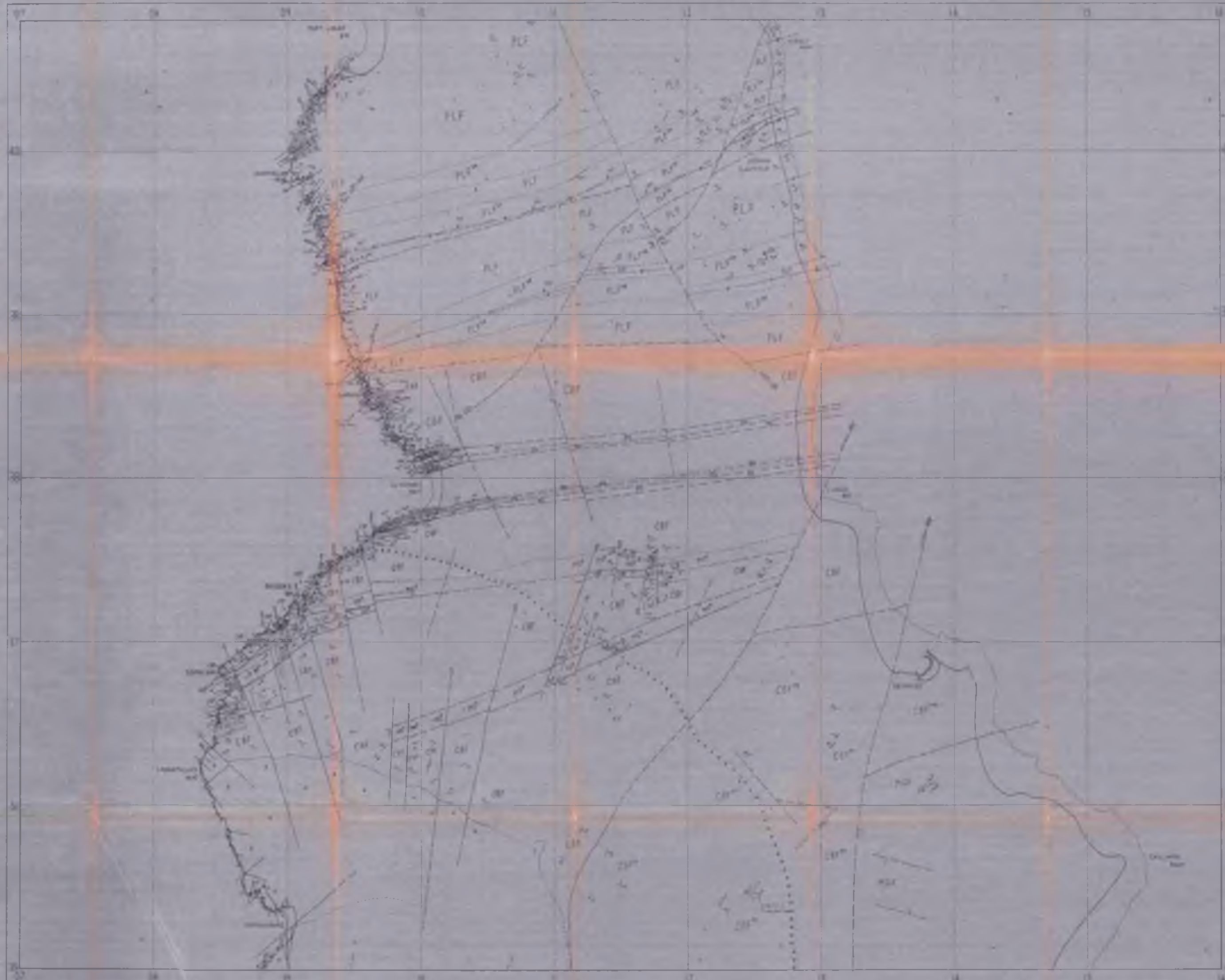
Grennan Point Block
• Poles to bedding (90). × F_1 fold axes (20)

Mull of Logan Block
• Poles to bedding (61). × F_1 fold axes (24)

1:10,000 Coastal Dip Section – Map B



MAP C
CLANYARD

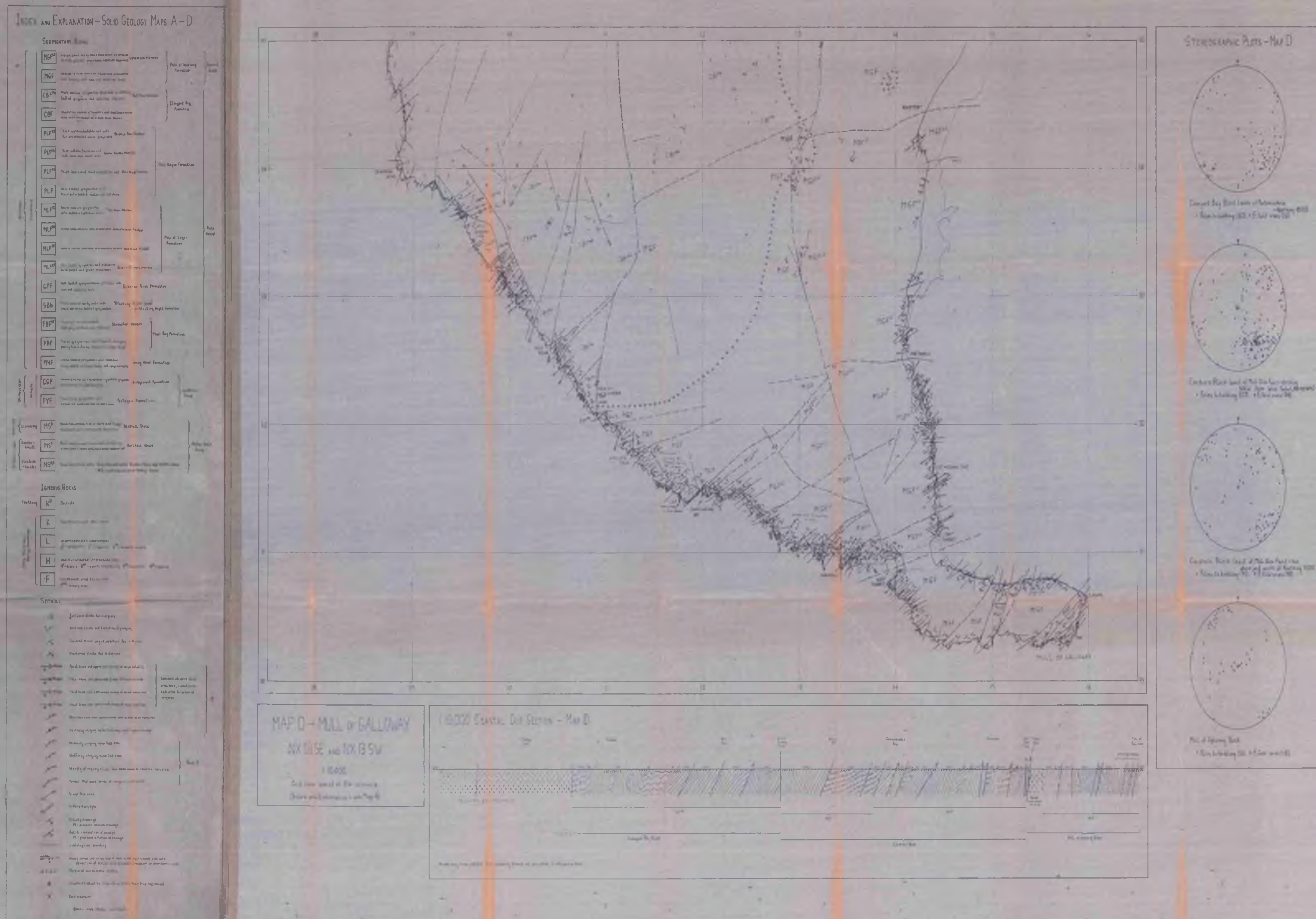


MAP C - CLANYARD

NX 03 NE, NX 13 NW

1:10,000

MAP D
MULL OF GALLOWAY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MULL OF GALLOWAY