THE SEDIMENTOLOGY AND GEOTECTONIC SIGNIFICANCE OF UPPER ORDOVICIAN AND LOWER SILURIAN SAND-BODIES IN THE RHINNS OF GALLOWAY AND ADJACENT AREAS, SOUTHWEST SCOTLAND.

Volume II

Paul Davies

(B.Sc. Hons., U.C.W. Aberystwyth)

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1988

The following have been excluded at the request of the university:

Fig 4.8 (pg 174)

Fig 4.9 (pg 178)

Fig 4.10 a, b & c (pgs 179-181)

Fig 4.11 (pg 183)

Table 5.1 (after pg 199)

Table 5.5 (pg 245)

Fig 6.4 (pg 302)

Fig 7.4 (pg 360)

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MAPS/CHARTS
RELATING TO THIS THESIS
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CHAPTER 5

SEDIMENTOLOGY

5.1 GENERAL

It is generally accepted that the sediments exposed within the Northern and Central belts of the Southern Uplands of Scotland, and the Longford-Down zone of Ireland, were exclusively deposited within deep-water sedimentary environments (Leggett 1980; Kelling *et al*. 1987). It is the purpose of this Chapter to describe the sediments exposed within the two study corridors transects in southwestern Scotland, and to evaluate the specific sedimentary environments in which they were deposited.

5.2 FACIES CLASSIFICATION

The deep-water facies classification scheme proposed by Pickering *et al*. (1986) is adopted within this study (Table 5.1 and Fig. 5.1). This classification scheme contains "41 formally defined facies contained within 15 conceptually distinct facies groups, subsumed within 7 facies classes" (Pickering *et al*. 1986, page 160). The term facies is used in a descriptive way and it is stated that the chief attributes used to define a facies are bedding style and thickness, sedimentary structures, composition and texture.

The facies classification scheme proposed by Pickering et al. (1986) has been employed in the present study for the following reasons:

(1) The scheme provides a fully comprehensive and up-to-date review of deep-water facies types and as such is a key reference on this subject which will most certainly be used and referred to in future studies;

(2) The facies types defined in the deep-water classification scheme devised by Mutti and Ricci-Lucchi (1972) can all be recognized as components of the scheme developed by Pickering et al. (1986) (Fig. 5.1). Comparison of the sediments described in this study and those described in many previous studies is facilitated by this relationship since the classification scheme devised by Mutti and Ricchi-Lucchi (1972) has been widely used since its introduction. Despite the popularity of the latter the classification scheme developed by Pickering et al. (1986) is favoured here, the main reason being that it contains more facies types and consequently enables subtle

sedimentological variations to be recognized, analysed and assessed. This is of crucial importance in the Southern Uplands where marked sedimentological variation is the exception rather than the rule;

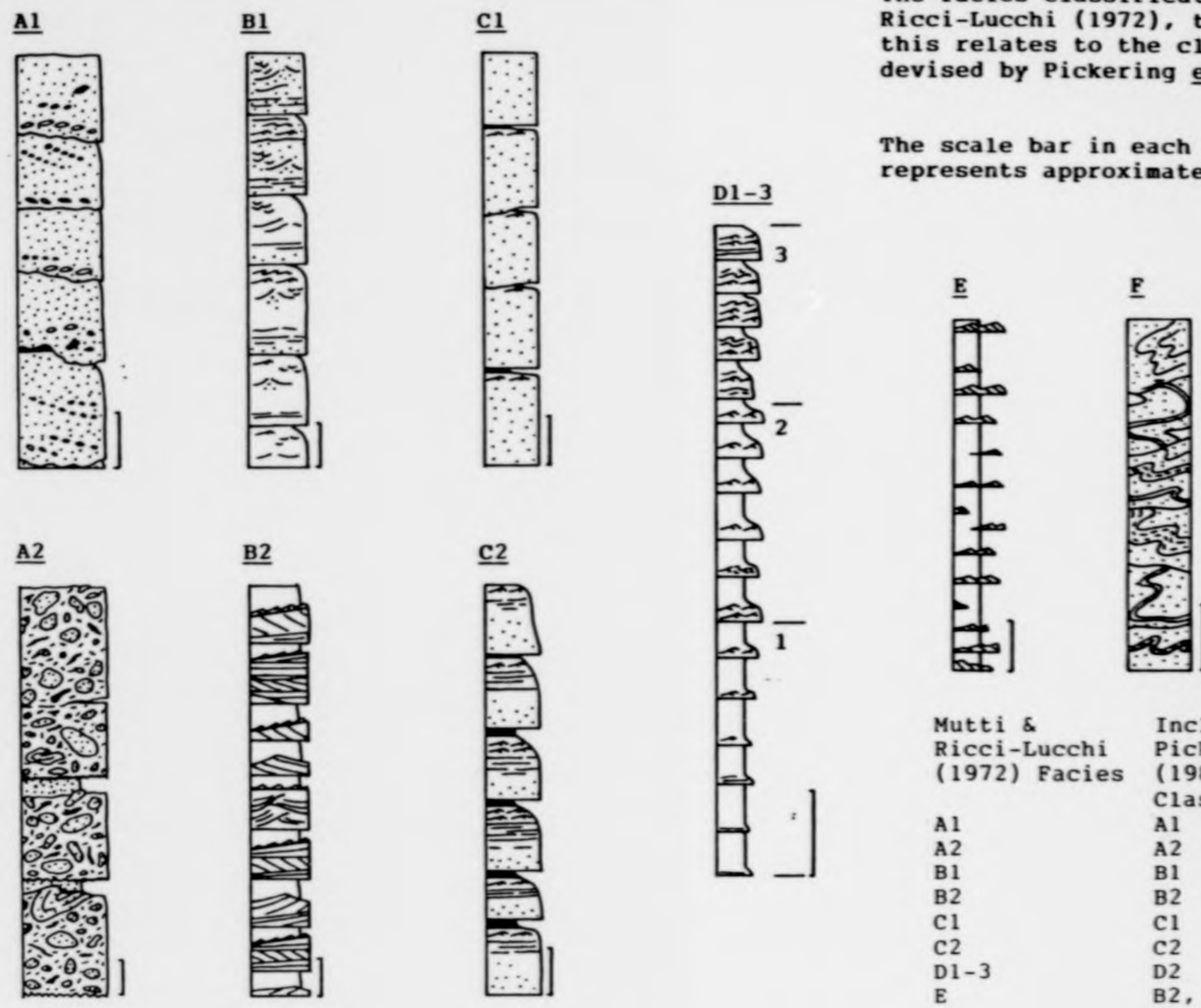
(3) The three levels of descriptive complexity which are inherent in the classification scheme allow the fullest possible standard descriptions to be made of both poorly and well exposed sediments which crop out within study area;

(4) Since both poorly and well exposed sediments can be described within the same classification scheme, objective comparisons can be made between the poorly exposed seen in inland exposures and the well exposed sediments which crop out on the coastline.

It should be noted that throughout this study the Wentworth grain size scale is used and bed thicknesses are defined in accordance with Ingram (1954): laminae less than 1cm; very thin beds 1-3cm; thin beds 3-10cm; medium beds 10-30cm; thick beds 30cm-1m; and very thick beds greater than 1m.

Table 5.1: The facies classification scheme used in this thesis. 'Diagram illustrates the hierarchical nature of the scheme. Facies classes are defined on the basis of grain size (Facies Classes A-E), internal organization (Facies Class F) and composition (Facies Class G). Facies groups are mainly distinguished on the basis of internal organization of structures and textures. Individual facies are based on internal structures, bed thickness and composition'. From Pickering et al. (1986).

Figure 5.1: The facies classification of Mutti and Ricci-Lucchi (1972) and their approximate equivalents in the Pickering et al. (1986) classification. See Table 5.1 for further explanation of the Pickering et al. (1986) classification.



The facies classification of Mutti and Ricci-Lucchi (1972), table shows how this relates to the classification devised by Pickering _et al_. (1986).

The scale bar in each diagram represents approximately 50cm.

Mutti & Ricci-Lucchi (1972) Facies	Included in Pickering _et al_. (1986) Facies Class(es)
A1	A1
A2	A2
B1	B1
B2	B2
C1	C1
C2	C2
D1-3	D2
E	B2, C2, D2
F	F2

5.3 FACIES ASSOCIATIONS

5.3.1 General

Thirteen distinctive facies associations have been identified within the study area. Certain facies associations commonly occur together, forming the four facies association groups which have been recognized.

The term 'facies association' is defined in accordance with Reading (1978) as a distinctive group of facies which occur together and which are considered to be genetically or environmentally related. Some facies associations may display a preferred vertical arrangement of facies types and/or vertical thickening or thinning trends. Table 5.2 lists the facies associations described within this Chapter. 'Facies association group' is a collective term used to identify genetically related facies associations. Thus the facies associations which were deposited in channel, channel margin and interchannel environments would all form one facies association group termed the 'channel related facies association group'. It is assumed in the discussions and interpretations of sedimentary environments which follow in this section (5.3) and the next (5.4) that the depositional environment in which a specific facies

Table 5.2: The main characteristics of each facies association and their interpreted depositional environments. For decriptions of Facies Groups see Table 5.1.

FACIES ASSOC.	COMPONENT FACIES GROUPS (Pickering et al. 1986)	GENERAL BED-GEOMETRY	CYCLIC CHARACTER	INTERPRETED ENVIRONMENTAL SETTING
1a	A1,A2,B1, B2,F1,F2	Irregular, 'Ghosted'. Contorted	Acyclic	Slumps, slides and sheet flows on unstable slopes
1b	A1,A2	Dis-continuous	Acyclic(?)	Slopes/or base of slopes as laterally impersistent sheets
1c	A1,B1,B2, C1,C2,D2, F1,F2	Sheet-like to broadly channelised. Contorted	Acyclic	Slope environment with minor channels and affected by sliding
2a	A1,A2,F1	Laterally dis-continuous irregular	Acyclic	Channels; major 'mid-fan' type channels
2b	A1,A2,B1, B2,C2	Lenticular. Beds frequently amalgamated	Acyclic, some ill-defined TNU cycles (4-10m)	Major 'upper mid-fan' type channels
2c	B1,B2,C1, C2,D1,D2, F2	Lenticular	Acyclic and TNU cycles (4-10m)	Minor, 'lower mid-fan' type channels
2d	B1,B2,C2, D2,F2	Very irregular; lensing, wedging and amalgamation are common	TKU cycles (2-14m)	Channel margin /terraces
2e	B1,B2,C2, D2,F2	Broadly lenticular, sheet-like or highly irregular	TKU cycles (5-6m),TNU cycles (2-3m), or acyclic	Interchannel, crevasse lobe and channel

Table 5.2 /Contd...

FACIES ASSOC.	COMPONENT FACIES GROUPS (Pickering et al. 1986)	GENERAL BED-GEOMETRY	CYCLIC CHARACTER	INTERPRETED ENVIRONMENTAL SETTING
2f	C2,D2,E2, F2	Sheet-like /laminated	Acyclic	Interchannel
3a	B1,B2,C1, C2,D2,F2	Broadly sheet-like some minor local basal erosion	TkU cycles (1.5-12m), or acyclic	Slopes/base of slopes as lobes and sheets
3b	C2,D1,D2, E1,E2	Tabular and laminated	Acyclic	As above, but relatively more 'distal'
4a	E1,G1,G2 (characterised by presence of Class G1.1)	-	-	Areas away from major clastic sources for example Basin floor
4b	E1,G1,G2	-	-	Areas away from major clastic sources for example Basin floor

association was formed can be determined from a study of the vertical arrangement of facies types, the bed-geometry and the relationships displayed with other facies associations.

5.3.2 Facies Association Group 1 - Unstable Slope Deposits

Facies Association Group 1 includes three facies associations, the salient characteristics of which are listed in Table 5.2. The broad distribution of each of the facies associations throughout the study area is summarised in Table 2.3.

5.3.2.1 Facies Association 1a - Unstable Upper Slope Deposits

(a) Recognition

Facies Association 1a comprises a number of facies types from Classes A, B and F, and Groups A1, A2, B1, B2, F1 and F2 (Tables 5.1 and 5.3). The sediments are mainly conglomeratic and exhibit a very disturbed appearance. Clasts within the conglomerates attain a maximum size of 15 x 10m (Plate 5.1). Bedding is undeveloped to very irregular and 'ghosted'. Sedimentary sequences through this Association are normally acyclic. Facies Association 1a dominates sedimentary sequences up to approximately 300m thick (e.g. the Duniehinnie

Table 5.3: Summary lithological descriptions of the main facies types included within Facies Associations 1a, 1b and 1c, Facies Association Group 1, as they actually occur in the study area.

FACIES ASSOCIATION GROUP 1

FACIES ASSOCIATION **1a**

Disorganized clast-supported conglomerates (Facies A1.1)

The component clasts are up to 60cm long and are angular to rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix is of medium to coarse sand. Bed-thickness ranges between 20cm and 3m. Irregular basal and top surfaces are observed. The sediments are internally disorganized. This lithology comprises approximately 15% of the Facies Association.

Disorganized matrix supported conglomerates (Facies A1.2, A1.3 & A1.4)

The component clasts are up to 60cm long and are angular to rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix is of medium to coarse sand. Bed-thickness ranges between 20cm and 1m. Irregular basal and top surfaces are observed. The sediments are internally disorganized. This lithology comprises approximately 15% of the Facies Association.

Organized matrix supported conglomerates (Facies A2.1 & A2.5)

The component clasts are up to 50cm long and are angular to rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix is of coarse to granular sand. Bed-thickness ranges between 20cm and 1.5m. The beds have irregular basal and top surfaces. The sediments display clast imbrication. This lithology comprises approximately 5% of the Facies Association.

Disorganized and organized sandstones (Facies B1.1 & B2.1)

The sandstones are composed of medium to coarse sand grade sediment. Bed-thickness ranges between 10cm and 1.5m. Tabular and irregular bed-geometries occur. The sandstones may be massive or planar stratified. Grading is only poorly developed, inverse grading has been noted. This lithology comprises approximately 5% of the Facies Association.

Very coarse, chaotic conglomerates (Facies F1.1 & F2.2)

The component clasts are up to 15m long and are angular to rounded. The clasts are exclusively intraformational sandstones,

(Table 5.3/continued)

siltstones and mudstones. The matrix varies between muddy fine sand to coarse and often granular sand. Bedding is not clearly developed although a vague, 'ghosted' bedding is sometimes evident. Internally these sediments are most commonly chaotic, however a rough stratification is sometimes picked out by clast alignment. The sediments are affected by numerous soft-sediment faults. This lithology comprises approximately 50% of the Facies Association.

FACIES ASSOCIATION 1b

Disorganized clast supported conglomerates (Facies A1.1)

The component clasts are up to 30cm long and are most commonly rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix is of medium to coarse sand. Bed-thickness ranges between 50cm-2m. Irregular basal and top surfaces are observed. The sediments are internally disorganized. This lithology comprises approximately 10% of the Facies Association.

Disorganized matrix-supported conglomerates (Facies A1.2, A1.3 & A1.4)

The component clasts are up to 20cm long and sub-angular to rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix is of muddy fine sandstone Bed-thickness ranges between 50cm and 1m. Irregular basal and top surfaces are observed. The sediments are internally disorganized. This lithology comprises approximately 5% of the Facies Association.

Organized conglomerates (Facies A2.1, A2.3, A2.5, A2.6 & A2.7)

The component clasts are up to 15cm long and are most commonly rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix is of coarse to very coarse sand. Bed-thickness ranges between 20cm and 1.7m. On outcrop scale the beds appear to have a tabular bed-geometry although mapping shows that the units are laterally impersistent. Internally imbrication and planar stratification are common. This lithology constitutes approximately 45% of the Facies Association.

Disorganized and organized sandstones (Facies B1.1 & B2.1)

Sandstones composed of coarse sand to granular grade sediment.

(Table 5.3/continued)

Bed-thickness ranges between 10cm and 1.5m. Tabular and irregular bed-geometries occur. The sandstones may be massive or planar stratified. Grading is only poorly developed, inverse grading has been noted. This lithology comprises approximately 30% of the Facies Association.

Sandstone/mudstone couplets (Facies C2.1 & C2.2)

The sandstones are composed of fine to coarse sand grade sediment and are poorly to moderately well graded. Bed-thickness ranges between 10cm and 80cm. Amalgamation is common. The beds display tabular bed-geometries. Planar stratification and ripple-cross lamination are developed within the sandstones. The mudstones range in thickness between 0.5cm and 5cm. This lithology comprises approximately 10% of the Facies Association.

FACIES ASSOCIATION 1c

Disorganized clast- and matrix-supported conglomerates (Facies A1.1 & A1.2)

The component clasts are up to 50cm long and are most commonly sub-rounded. The clasts are exclusively intraformational sandstones, siltstones and mudstones. The matrix varies from muddy fine sand in the matrix supported conglomerates to coarse sand in the clast supported conglomerates. Bed thickness varies between 20cm and 50cm. The beds have irregular top and basal surfaces. Internally the sediments are chaotic. This lithology comprises approximately 15% of the Facies Association.

Disorganized and organized sandstones (Facies B1.2 & B2.1)

The sandstones are composed of medium to coarse sand grade sediment. Bed-thickness ranges between 3cm and 25cm. Bed-geometry varies between tabular and broadly lenticular. The sediments are massive to planar stratified. Grading is poorly developed in places otherwise it does not occur. This lithology comprises approximately 15% of the Facies Association.

Sandstone/mudstone couplets (Facies C2.2 & C2.3)

The sandstones are composed of fine to coarse sand grade sediment. Grading is moderately to well developed. Bed-thickness ranges between 5cm and 25cm. Both tabular and broadly lenticular bed-geometries have been observed. Amalgamation is relatively

(Table 5.3/continued)

common. The sandstones display partial Bouma sequences. The mudstones range in thickness between 0.1cm and 2cm. This lithology comprises approximately 40% of the Facies Association.

Organized, laminated siltstones and mudstones (Facies D2.1, D2.2 & D2.3)

These sediments occur in packages up to 55cm thick. Sedimentary structures are very well developed and include planar lamination, ripple cross lamination, load and flame structures and a variety of small scale dewatering structures. Some of the thicker coarser laminae display bottom absent Bouma sequences and very well defined normal grading. This lithology comprises approximately 15% of the Facies Association.

Slumps and slides (Facies F2.1 & F2.2)

Coherently folded and intensely disrupted sediments occur in packets of up to 8m thick. The bounding surfaces range from planar and parallel-sided, to very irregular with deep erosional scours at the packet bases. This lithology comprises approximately 15% of the Facies Association.

Member, see Table 2.3 and Fig. 6.8; Kelling et al. 1987).

Various conglomeratic facies types occur within Facies Association 1a, ranging from disorganized, clast-supported gravels (A1.1), to disorganized, matrix-supported gravels (A1.2, A1.3 and A1.4), stratified gravels (A2.1), stratified pebbly sandstones (A2.5), disorganized 'rubble' (F1.1) and dislocated, brecciated and balled strata (F2.2) (Pickering et al. 1986; Tables 5.1 and 5.3). The majority of the disorganized conglomerates (A1.1, A1.2, A1.3, A1.4, F1.1 and F2.2) exhibit an irregular bed-geometry. The irregularity of bedding surfaces appears to be a function of:

(1) clast size; clasts commonly protrude from the top of one unit into the base of the overlying one (Plate 5.5 and Fig. 5.7).

(2) the depositional morphology of some units - many display hummocky, irregular top surfaces (Plate 5.5 and Fig. 5.7).

Some conglomeratic units, particularly those belonging to Facies A2.1 and A2.5 exhibit either, irregular basal and flat top surfaces, or flat top and bottom surfaces. 'Ghosted' bedding is most commonly displayed by Facies F2.2 (Plate 5.2).

Plate 5.1: Very coarse, disorganized conglomerates (Facies F1.1, Pickering et al. 1986). Duniehinnie Member (NX 0755 4255). View to north. Human scale.

Plate 5.2: Conglomerates showing rough alignment of clast long axes (Facies F2.2). Duniehinnie Member (NX 07642 4200). Younging to top of Plate. Hammer for scale.

Clast sizes are highly variable within the conglomerates included within Facies Association 1a; Facies A1.1, A1.2, A1.3, A1.4, A2.1 and A2.5 usually contain clasts up to 50-60cm in length. In contrast, Facies types F1.1 and F2.2 (Plates 5.1, 5.2 and 5.5). contain clasts which attain sizes of at least 15 x 10m. The shape of clasts varies considerably between well-rounded and sub-angular; however, the majority appear to be sub-rounded or sub-angular. Dewatering structures are displayed within some conglomerates, particularly Facies F2.2.

Contorted, folded and brecciated sediments (Facies F2.1 and F2.2) occur at random amongst the other facies in Association 1a. Facies F2.2 often exhibits lateral and vertical grading, from disrupted beds, into 'conglomerates' which exhibit a 'ghosted' bedding, and into more disorganized conglomerates. All are included within Facies F2.2. Coherently folded sediments (F2.1) are not commonly developed within Facies Association 1a. Soft-sediment faults occur in association with Facies F2.1 and F2.2.

Facies Association 1a also includes disorganized and organized sandy units (B1.1 and B2.1). These are medium- to very thick-bedded and exhibit both irregular and tabular bed-geometries. Bed geometry appears to be controlled by: (1) the top surface morphology of the underlying units, which can be hummocky or flat, and (2) post-depositional effects, including soft-sediment deformation and erosion. Although many of these units are wedge-shaped there is little evidence of associated basal erosion.

(b) Depositional Processes and Environmental Setting

It is suggested that the sediments included within Facies Association 1a were deposited by four processes (Pickering et al 1986; Table 5.1):

(1) Facies A1.1, A1.4, A2.1, A2.5, B1.1 and B2.1 are considered to have formed from high-concentration turbid, sheet-flows.

(2) Facies A1.2 and A1.3 are ascribed to deposition from debris flows.

(3) Facies F1.1 is attributed to gravity-induced 'rockfalls' and sediment avalanches.

(4) Facies F2.1 and F2.2 probably resulted from gravity-induced slides and slumps.

The general characteristics of Facies Association 1a, outlined above, suggest that these sediments were deposited on unstable slopes, which received coarse sediment in the form of debris-flows and turbid sheet-flows. These sediments, often conglomeratic, were frequently affected by gravity induced sliding and slumping, which produced dislocated, disturbed units, 'conglomerates' with a 'ghosted' bedding, disorganized conglomerates (F2.2) and folded strata (F2.1). Syn-sedimentary fault scarps, developed as a result of slope instability and tectonic movements probably gave rise to the topographic irregularities necessary to form Facies F1.1 and F2.2 (Section 5.4.1).

5.3.2.2 Facies Association 1b - Unstable Lower Slope Deposits

(a) Recognition

Facies Association 1b includes a variety of facies from Classes A, B and C and Groups A1, A2, B1, B2 and C2 of Pickering *et al*. (1986) (Tables 5.1 and 5.3). The sediments are medium- to very thick-bedded and are often conglomeratic and 'blocky'. Cyclicity is not obvious on outcrop scale. Facies Association 1b dominates sequences up to approximately 150m in thickness (e.g. the Alticry Member, see Table 2.3 and Fig. 6.8; Kelling *et al*. 1987).

Various conglomeratic facies types occur within Facies Association 1b, including disorganized clast-supported gravels (A1.1), disorganized matrix-supported gravels (A1.2, A1.3 and A1.4), stratified

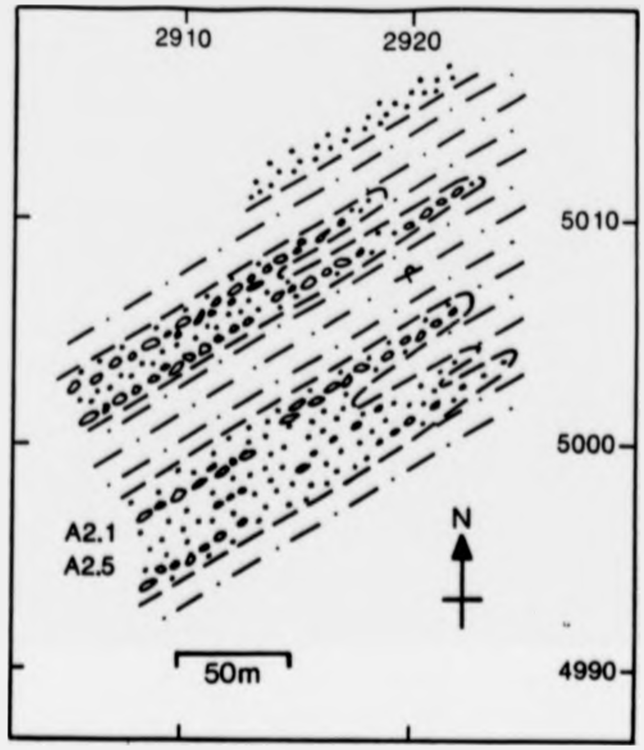


Figure 5.2: Sketch map showing the lateral impersistence of conglomeratic units (Facies A2.1 and A2.5) in Facies Association 1b. 700m northeast of Corwall (NX 292 500).

gravels (Plate 5.3) and pebbly sandstones (A2.1 and A2.5), normally graded gravels and pebbly sandstones (A2.3 and A2.7) and inversely graded pebbly sandstones (A2.6) (Pickering et al. 1986; Tables 5.1 and 5.3). Since this Facies Association is only seen in small patchy exposures the geometries of the conglomeratic beds are difficult to ascertain. Many beds, however, appear to be laterally discontinuous (Fig. 5.2), but at least, on a small scale, they display basal surfaces which may be either erosive or non-erosive (Fig. 5.3). Clasts within the conglomeratic facies do not usually exceed 30 x 15cm, and most are sub-rounded.

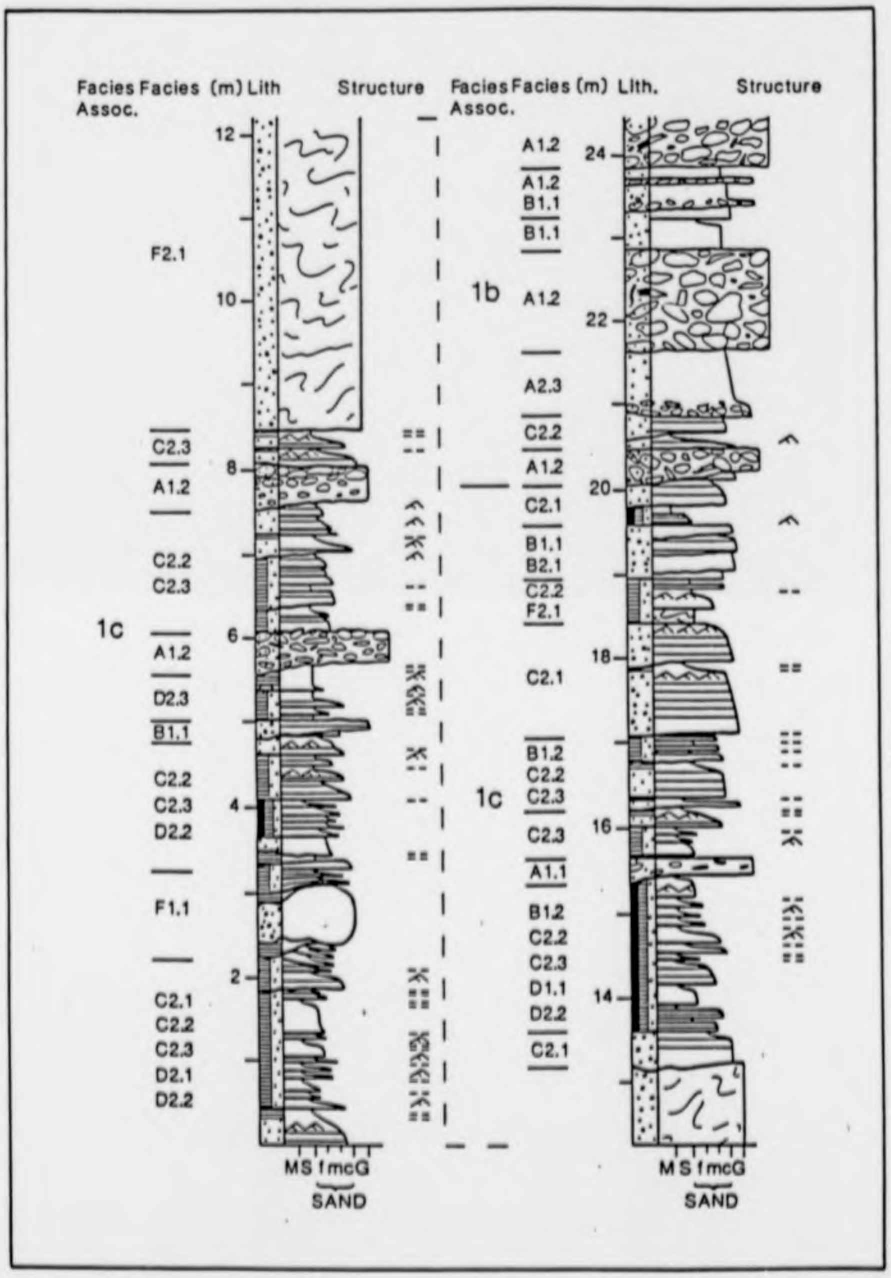
Medium- to very thick-bedded, disorganized and stratified sandstones (B1.1, B2.1), and sandstone-mudstone couplets (C2.2, C2.1) are interbedded with the conglomeratic sediments, briefly described above (Fig. 5.4). Bed-geometries are difficult to ascertain due to the patchy nature of exposures of this Facies Association. Both erosive and non-erosive bases have been observed.

(b) Depositional Processes and Environmental Setting

The sediments which comprise Facies Association 1b were probably deposited as a result of the following processes (Pickering et al. 1986; Table 5.1):

Plate 5.3: Stratified pebbly sandstone (Facies A2.1). Alticry Member (NX 2783 4965). View to the northeast, younging to the left of the Plate. Camera lens cap for scale.

Figure 5.3: Graphic log illustrating the typical sedimentological features of Facies Associations 1b and 1c. Note the transitional nature of the contact between Facies Associations 1b and 1c. Log from Peter's Paps (NX 0760 4226). Mull of Logan Formation, Dunniehinnie Member.



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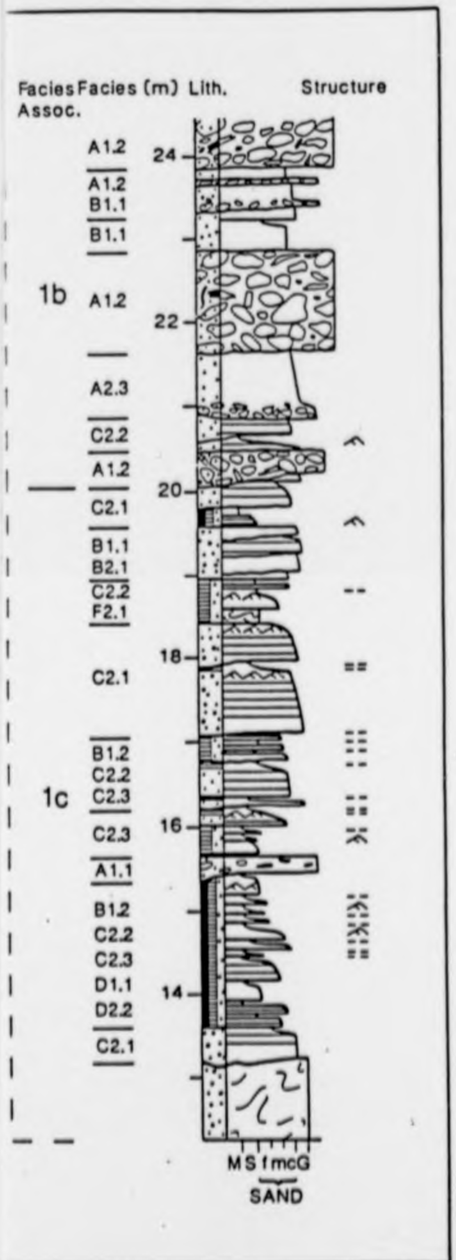
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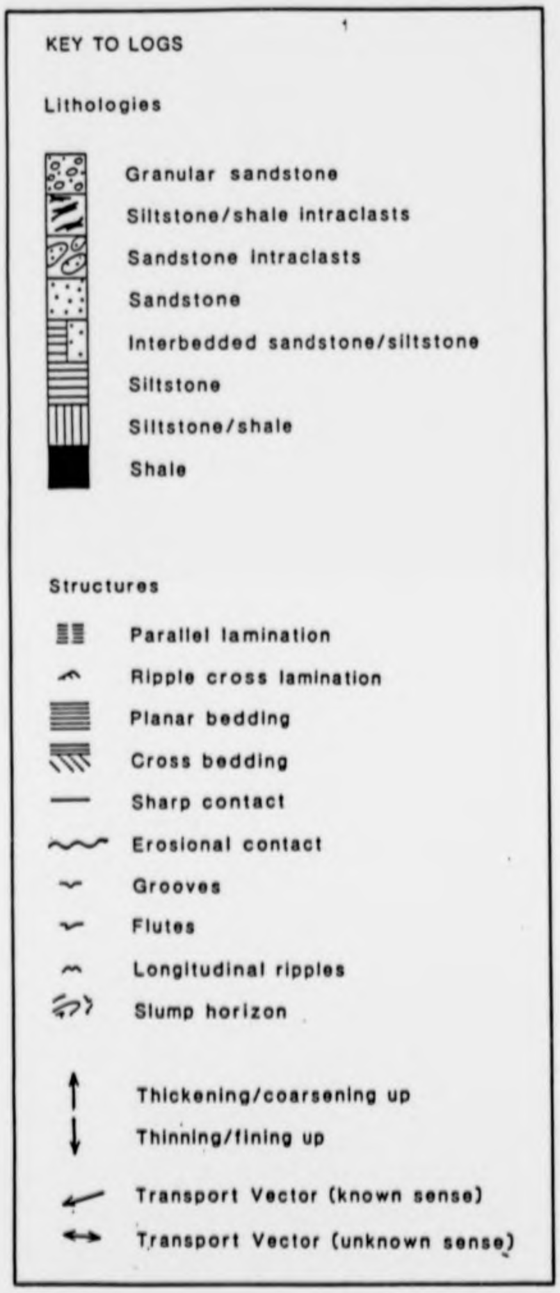
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Structures
Parallel lamination
Ripple cross lamination
Planar bedding
Cross bedding
Sharp contact
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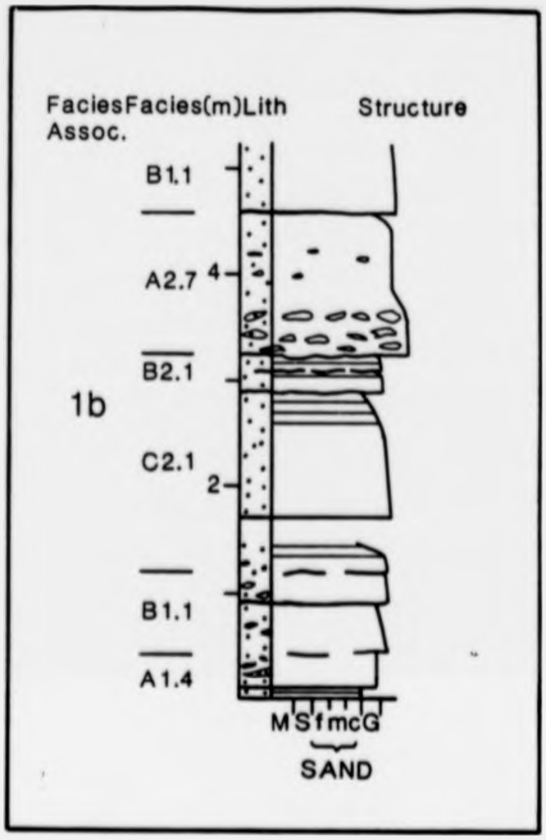


Figure 5.4: Graphic log illustrating the interbedding of disorganized and stratified sands (Facies B1.1 and B2.1) and sandstone-mudstone couplets (Facies C2.2 and C2.1) with conglomeratic facies (Facies A1.4 and A2.7) in Facies Association 1b. Log from Corwall (NX 2914 4984). Corwall Formation, Alticry Member. For legend see Figure 5.3.

(1) The disorganized matrix-supported gravels included within Facies A1.2 and A1.3 were probably formed by 'freezing' of debris flows.

(2) Some of the disorganized conglomerates (A1.1 and A1.4), and all of the organized conglomerates (A2.1, A2.3, A2.5, A2.6 and A2.7), the disorganized and stratified sandstones (B1.1 and B2.1) and sandstone-mudstone couplets (C2.2 and C2.1) are considered to have been deposited from high- to low-density turbidity currents.

The general characteristics of Facies Association 1b, outlined above, suggest that the sediments were largely deposited as laterally impersistent sheets. Some of the sediments may have been deposited as debris flow lobes and perhaps within minor channels.

5.3.2.3 Facies Association 1c - Slope Basin Deposits

(a) Recognition

Facies Association 1c includes a very wide range of facies types from Classes A, B, C, D and F, and Groups A1, B1, B2, C1, C2, D2, F1 and F2 (Tables 5.1 and 5.3). The Facies Association is predominantly thin- to medium-bedded. The sediments are usually acyclic. Facies Association 1c dominates sedimentary sequences which are up to 30m in thickness (e.g. Duniehinnie Member, see Table 2.3 and Section 2.4.1.5; Kelling et al. 1987).

Thin- to medium-bedded, disorganized and organized sandstones, and organized sandstone-mudstone couplets dominate Facies Association 1c (Fig. 5.3) (B1.1, B1.2, B2.1, C2.2 and C2.3). Bed-geometry is variable between broadly-channelised and sheet-like. Some beds exhibit irregular basal surfaces which are clearly non-erosive. Such irregularity is a result of deposition over hummocky surfaces, the development of meniscus bedding above some surface depressions is clear testimony to this process (Plate 5.4).

Laminated organized siltstones, muddy siltstones and siltstone-mudstone couplets (D2.1, D2.2 and D2.3) are interbedded with the thin- and medium-bedded sandstones described above (Fig.5.3). Thick-bedded, disorganized muddy sandstones (C1.1), and organized sandstone-mudstone couplets (C2.1) also occur within Facies Association 1c. These units commonly display scoured bases.

Disorganized, clast-supported gravel conglomerates (A1.1) and muddy, matrix-supported gravel conglomerates (A1.2) are present within Facies Association 1c. They form units which range between

Plate 5.4: Lens-shaped bedding in Facies Association 1c, resulting from deposition on the irregular upper surface of a slump sheet. Duniehinnie Member (NX 0756 4228). View to northeast. Beds young towards left of Plate. Camera lens cap for scale.

20 and 50cm in thickness and contain clasts with a maximum two-dimensional size of 50 x 15cm. The clasts are modally sub-rounded, and those which are coarser than pebble grade are exclusively intraformational. The beds of conglomerate often exhibit scoured bases and hummocky irregular tops (Plate 5.5 and Fig. 5.3). Some of these units may be channelised.

Chaotic facies (F1.1, F2.1 and F2.2) are also represented within Facies Association 1c (Fig. 5.3). The facies range from dislocated boulders (F1.1) which have loaded and deformed underlying strata (Fig. 5.3), contorted and folded sediments (F2.1), and dislocated and brecciated strata (F2.2). All of these facies form units which have irregular top and bottom surfaces.

(b) Depositional Processes and Environmental Setting

The sediments included within the Facies Association 1c are considered to have been deposited by a variety of processes, all of which were operative within a single sedimentary environment.

The medium- to thick-bedded organized sandstones (B2.1), sandstone-mudstone couplets (C2.1, C2.2 and C2.3), and the laminated siltstone-mudstone couplets (D2.1, D2.2 and D2.3), are attributed to high- to

Plate 5.5: Disorganized, clast-supported gravel conglomerate (Facies A1.1). Note the hummocky irregular top surface and the scoured base associated with this conglomerate. Duniehinnie Member (NX 0756 4228). View to northeast. Beds young towards left of Plate. Hammer for scale.

low- density turbidity currents (Pickering et al. 1986; Table 5.1). Some were probably broadly channelised, but the majority were undoubtedly sheet-flows.

The medium- to thick-bedded disorganized sandstones (B1.1) and the muddy sandstones (C1.1) also may have been deposited from high-density turbidity currents. However, this depositional process need not have been responsible for all the occurrences of these facies. The disorganized sandstones (B1.1) may, at least partly, have been deposited by sand creep or other grain-flow processes on steep slopes, and the disorganized muddy sandstones (C1.1) can be assigned to fluid sand-mud debris flows (Pickering et al. 1986; Table 5.1).

The disorganized gravel conglomerates (A1.1) and muddy gravel conglomerates (A1.2) were probably deposited from a combination of high-concentration turbidity currents and debris flows. An evaluation of the bed geometries displayed by Facies A1.1, in particular, suggests that some of the conglomerates were deposited within broad, shallow channels, while others were deposited as debris flow lobes.

The chaotic facies (F1.1, F2.1 and F2.2) which are present within Facies Association 1c were produced as a result of gravity-induced 'rockfalls', sliding and slumping, and dislocation of sediments.

The sedimentological characteristics of Facies Assocation 1c are indicative of a sedimentary environment in which low- to high-density turbidity currents operated, alongside debris flows, rockfalls, slides and slumps. The occurrence of debris flow (A1.2 and C1.1), and slide and slump deposits (F1.1, F2.1 and F2.2) indicates deposition upon, or near slopes. The predominance of beds with non-erosive to only gently scoured bases and flat tops, suggests that most units were deposited as sheets. This is considered to have generated a flat, probably inclined topographic surface which was cut by a few minor, broad, shallow channels, and covered by debris flow lobes, minor 'screes', and slide and slump sheets (Section 5.4.1).

5.3.3. Facies Association Group 2 - Channel Related Deposits

Facies Association Group 2 includes six facies associations, the main characteristics of which are listed in Table 5.2. The distribution of each of these facies associations within the study area is summarised in Table 2.3.

5.3.3.1 Facies Association 2a - 'Upper Mid-fan' Channel Deposits

(a) Recognition

Facies Association 2a is dominated by a very limited number of facies types, from Classes A and F, and Groups A1, A2, and F1 (Pickering et al. 1986; Tables 5.1 and 5.4). The sediments are almost exclusively conglomeratic. The association forms sedimentary sequences up to 50m thick (e.g. the Barhaskine Conglomerate, Gordon 1962; Fig. 5.5).

Various conglomeratic facies are included within Facies Assocation 2a. Disorganized clast-supported (A1.1) and matrix-supported (A1.2) gravel conglomerates, and organized gravel conglomerates (A2.1) dominate the Association (Tables 5.1 and 5.4). These sediments are thick- to very thick-bedded (80m to at least 3m). Many beds exhibit basal erosion surfaces and are laterally discontinuous (Fig. 5.5).

Large intraformational blocks, up to 2m in length, occur within the conglomerates (Fig. 5.6). The average size and internally deformed nature of these clasts suggest that they belong to Facies F1.1 (Tables 5.1 and 5.4).

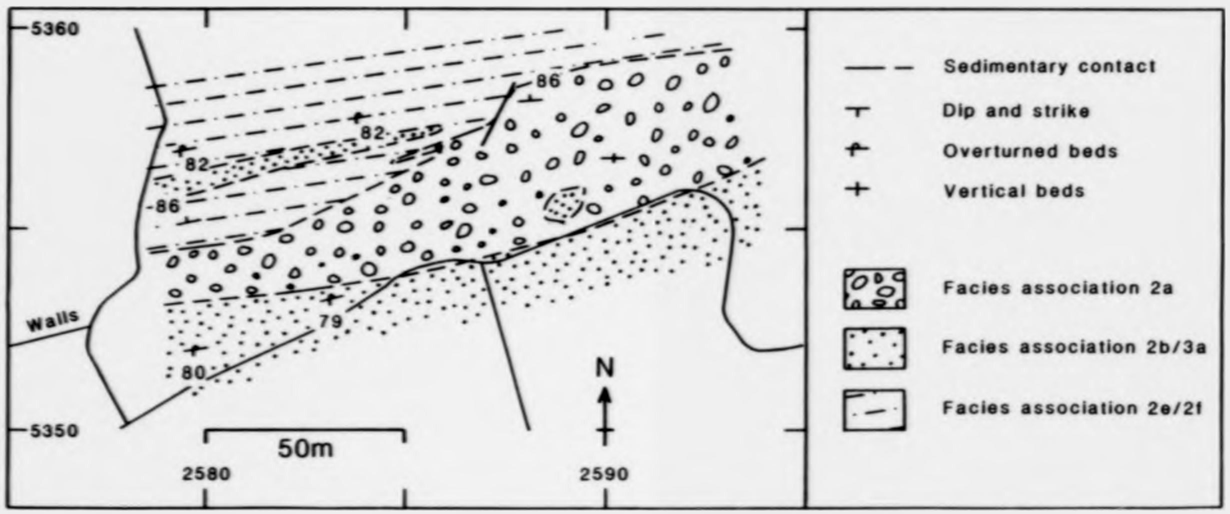


Figure 5.5: Map showing the lenticular geometry of Facies Association 2a sediment-bodies. Barhaskine Conglomerate, near Barhaskine (NX 269 536).

Table 5.4: Summary lithological descriptions of the main facies types included within Facies Associations 2a, 2b, 2c, 2d, 2e and 2f, Facies Association Group 2, as they actually occur in the study area.

FACIES ASSOCIATION GROUP 2

FACIES ASSOCIATION 2a

Disorganized clast-supported conglomerates (Facies A1.1)

The component clasts are up to 15cm long and are rounded to well rounded. The clasts may be intraformational and/or extraformational in origin. The matrix is of coarse sand. Bed-thickness ranges between 80cm and 3m. Many beds display strongly erosive bases. They are predominantly laterally discontinuous. The sediments are internally disorganized. This lithology comprises approximately 20% of the Facies Association.

Disorganized matrix-supported conglomerates (Facies A1.2)

The component clasts are up to 15cm long and are sub-rounded to well rounded. The clasts may be intraformational and/or extraformational. The matrix is of muddy fine to medium sand. Bed-thickness ranges between 20cm and 1m. The beds are laterally impersistent and display irregular top and basal surfaces. The sediments are internally disorganized. This lithology comprises approximately 10% of the Facies Association.

Organized clast-supported conglomerates (Facies A2.1)

The component clasts are up to 20cm long and are sub-rounded to well rounded. The clasts may be intraformational and/or extraformational. The matrix is of coarse sand. Bed-thickness ranges between 50cm and 2.5m. The beds display strongly erosive bases and are laterally impersistent. Internally the bed are planar stratified and the component clasts are imbricated. This lithology comprises approximately 65% of the Facies Association.

Large, intraformational 'slide' blocks (Facies F1.1)

Large intraformational blocks of sandstone and siltstone attain lengths of 2m and widths of 1.5m. The clasts are often internally deformed. This lithology comprises approximately 5% of the Facies Association.

FACIES ASSOCIATION 2b

Disorganized clast- and matrix-supported conglomerates (Facies A1.1 & A1.2)

The component clasts are up to 25cm long and are angular to sub-rounded. The clasts are predominantly intraformational

(Table 5.4/continued)

sandstones, siltstones and mudstones. The matrix is of muddy medium sand. Bed-thickness ranges between 40cm and 1.2m. The beds display relatively flat non-erosive bases and irregular top surfaces. This lithology comprises approximately 2% of the Facies Association.

Disorganized and organized pebbly sandstones (Facies A1.4 & A1.5)

The sandstones are composed predominantly of coarse sand grade sediment. Bed-thickness ranges between 80cm and 8m. Tabular and broadly lenticular bed-geometries occur. Some bases are strongly erosional. The sediments may be massive or planar stratified. Grading is only poorly developed. This lithology constitutes approximately 8% of the Facies Association.

Disorganized and organized sandstones (Facies B1.1, B2.1 & B2.2)

The sandstones are composed of coarse sand to granular grade sediment. Bed-thickness ranges between 80cm and 1.2m. The beds commonly have erosive bases. The sandstones may be massive, planar stratified or cross stratified. Cross stratification is generally low angle. This lithology comprises approximately 60% of the Facies Association.

Sandstone/mudstone couplets (Facies C2.1)

The sandstones are composed of fine to coarse sand grade sediment and are poorly to moderately well graded. Bed-thickness ranges between 50cm and 1.2m. Amalgamation is very common. The beds generally display tabular bed-geometries and display moderately erosive bases. Planar and ripple cross lamination are commonly developed. The mudstones range up to 7cm in thickness. This lithology comprises approximately 20% of the Facies Association.

FACIES ASSOCIATION 2c

Disorganized and organized sandstones (Facies B1.1, B2.1 & B2.2)

The sandstones are composed of medium to coarse sand grade sediment. Bed-thickness ranges between 3cm and 2.2m thick. Tabular and lenticular bed-geometries occur. Amalgamation is commonly developed. Grading is rarely displayed. The sandstones may be massive, planar stratified or cross stratified. This lithology comprises approximately 15% of the Facies Association.

Disorganized and organized sandstone/mudstone couplets (Facies C1.1, C2.1 & C2.2)

(Table 5.4/continued)

The sandstones are composed of fine to coarse sand grade sediment and are commonly well graded. Bed-thickness ranges between 3cm and 1m. Amalgamation is common. The beds display tabular bed-geometries but their bases are frequently erosive. The sandstones may be massive or planar and ripple cross stratified. The mudstones range up to 15cm in thickness. This lithology comprises approximately 45% of the Facies Association.

Massive and laminated siltstones and mudstones (Facies D1.1, D1.2, D2.1, D2.2 & D2.3)

These sediments occur in packets up to 1.4m thick. They may be massive or internally structured. Where structured, planar lamination, ripple cross lamination, load and flame structures and grading, are all very well developed. This lithology comprises approximately 25% of the Facies Association.

Contorted and disturbed sediments (Facies F2.1 & F2.2)

Coherently folded and intensely disrupted sediments occur in packets which attain a maximum thickness of 2m. The bounding surfaces are often very irregular, erosive bases and undulatory tops being commonly displayed. This lithology comprises approximately 15% of the Facies Association.

FACIES ASSOCIATION 2d

Disorganized and organized sandstones (Facies B1.1 & B2.2)

The sandstones are composed of medium to coarse sand grade sediment. Bed-thickness ranges between 1cm and 30cm. Bed-geometry is very irregular and basal scouring is extremely common. The sediments may be massive or cross stratified. This lithology comprises 10% of the Facies Association.

Organized sandstone/mudstone couplets (Facies C2.2 & C2.3)

The sandstones are composed of fine to coarse sand grade sediment and are moderately well to well graded. Bed-thickness ranges between 1cm and 30cm. Amalgamation is common. The beds display broadly lenticular bed-geometries and have strongly erosive bases. Planar stratification and ripple cross lamination are commonly developed. The mudstones are up to 2cm thick. This lithology comprises 75% of the Facies Association.

Laminated siltstones and mudstones (Facies D2.1, D2.2 & D2.3)

(Table 5.4/continued)

These sediments occur in packets up to 15cm thick. Sedimentary structures are very well developed and include planar lamination, ripple cross lamination and load and flame structures. Grading is commonly very well developed. This lithology comprises approximately 5% of the Facies Association.

Slumps (Facies F2.1)

Coherently folded sediments occur in packets up to 25cm thick. The bounding surfaces are usually irregular. This lithology comprises approximately 10% of the Facies Association.

FACIES ASSOCIATION 2e

Disorganized and organized sandstones (Facies B1.1, B1.2, B2.1 & B2.2)

The sandstones are composed of medium to coarse sand grade sediment. Bed-thickness ranges between 3cm and 40cm. Tabular and broadly lenticular bed-geometries occur. The sandstones may be massive, planar stratified or cross stratified. This lithology comprises approximately 20% of the Facies Association.

Organized sandstone/mudstone couplets (Facies C2.1, C2.2 & C2.3)

The sandstones are composed of fine to coarse sand grade sediment and are moderately well graded. Bed-thickness ranges between 3cm and 55cm. The sediments are tabular to broadly lenticular. The sandstones are massive, planar stratified and ripple cross laminated. This lithology comprises approximately 50% of the Facies Association.

Laminated siltstones and mudstones (Facies D2.2 & D2.3)

These sediments occur in packets between 2cm and 1m thick. Sedimentary structures are very well developed and include planar stratification, ripple cross lamination and a range of small scale dewatering structures. Grading is often very well developed. This lithology comprises approximately 35% of the Facies Association.

Slumps (Facies F2.1)

Coherently folded sediments occur in packets up to 50cm thick. The bounding surfaces are most commonly flat. This lithology comprises approximately 5% of the Facies Association.

FACIES ASSOCIATION 2f

Organized sandstone/mudstone couplets (Facies C2.2 & C2.3)

The sandstones are composed of fine to medium sand grade sediment

(Table 5.4/continued)

and are moderately well to well graded. Bed-thickness ranges between 3cm and 25cm. The beds display tabular to lenticular geometries. Amalgamation is common. Internally the sands display planar stratification and ripple cross lamination. This lithology comprises approximately 20% of the Facies Association.

Laminated siltstones and mudstones (Facies D2.1, D2.2 & D2.3)

These sediments occur in packets up to 1.2m thick. Sedimentary structures are very well developed including planar lamination, ripple cross lamination and a variety of small scale dewatering structures. Grading is commonly well developed. This lithology comprises approximately 50% of the Facies Association.

Laminated fine siltstones and mudstones (Facies E2.1 & E2.2)

These sediments occur in packets up to 10cm thick. They are sometimes graptolitic. Grading occurs within these units. This lithology comprises approximately 10% of the Facies Association.

Slumps (Facies F2.1)

Coherently folded sediments occur in packets up to 50cm thick. The bounding surfaces are most commonly flat. This lithology comprises approximately 10% of the Facies Association.

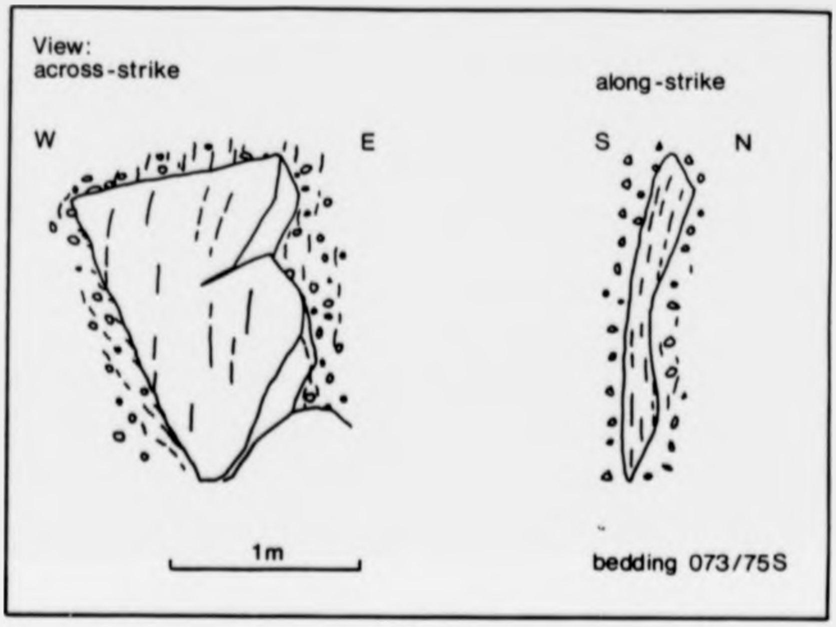


Figure 5.6: Sketch of a large intraformation block (Facies F1.1) included within Facies Association 2a. Barhaskine Conglomerate, near Barhaskine (NX 2589 5354). View to the southwest, younging to northwest.

(b) Depositional Processes and Environmental Setting

The conglomerates within Facies Association 2a were probably formed by a combination of processes. The disorganized (A1.1), and the stratified (A2.1) gravel conglomerates were probably deposited from high-concentration turbidity currents, while the disorganized muddy gravel conglomerates (A1.2) may have been deposited from debris flows (Pickering et al. 1986; Tables 5.1 and 5.4). The large intraformational blocks (F1.1) were probably formed by gravity-induced sliding (Pickering et al. 1986; Tables 5.1 and 5.4).

The very coarse, conglomeratic nature, and the laterally discontinuous, erosive characteristics of the majority of the units (Fig. 5.6), suggest that the sediments included within Facies Association 2a are channel deposits. However, the Association is acyclic, a feature not regarded as typical of channel deposis. Mutti and Ricci-Lucchi (1972), Ricci-Lucchi (1975), Walker (1979) and Nilsen (1984), all suggest that channel deposits typically exhibit thinning- and fining-up cycles. However, published analyses of channel deposits from southern South America (Winn and Dott 1978) and Alaska (Nilsen and Moore 1979, their Fig.10) contain illustrations of sequences which are acyclic. Acyclicity is probably the result of channel stacking caused by minimal, lateral channel or thalweg migration. The high-density turbidity currents which deposited the majority of the conglomerates (A1.1 and A2.1) were thus probably channelised. The debris flows responsible for the deposition of the muddy conglomerates (A1.2) may have been derived from the channel margins.

Since this Facies Association only forms sequences up to 50m thick, it is here suggested that it represents channels with dimensions typical of 'upper-mid-fan' (Walker 1978) environmental settings, which feed sediment to 'lower-mid-fan' areas. The large intraformational blocks of Facies F1.1 were probably derived from the channel margins as a result of local 'rockfalls' (Section 5.4.2).

5.3.3.2 Facies Association 2b - 'Upper Mid-fan' Channel Deposits

(a) Recognition

Facies Association 2b comprises a variety of facies from Classes A, B and C and Groups A1, A2, B1, B2 and C2 (Pickering et al. 1986). The sediments are predominantly thick- to very thick-bedded sandstones and pebbly sandstones, while gravel conglomerates are locally important. Sequences assigned to Facies Association 2b are typically acyclic (Plate 5.6), however, some ill-defined thinning- and fining-up cycles occur. Facies Assocation 2b dominates

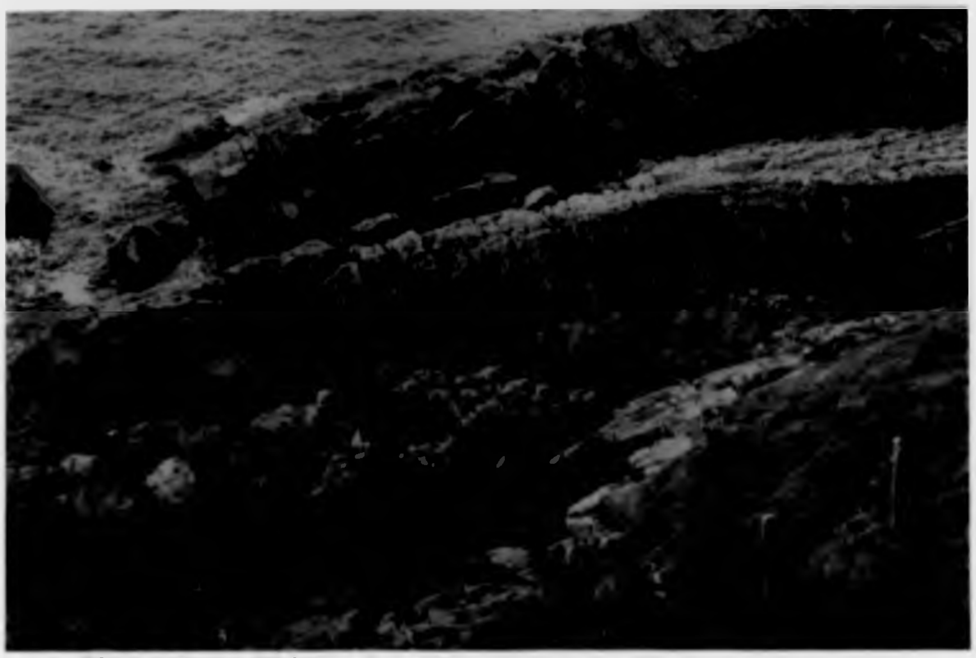


Plate 5.6: Thick- to very thick-bedded, amalgamated sandstones of Facies Association 2b. Money Head Formation (NX 0494 4826). View to southwest. Beds young to right of Plate. 1m high fence posts.

Plate 5.7: Organized, stratified gravels (Facies A2.1). Garheugh -A Formation (NX 2600 5144). View to north-northwest. Younging is towards top of Plate.

sequences up to approximately 150m thick (e.g. Daw Point Member, see Table 2.3 and Section 2.4.1.5; Kelling et al. 1987).

Thick- to very thick-bedded (80cm to 8m), disorganized and organized (stratified) pebbly sandstones (A1.4 and A2.5), disorganized and organized (planar and cross-stratified) sandstones (B1.1, B2.1 and B2.2), and organized sandstone-mudstone couplets (C2.1), dominate Facies Association 2b. Disorganized gravel, and muddy gravel conglomerates (A1.1 and A1.2) (Fig. 5.7), and organized, stratified gravel conglomerates (A2.1) (Fig. 5.8 and Plate 5.7) are locally important.

Facies Association 2b is predominantly acyclic, but thinning- and fining-up cycles are occasionally developed. These cycles typically commence with very thick-bedded (>1 5m) pebbly sandstones (A1.4 and A2.5) and sandstones (B1.1, B2.1 and B2.2). These exhibit strongly erosive bases and pass upwards into more thinly bedded (80cm to 120cm thick) sandstones (B1.1, B2.1 and B2.2) and sandstone-mudstone couplets, with less strongly scoured to non-erosive bases. The thinning- and fining-up cycles are usually 10 to 15m thick.

The disorganized muddy gravel conglomerates (A1.2), which are locally important (Fig. 5.7), exhibit

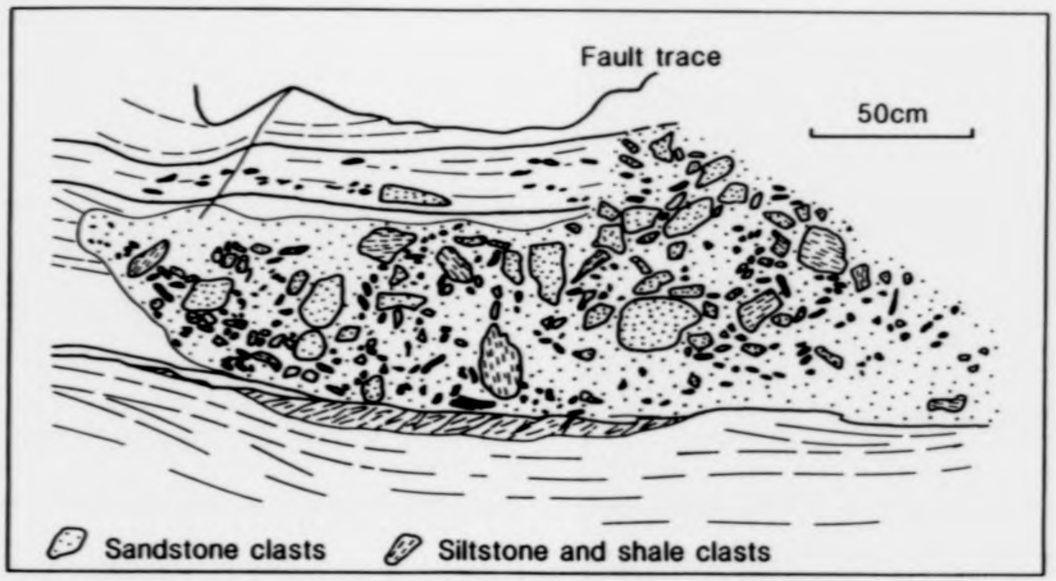


Figure 5.7: Sketch of disorganized conglomerate (Facies A1.2) within Facies Association 2b. Note the planar and low-angle cross stratification in the surrounding sandstones (Facies B2.1 and B2.2). Money Head Formation at Fox Rattle (NX 0460 4884), 300m south of Cairngarroch Bay. View down dip, to northwest. Beds young to northwest.

Plate 5.8: Facies Association 2c. Note the strongly erosive bases of the thick-bedded sandstones and sharp transition to thin-bedded sediment. Stinking Bight Formation (NX 0708 4604). View to northwest. Hammer for scale.

Plate 5.9: Facies Association 2c. Note the thinning-up sequence. Money Head Formation (NX 0484 4832). View to southeast. Younging to right of Plate. 80cm high back-pack for scale.

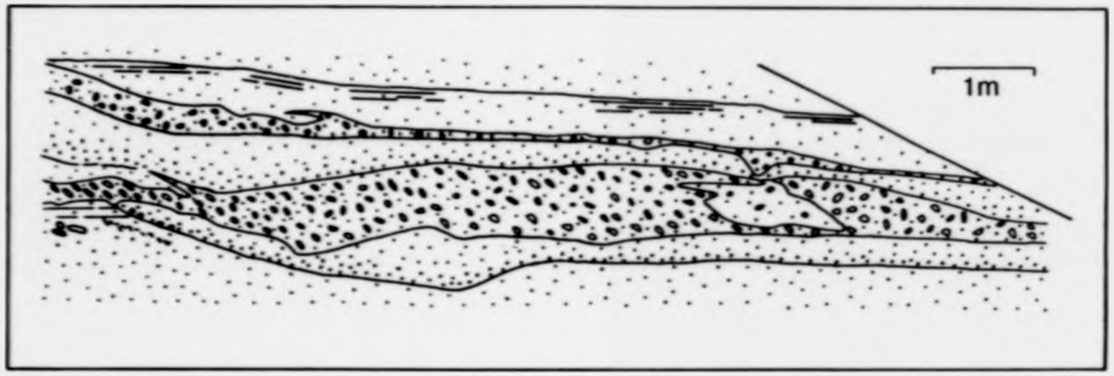


Figure 5.8: Measured sketch of organized conglomerates (Facies A2.1). Note the lateral impersistence of units, their scoured bases and top surface relief. Garheugh -A Formation, 400m east of Craignarget (NX 2600 5144). View to northeast.

relatively flat, non-erosive bases and undulatory hummocky tops. Most units are laterally impersistent and often taper to a blunt snout.

The majority of the disorganized, clast-supported (A1.1), and organized, stratified (A2.1), gravel conglomerates, form laterally impersistent, erosively-based beds with flat to mildly undulatory tops. Some units, however, display strong top surface relief (Fig. 5.8).

(b) Depositional Processes and Environmental Setting

The majority of the sediments within Facies Association 2b, including many of the gravel conglomerates (A1.1 and A2.1), the pebbly sandstones (A1.4 and A2.5), the sandstones (B1.1, B2.1 and B2.2) and the sandstone-mudstone couplets (C2.1), are considered to have been deposited from high-concentration turbidity currents. The disorganized muddy gravel conglomerates (A1.2) were probably deposited from debris flows (Pickering et al. 1986; Tables 5.1 and 5.4).

The general characteristics of the sediments included within Facies Association 2b, for example their persistently coarse-grained nature and the importance of basal erosion surfaces, suggest that these are channel deposits (Walker 1979; Nilsen 1984). The rare thinning- and fining-up cycles (4-10m thick) support a channel interpretation and suggests that some channel migration did take place.

The often great stratigraphical thickness which this Facies Association dominates (150m in the Daw Point Member, see Section 2.4.1.5) indicates that these were relatively major channels, equivalent to Walker's (1978) 'upper mid-fan' channels. The stratified gravel conglomerates (A2.1), which display strong depositional topographies (Fig. 5.8), probably represent in-channel bar-forms, deposited from traction bed-load beneath high-density turbidity currents.

The muddy gravel conglomerates (A1.2) (Fig. 5.7) appear to represent debris flow lobes, probably derived from the channel margins (Section 5.4.2).

5.3.3.3 <u>Facies Association 2c - 'Lower Mid-fan' Channel Deposits</u>

(a) <u>Recognition</u>

Facies Association 2c comprises a wide range of facies types, from Classes B, C, D and F, and Groups B1, B2, C1, C2, D1, D2 and F2 (Pickering <u>et al</u>. 1986; Tables 5.1 and 5.4). The sediments form 2-11m thick couplets, the lower divisions of which comprise medium-to very thick-bedded sandstones, while the upper divisions comprise laminated and thin-bedded siltstones and sandstones. The transition between the two 'divisions' may be sharp (Plate 5.8 and Fig. 5.9), or transitional, forming thinning- and fining-up sequences (Plate 5.9 and Fig. 5.9). Facies Association 2c dominates sedimentary sequences up to approximately 35m thick (e.g. Portpatrick Formation, Tables2.3; Kelling et al. 1987).

The lower divisions of the couplets, which dominate the Association, are dominated by medium- to very thick-bedded (30cm to 2.2m), disorganized and organized (planar- and cross-stratified) sandstones (B1.1, B2.1 and B2.2) and sandstone-mudstone couplets (C1.1, C2.1 and C2.2). Erosional bed bases and amalgamation are common featues (Plates 5.8, 5.9 and 5.10).

The upper divisions of the couplets are dominated by thin- to medium-bedded (3 to 30cm thick), disorganized sandstones (B1.1), disorganized and organized sandstone-mudstone couplets (C2.1 and C2.2) and siltstones, muddy siltstones and siltstone-mudstone couplets (D1.1, D1.2, D2.1, D2.2 and D2.3).

Contorted and disturbed strata (F2.1 and F2.2) (Plate 5.21) occur within both the upper and lower couplet divisions. Dewatering structures are common, particularly in the sand-rich parts of sequences

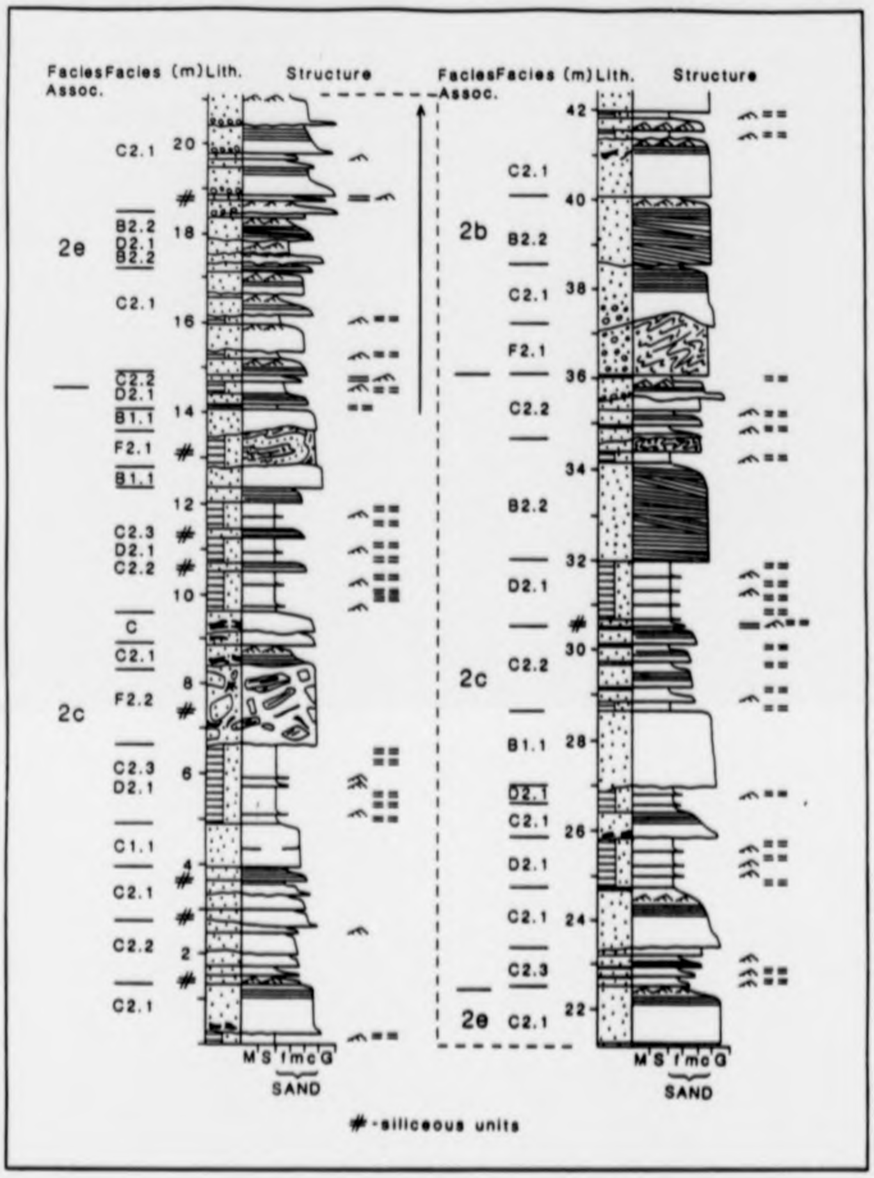


Figure 5.9: Graphic log illustrating the typical sedimentological features of Facies Association 2c. Log from Mill Bawn (NX 9821 5600), 500m south of Black Head. Portpatrick Formation, Basic-clast Division, Hairyhorroch Member. For legend see Figure 5.3.

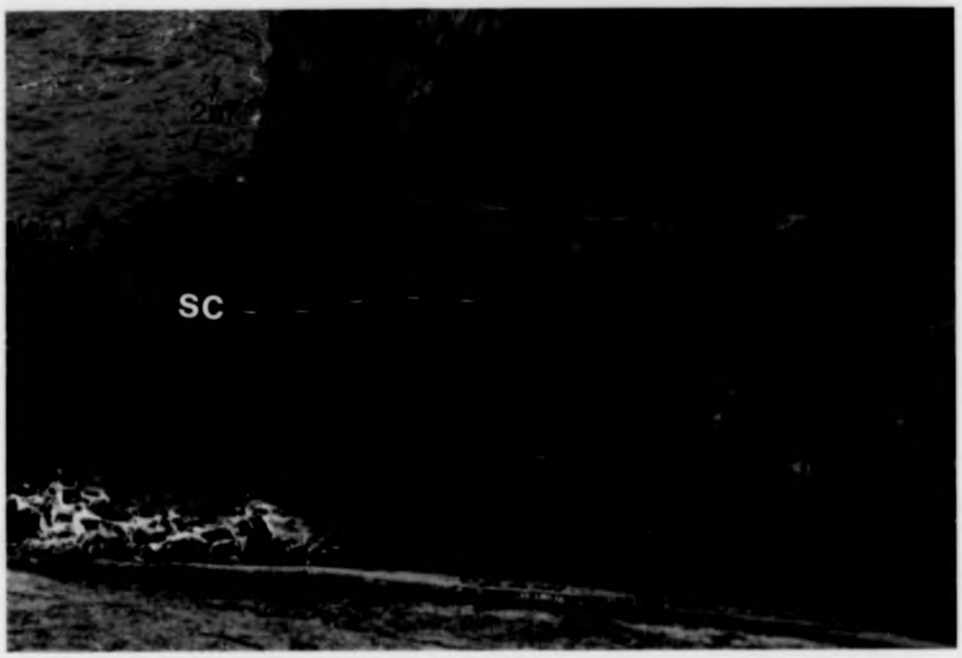


Plate 5.10: Basal erosion and amalgamation in Facies Association 2c. Port Logan Formation (NX 0914 4021). View down dip to north. Beds young to north.

Plate 5.11: Dewatering structures. Stinking Bight Formation (NX 0708 4604). Bed youngs towards top of Plate. Hammer for scale.

(Plates 5.11, 5.27 and 5.28). Sole structures are developed (Plates 5.23 to 5.26 inclusive).

Transitions between the lower and upper couplet divisions may be sharp or gradational, forming 4 to 10m thick thinning- and fining-up cycles (Plates 5.8 and 5.9).

(b) Depositional Processes and Environmental Setting

The majority of the sediments included within Facies Association 2c are ascribed to high- to low-density turbidity currents (B1.1, B1.2, B2.1, B2.2, C1.1, C2.1, C2.2, C2.3, D1.1, D1.2, D2.1, D2.2 and D2.3) (Pickering et al. 1986). There is some evidence of sediment reworking, in the form of stepped grading of the 'tops' of some beds. In general the medium- to very thick-bedded sandstones which dominate the lower divisions of the couplets were probably deposited from high-density turbidity currents, while the laminated to medium-bedded mudstones, siltstones and sandstones which dominate the upper divisions were probably formed by low-density turbidity currents (Pickering et al. 1986; Tables 5.1 and 5.4). The chaotic, contorted and disrupted sediments (F2.1 and F2.2) are attributed to gravity-induced sliding and slumping, and debris flows generated as a result of the latter processes.

The general characteristics of the sediments included within Facies Association 2c, which comprises 2-11m thick, erosively-based couplets, suggest that they were deposited in channels (Walker 1979; Nilsen 1984). The medium- to very thick-bedded, erosively-based sediments which make up the lower divisions of the couplets, were probably deposited within active channel thalwegs. The upper couplet divisions, composed of laminated to medium-bedded sediments, are clearly related to the sediments within the lower divisions, and probably represent channel fills, deposited after channel or thalweg abandonment. Gradual transitions between the lower and upper couplet divisions (thinning- and fining-up cycles) represent a gradual channel or thalweg migration laterally away from the depositional area. Sharp transitions represent abrupt abandonment, probably as a result of sudden avulsion.

The relatively thin couplet thicknesses indicate that they were deposited in 'lower mid-fan' type channels (Walker 1978). The chaotic, contorted and disturbed sediments (F2.1 and F2.2) probably represent slump and slide sheets, and debris flow lobes, derived from the channel margins.

Mutti et al. (1981, their Fig.2) document a similar facies association from the Hecho Group of the

Spanish Pyrenees which they interpret in a similar way.

5.3.3.4 Facies Association 2d - Channel Margin Deposits

(a) Recognition

Facies Association 2d is dominated by very thin- to medium-bedded (1cm to 30cm thick) sandstones, representative of Facies Classes B and C, and Groups B1, B2 and C2 (Pickering et al. 1986; Tables 5.1 and 5.4). Chaotic deposits of Facies Class F (Group F2) are present. Facies class D (Group D2) occurs but is only of very minor importance. Facies Assocation 2d dominates sedimentary sequences up to approximately 15m in thickness (e.g. in the Money Head Formation, see Table 2.3).

Facies Association 2d is dominated by very thin- to medium-bedded (1-30cm thick) disorganized and organized (planar stratified) sandstones (B1.1 and B2.2), and organized sandstone-mudstone couplets (C2.2 and C2.3). Well developed thickening- and coarsening-up (2m to 14m thick) sequences are apparent (Fig. 5.10). The bedding pattern is extremely irregular; lensing, wedging and amalgamation of beds is common (Fig. 5.11). Some beds exhibit strogly scoured, broadly concave-up,

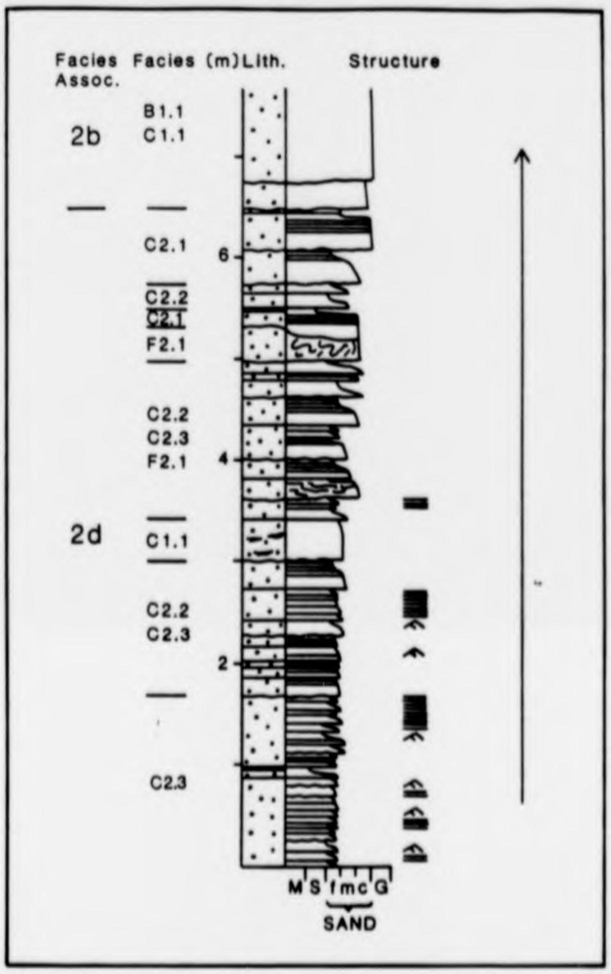


Figure 5.10: Graphic log illustrating some of the typical sedimentological features of Facies Associations 2d and 2b. Log from north of Money Head 50m north of Money Head (NX 0449 4856). Money Head Formation. For legend see Figure 5.3.

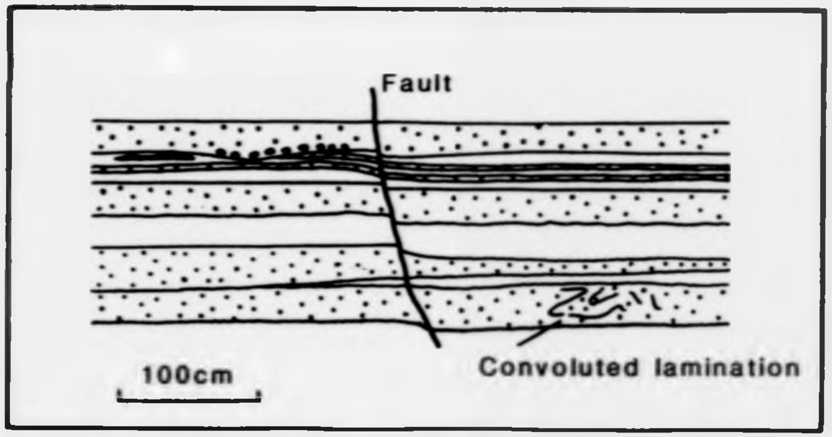


Figure 5.11: Sketch illustrating lensing and wedging of beds in Facies Association 2d. From 175m north of Money Head (NX 0452 4856), Money Head Formation. View down dip to the north. Beds dip and young to the north. Dip 072/67N.

bases, while others display convex-up depositional top surfaces.

Organized siltstones, muddy siltstones and siltstone-mudstone couplets (D2.1, D2.2 and D2.3), make up a minor part of the Facies Association 2d. Chaotic, folded and contorted sediments (F2.2) are interbedded with the facies described above.

Sole Structures are relatively common (Plates 5.23 to 5.26 inclusive).

(b) <u>Depositional Processes and Environmental Setting</u>

The vast majority of the sediments included within Facies Association 2d, including the disorganized and organized sandstones (B1.1 and B2.1), the sandstone-mudstone couplets (C2.2 and C2.3) and the siltstones, muddy siltstones and the siltstone-mudstone couplets (D2.1, D2.2 and D2.3), were probably deposited from high- to low-density turbidity currents (Pickering et al. 1986). The chaotic, contorted and folded sediments (F2.2) are considered to result from gravity-induced sliding and slumping.

The general characteristics of the sediments included within Facies Association 2d, for example, its close association with sediments interpreted as channel deposits (particularly Facies Association 2b and 2c), the irregularity of bedding, and the thin- to medium-bed thicknesses it exhibits, are all suggestive of deposition in a channel margin environment (Mutti 1977) (Table 5.5). Thickening- and coarsening-up cycles (Fig. 5.10) are considered to represent the gradual migration of a channel axis or thalweg towards and over its margin. Hein and Walker (1982) acknowledge the importance of this process in forming thickening- and coarsening-up cycles in channel-related sequences. They suggest that these cycles probably represent the gradual lateral migration of a main channel, over its marginal terraces, during overall aggradation. The broad, concave-up erosion surfaces probably represent crevasse-channel bases. The chaotic, folded and contorted sediments (F2.1) are testimony to the presence of local slopes.

5.3.3.5 Facies Association 2e - Interchannel/Crevasse Deposits

(a) Recognition

Facies Association 2e comprises a wide range of facies types from Classes B, C, D and F, and Groups B1, B2, C2, D2 and F2 (Pickering et al.1986; Tables 5.1 and 5.4). The sediments are dominantly thin- to thick-bedded (10cm to 100cm thick) sandstones and sandstone-mudstone couplets. Facies Association 2e dominates sequences up to approximately 20m thick.

Table 5.5: Distinctive features of thin-bedded turbidite facies. From Mutti (1977).

(e.g. the Port Logan Formation, see Table 2.3; Kelling et al. 1987).

Facies Association 2e is dominated by thin- to thick-bedded, disorganized sandstones (B1.1 and B1.2), organized, planar and cross-stratified sandstones (B2.1 and B2.2), organized sandstone-mudstone couplets (C2.1, C2.2 and C2.3) and by thick, irregularly, and thin, regularly laminated siltstones and mudstones (D2.2 and D2.3) (Figs. 5.12 and 5.13). Chaotic, contorted, folded and dislocated sediments (F2.1 and F2.2) are interbedded with the facies listed above.

The sediments included within Facies Association 2e display acyclic (Fig. 5.12), thickening- and coarsening-up (2m to 6m thick) (Fig. 5.9), and thinning- and fining-up (1m to 3m thick) (Fig. 5.12, Plate 5.12) sequences. Within the acyclic sequences, sheet-like to broadly lenticular beds of sandstone (Facies Groups B1, B2 and C2) (Fig. 5.13) are interbedded with medium to thick packets of laminated siltstone and mudstone (Facies Group D2). The sandstones occasionally exhibit erosional bases and are sometimes amalgamated (Fig. 5.12). Contorted and dislocated sediments (F2.1, F2.2) are interbedded with the facies types briefly described above Fig. 5.14).

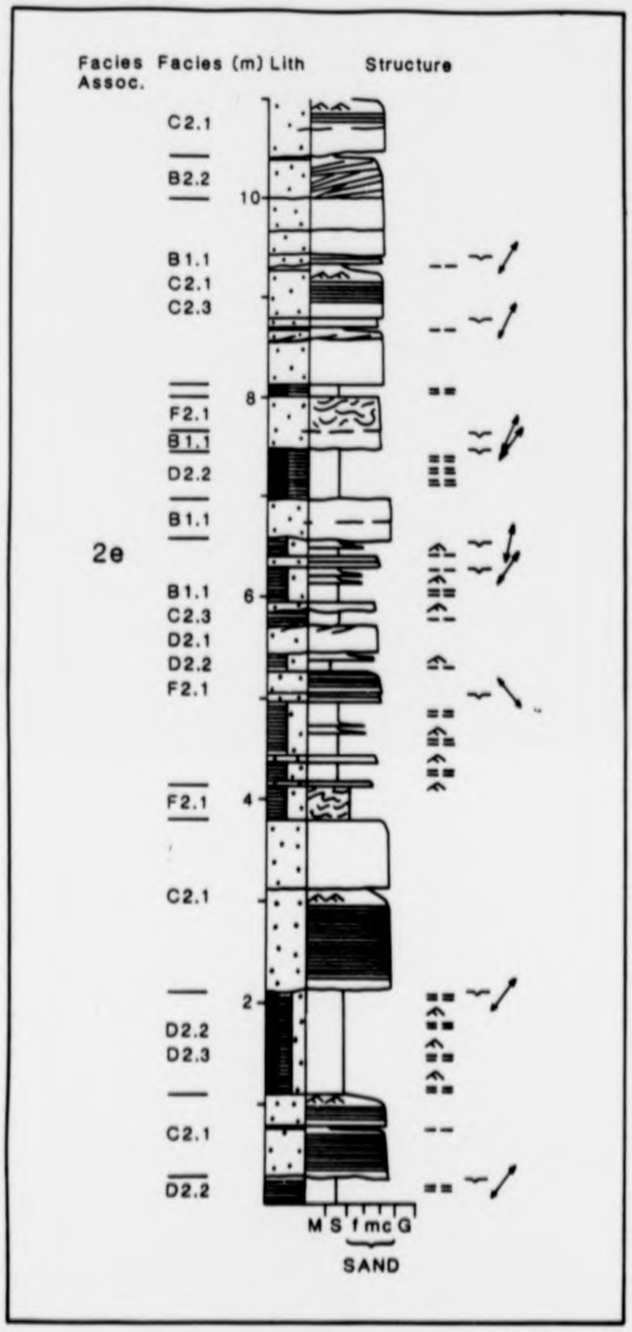


Figure 5.12: Graphic log illustrating some of the typical sedimentological features of Facies Association 2e. Log from Quarry Bay (NX 0922 4032). Port Logan Formation. For legend see Figure 5.3.

Plate 5.12: Small scale thinning-up and thickening-up cycles in Facies Association 2e. Port Logan Formation (NX 0914 4022). View down dip to north. Beds young to north

Plate 5.13: Interbedding of lenticular and sheet sandstones with siltstones and shales, Facies Association 2e. Port Logan Formation (NX 0922 4032). View to east. Beds young to left of Plate. Hammer for scale.

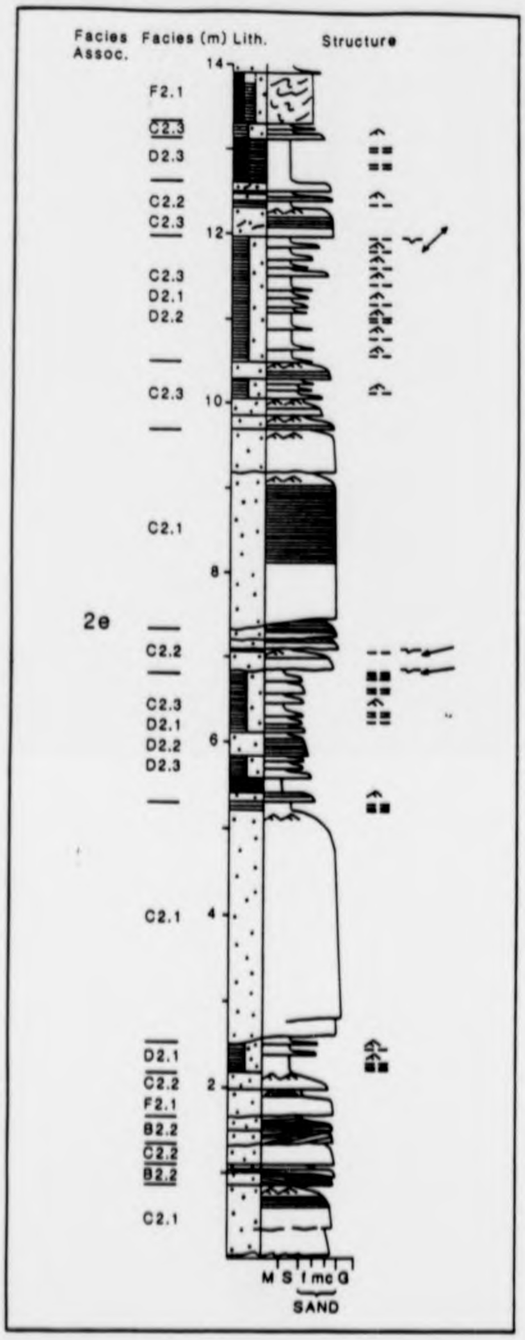


Figure 5.13: Graphic log illustrating acyclicity within Facies Association 2e. Log from 100m east of Money Head (NX 0484 4832). Money Head Formation. For legend see Figure 5.3.

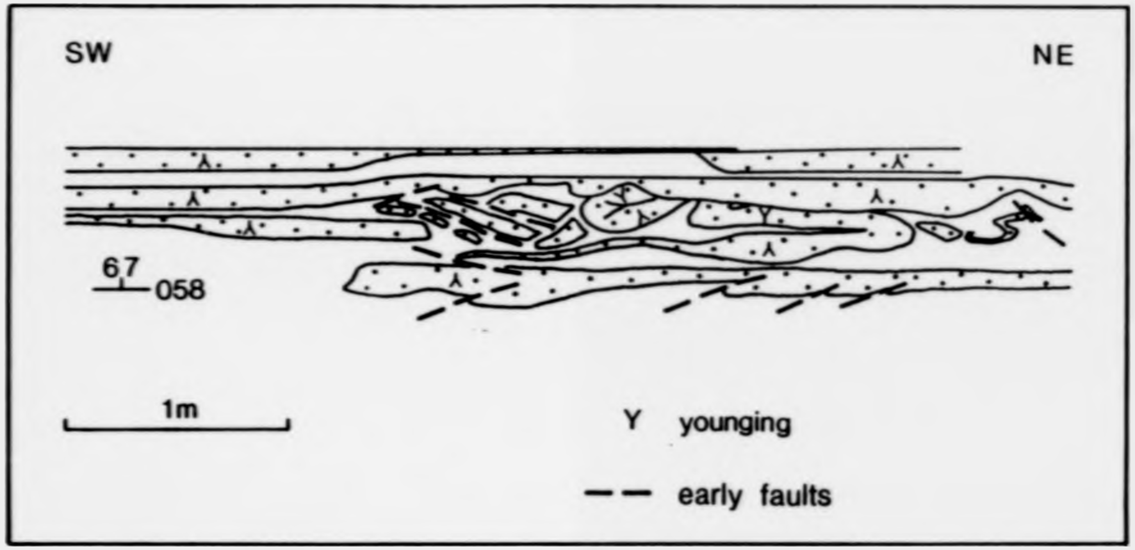


Figure 5.14: Measured sketch of a slump sheet within Facies Association 2e. Money Head Formation, 100m east of Money Head (NX 0485 4833).

The 2m to 6m thick, thickening- and coarsening-up cycles which occur within Facies Association 2e, comprise laminated siltstones and mudstones (Facies Group D2), and medium- to very thick-bedded sandstones (Facies Groups B1, B2 and C2) (Fig. 5.9). The sandstones commonly display erosional bases and amalgamation. Bedding is often broadly lenticular and is occasionally highly irregular (Fig. 5.15). Some thickening and coarsening-up sequences are topped by units which exhibit concave-up, erosional bases. These units form the bases of the 1m to 2.5m thick, thinning-and fining-up cycles mentioned above. Thin- to very thick-bedded sandstones (Facies Groups B1, B2 and C2), and laminated mudstones and siltstones (Facies Group D2) dominate these cycles. Chaotic, contorted and folded sediments (Facies F2) are occasionally developed. The sandstones commonly exhibit erosional bases.

Sole structures are commonly developed within Facies Association 2e (Plates 5.23 to 5.26 inclusive).

(b) Depositional Processes and Environmental Setting

It is suggested that the majority of the sediments included within Facies Association 2e were deposited from high- to low-density turbidity currents (B1.1, B2.1, C2.1, C2.2, C2.3, D2.2 and D2.3) (Pickering et al 1986; Tables 5.1 and 5.4). The relative

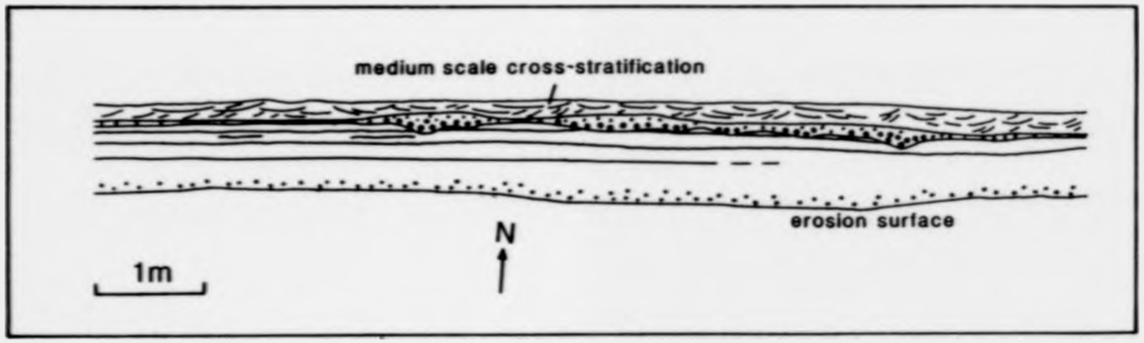


Figure 5.15: Measured sketch illustrating the lenticular nature of some units included within Facies Association 2e. Portpatrick Formation, Basic-clast Division, Hairyhorroch Member at Mill Bawa (NW 9820 5604), 500m south of Black Head. View down dip to north. Beds dip 080/85n and young northwards.

importance of Facies B1.2 and B2.2 within the association suggests that sediments were occasionally reworked beneath turbidity currents (Pickering et al 1986). Gravity induced sliding, slumping and dislocation are held responsible for the formation of Facies F2.1 and F2.2.

The general characteristics of the sediments included within Facies Association 2e, such as their frequent concurrence with Facies Associations 2b and 2c, (interpreted as channel deposits), the development of both thickening- and coarsening-up, and thinning- and fining-up sequences, and the sheet-like to broadly 'channelised' bed geometries, are here interpreted as resulting from deposition in crevasse channels and as crevasse splays and lobes. The acyclic, the thickening-up and the thinning-up sequences are discussed in turn, below.

The sandstones included within the acyclic sequences (Fig. 5.13) probably represent unchannelised to broadly channelised crevasse splays. The medium to thick packets (20-80cm thick) of laminated siltstone and mudstone, which are interbedded with the latter, were probably deposited from dilute turbidity currents which overtopped the channel banks, accompanied by hemipelagic settling. In contrast, the sandstones were deposited from low- to high-density, turbid sheet- and channelised-flows. These were probably transported to the depositional area via crevasse breaches in the channel banks. Some of the broadly channelised sandstones and the siltstone and mudstone packets which overlie them probably represent crevasse-channel-fills, which in isolation are indistinguishable from some forms of Facies Association 2c, also considered to be minor channels. The absence of associated thinning- and fining-up sequences indicates that these channels were rapidly abandoned and infilled.

The thickening- and coarsening-up sequences (Fig. 5.9) are indicative of crevase-lobe progradation. The occurrence of Facies B2.1 and B2.2 within these sequences, indicates that occasionally currents reworked the topographic surfaces of the crevasse-lobes. The general characteristics of these sediments are broadly similar to Mutti's (1977) channel-mouth bar facies (Table 5.5).

The thinning- and fining-up sequences are indicative of gradual crevasse-channel-filling, due to channel migration. In isolation these sequences are indistinguishable from some examples of Facies Association 2c (the sediments included within this Association are interpreted as minor channel deposits).

5.3.3.6 Facies Association 2f - Interchannel/Levee Deposits

(a) Recognition

Facies Association 2f comprises a number of facies types from Classes C, D, E and F and Groups C2, D2, E2 and F2 (Pickering et al. 1986; Tables 5.1 and 5.4). The sediments are largely laminated siltstones and mudstones (Facies Groups D2 and E2), very thin- to medium-bedded, sandstone-mudstone couplets (C2) are occasionally important and chaotic sediments (F2) occur. The sediment sequences are acyclic. This Facies Association dominates sedimentary sequences up to approximately 15m thick.

Facies Association 2f is dominated by graded stratified, thick irregularly laminated and thin regularly laminated siltstones and mudstones (D2.1, D2.2 and D2.3) together with graded and laminated mudstones (E2.1 and E2.2). Very thin- to medium-bedded, tabular sandstone-mudstone couplets (C2.2 and C2.3) are locally important. Chaotic and contorted sediments (F2.1) are occasionally interbedded with the facies listed above (Fig. 5.16, and Plates 5.14 and 5.15).

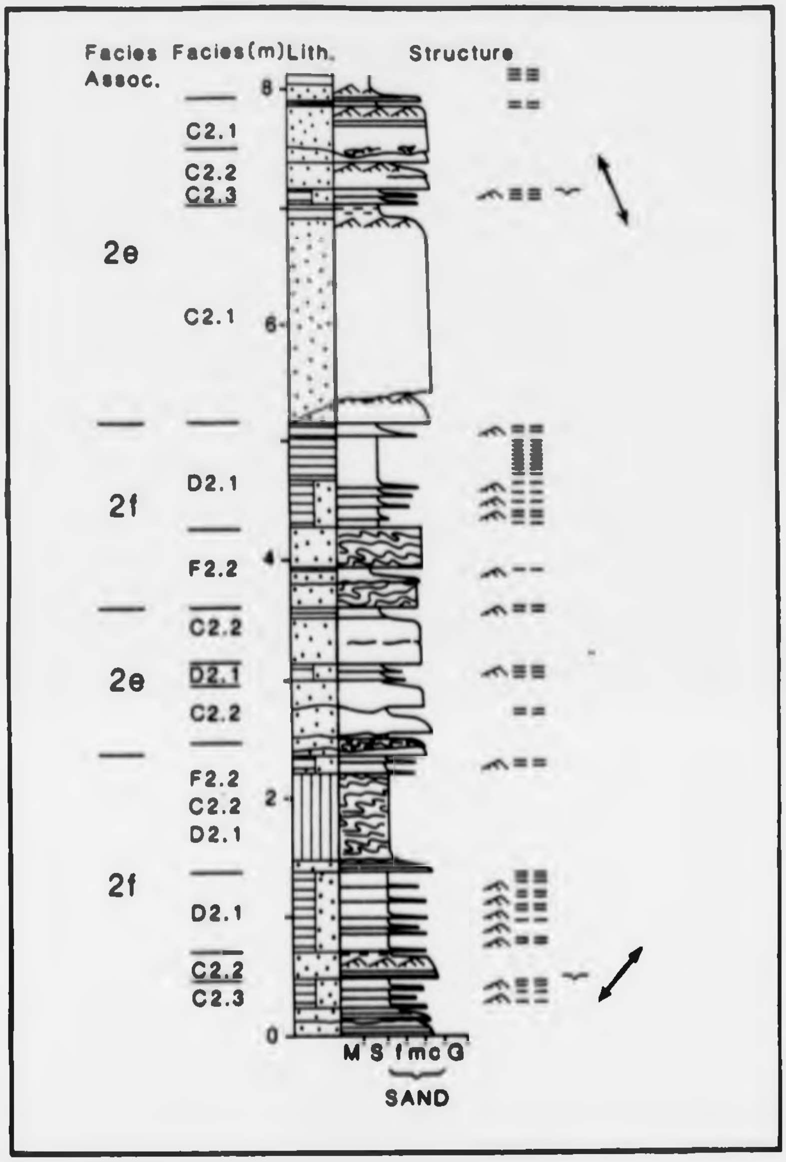


Figure 5.16: Graphic log illustrating the close interrelationships often displayed between Facies Associations 2e and 2f. Log from Scrangie (NX 0910 4016), 450m southwest of Port Logan Bay. Port Logan Formation. For legend see Figure 5.3.

Plate 5.14: Laminated siltstones and mudstones of Facies Association 2f, underlying sandstones of Facies Association 2b. Port Logan Formation (NX 0922 4031). View to west. Beds young in direction of dip.

Plate 5.15: Laminated siltstones and shales (Facies D2.2). Port Logan Formation (NX 0922 4031). Younging is towards top of Plate. Scale is graduated in centimeters and inches.

(b) Depositional Processes and Environmental Setting

The vast majority of the sediments (C2.2, C2.3, D2.1, D2.2, D2.3, E2.1 and E2.2) probably were deposited from low-density turbidity currents. The contorted and folded sediments (F2.1) probably formed from gravity-induced sliding and slumping (Pickering et al. 1986; Table 5.1).

The general characteristics displayed by the sediments included within Facies Association 2f, for example their frequent concurrence with sediments interpreted as channel (Facies Associations 2b and 2c) and crevasse (Facies Association 2e) deposits, and their predominantly fine-grained nature, suggest that they are interchannel deposits. Sandstone-mudstone couplets (C2.2 and C2.3) are only locally important. The probability that some of these sandstones are crevasse deposits cannot be ruled out. The common occurrence of slump folds (F2.2) within the more sand-rich sequences suggests that Facies Association 2f is at least partly representative of levee environments. Facies Association 2f is therefore considered to represent both inter-channel and levee environments.

5.3.4. Facies Association Group 3 - Sheet and Lobe Deposits

Facies Association Group 3 includes two facies associations, the salient characteristics of which are listed in Table 5.2. The distribution of each of these facies associations within the study area is summarized in Tables 2.3. and 5.6.

5.3.4.1 Facies Association 3a - Sheet and Lobe Deposits (Proximal)

(a) Recognition

Facies Association 3a comprises a number of facies types from Classes B, C, D and F, and Groups B1, B2, C1, C2, D2 and F2 and comprises sequences which are up to 200m in thickness (e.g. in the Grennan Point and Garheugh -B Formations, see Tables 2.3 and 5.6).

Facies Association 3a is dominated by disorganized and organized thin- to very thick-bedded sandstones (B1.1, B2.1 and B2.2) and sandstone-mudstone couplets (C1.1, C2.1, C2.2 and C2.3) (Fig. 5.17). Laminated siltstones and mudstones (D2.1, D2.2 and D2.3) usually comprise less than 25% of Facies Association 3a sequences. Slump sheets comprising chaotic, contorted and folded sediments (F2.1 and F2.2) are interbedded with the sediments listed above (Plate

Table 5.6: Summary lithological descriptions of the main facies types included within Facies Associations 3a and 3b, Facies Association Group 3, as they actually occur in the study area.

FACIES ASSOCIATION GROUP 3

FACIES ASSOCIATION 3a

Disorganized and organized sandstones (Facies B1.1, B2.1 & B2.2)

The sandstones are composed of medium to coarse sand grade sediment. Bed-thickness ranges between 5cm and 1.2m. The beds are generally tabular, some display scoured bases. The sandstones may be massive, planar stratified or cross stratified. Grading is at best only poorly developed. This lithology comprises approximately 15% of the Facies Association.

Disorganized and organized sandstone/mudstone couplets (Facies C1.1, C2.1, C2.2 & C2.3)

The sandstones are composed of medium to coarse sand grade sediment and are poorly to very well graded. Bed-thickness ranges between 5cm to 1.4m. The beds are generally tabular. Amalgamation is common. Internally the sandstones may be massive or they may display partial Bouma sequences. This lithology comprises approximately 70% of the Facies Association.

Laminated siltstones and mudstones (Facies D2.1, D2.2 & D2.3)

These sediments occur in packets up to 1.5m thick. Sedimentary structures are very well developed and include planar lamination, ripple cross lamination and a variety of small scale dewatering structures. Grading is commonly developed. This lithology comprises approximately 10% of the Facies Association.

Slumps (Facies F2.1)

Coherently folded sediments occur in packets up to 3m thick. The bounding surfaces are slightly irregular. This lithology comprises approximately 5% of the Facies Association.

FACIES ASSOCIATION 3b

Organized sandstone/mudstone couplets (Facies C2.3)

The sandstones are composed of fine to medium sand grade sediment and are well graded. Bed-thickness ranges between 3cm and 10cm. The sands are generally tabular. Internally the sandstones are planar and ripple cross stratified. This lithology comprises approximately 30% of the Facies Association.

(Table 5.6/continued)

Laminated siltstones and mudstones (Facies D1.1, D1.2, D2.1, D2.2, D2.3, E1.1, E1.2, E2.1, E2.2 & G2.1)

This lithology comprises approximately 70% of the Facies Association. The sediments are planar laminated and ripple cross laminated or structureless. The mudstones are occasionally graptolitic.

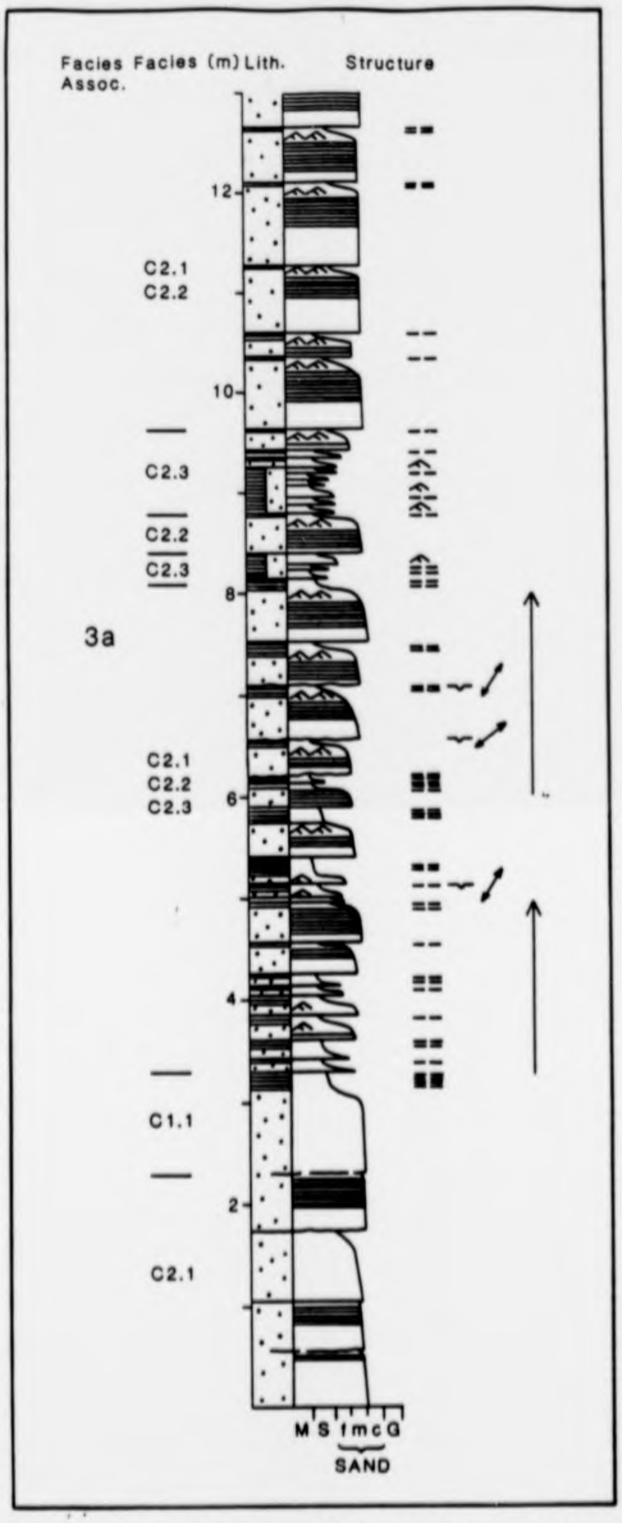


Figure 5.17: Graphic log illustrating thickening- and coarsening-up cycles in Facies Association 3a. Log from Grennan Point (NX 0748 4370). Grennan Point Formation. For legend see Figure 5.3.

5.22). Trace fossils, notably Palaeodictyon (Plate 5.16), are locally common.

Most Facies Association 3a sequences are acyclic (Figs. 5.18 and 19), but some thickening- and coarsening-up cycles are developed and are locally very important (Figs. 5.17 and Plate 5.17). The cycles range in thickness between 1.5m and 12m. Erosional bed bases are relatively common, but the sandstones are rarely channelised, and individual beds generally have a tabular, sheet-like appearance (Plate 5.18). Sole structures and dewatering structures are common (Plates 5.23 to 5.28 inclusive). The laminated siltstones and mudstones (D2.1, D2.2 and D2.3) occupy discrete, 15cm to 110cm thick packets (Fig. 5.18 and Plate 5.19).

(b) Depositional Processes and Environmental Setting

It is suggested that the majority of sediments included within Facies Association 3a (Facies B1.1, B2.1, C1.1, C2.1, C2.2, C2.3, D2.1, D2.2 and D2.3) were deposited from high- to low-density turbidity currents. Most of the beds display a tabular geometry, indicating these currents were non-channelised, sheet-flows. The sporadic occurrence of Facies B2.2 (Plate 5.20) is testimony to occasional sediment reworking. Gravity induced slumping and

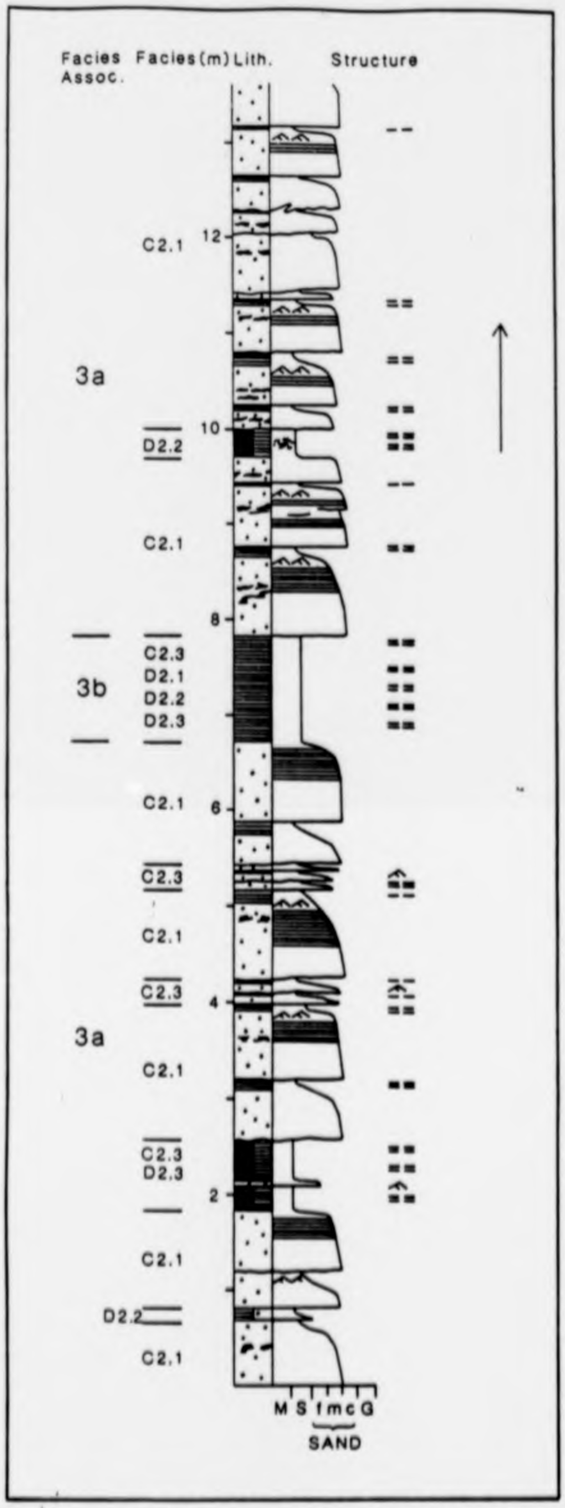


Figure 5.18: Graphic log illustrating an acyclic occurrence of Facies Association 3a. Log from Port of Spittal Bay (NX 0195 5218). Portpatrick Formation, Basic-clast Division, Port of Spittal Bay Member. For legend see Figure 5.3.

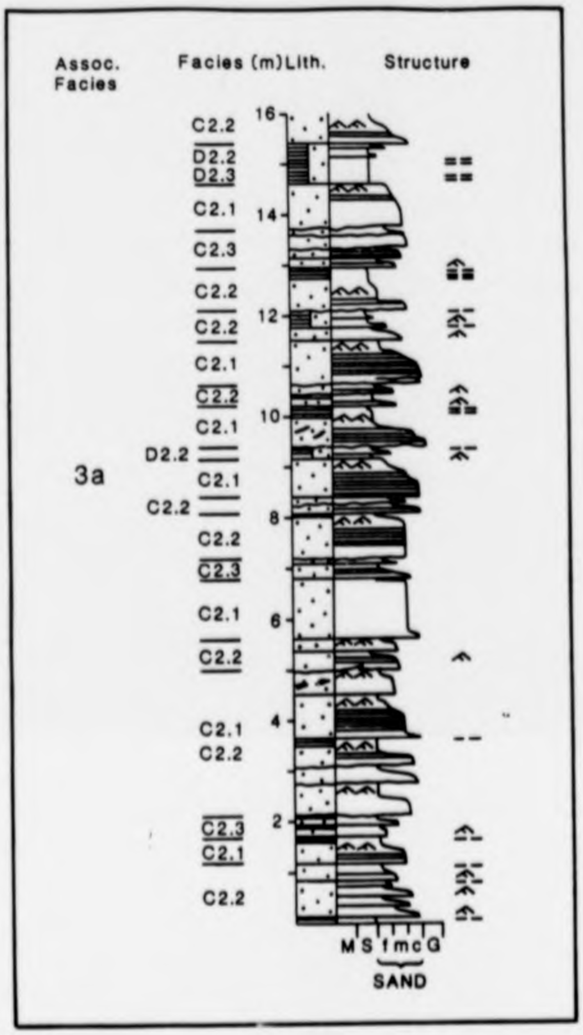


Figure 5.19: Graphic log illustrating some of the typical sedimentological features of Facies Association 3a. Log from north of Tandoo Cave (NX 0060 5289). Portpatrick Formation, Acid-clast Division. For legend see Figure 5.3.

Plate 5.16: Trace fossils developed in Facies Association 3a. Port of Spittal Bay Member (NX 0195 5218). Scale is graduated in centimeters and inches.

Plate 5.17: Thickening-up sequence developed in Facies Association 3a. Grennan Point Formation (NX 0747 4370). View to southwest. Beds young towards right of Plate.

Plate 5.18: Tabular and sheet-like bedding, Facies Association 3a. Portpatrick Formation, Acid-clast Division (NX 0080 5270). View to south. Beds young towards top of Plate.

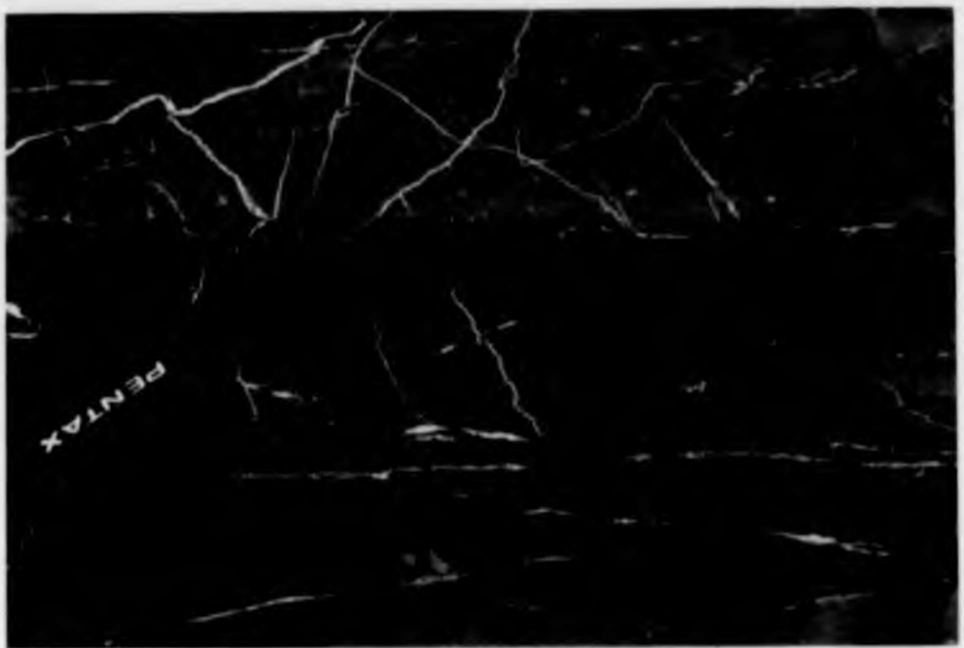


Plate 5.19: Thin-bedded and laminated fine sandstones, siltstones and shales (Facies D2.1 and D2.2) Portpatrick Formation, Acid-clast Division (NX 0004 5368). Beds young to top of Plate. Camera lens cap for scale.

Plate 5.20: Cross-bedded sandstones (Facies B2.2). Portpatrick Formation, Basic-clast Division (NX 9850 5565). Bed youngs to top of Plate. Hammer for scale.

sliding is considered to have formed the contorted sediments of Facies F2.1.

Thickening- and coarsening-up cycles, commonly developed within Facies Association 3a sequences (Plate 5.17), have been interpreted widely as deposits of mid-fan lobes (Walker 1978; Nilsen 1984). Various mechanisms have been proposed for the formtion of these cycles, all of which involve the progressive migration of the depocenter:

(a) Mutti and Sonnino (1981) suggest that migration might result from the progressive smoothing of depositional relief. Migration need not be progressive. These authors cite examples of thickening- and coarsening-up cycles formed in this way, which in turbidite basins from the Appenines have an average thickness of 2.5m, and refer to them as compensation cycles.

(b) Walker (1978) suggests that migration results from the progradation of feeder channels. It is suggested (Walker 1978) that cycles which are less than 5m thick are related to minor channels, while those thicker than 20m are related to larger, deeper channels.

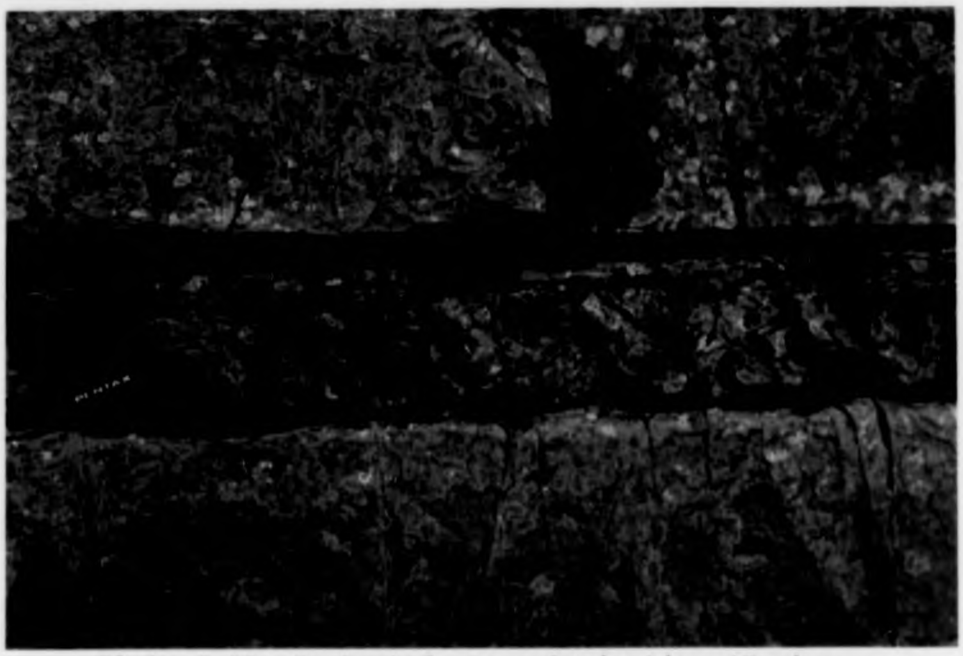


Plate 5.21: Contorted cross-lamination (Facies F2.1). Money Head Formation (NX 0485 4833). Beds young to top of Plate. Camera lens cap for scale.

Plate 5.22: Disturbed strata (Facies F2.2). Port Logan Formation (NX 0922 4032). Beds young to top of Plate. Pencil for scale (10cm).

Although it is impossible to determine which of the above mechanisms might be responsible for the development of the thickening- and coarsening-up cycles observed within Facies Association 3a sequences, it is clear that, for their formation, a single feeder source must be dominant within a particular depositional area. A channel mouth could well provide such a feeder source.

In contrast, the acyclic Facies Association 3a sequences were probably formed in environments influenced by more than one feeder source. This scenario would, theoretically, prevent the development of thickening- and coarsening-up cycles.

The locally common occurrence of trace fossils, particularly Palaeodictyon (Plate 5.16), is testimony to periods of quiesence during the deposition of some Facies Association 3a sequences.

The presence of contorted and folded sediments (F2.1) within the association, is indicative of periodic slope instability. Slump sheets are subsequently eroded (Fig.3.6). The irregularity displayed by the upper surfaces of some sheets appears to have partially channelised some flows.

Plate 5.23: Flute casts. Garheugh -A Formation (NX 2589 5114). View to northwest. Hammer for scale.

Plate 5.24: Flute casts. Grennan Point Formation (NX 0763 4367). View to northwest. Hammer for scale

Plate 5.25: Longitudinal ridges and furrows. Garheugh -A Formation (NX 2589 5114). Bed youngs to northwest. Hammer for scale.

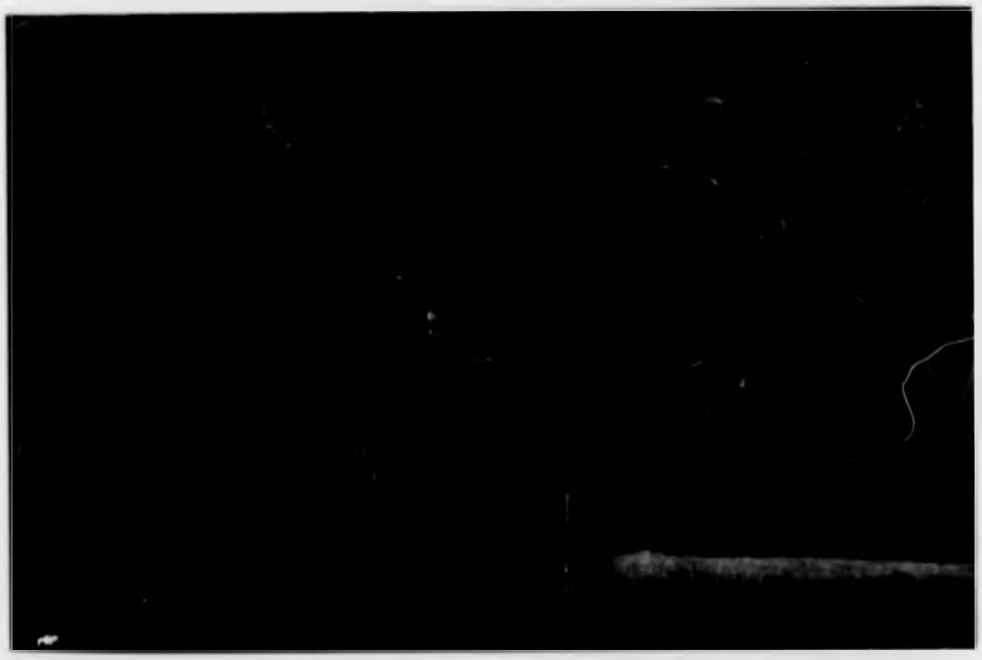


Plate 5.26: Elongated flute casts superimposed on crescentic ripple moulds. Stinking Bight Formation (NX 0664 4483). View to northwest. Hammer for scale.

5.3.4.2 Facies Association 3b - Sheet and Lobe Deposits (Distal)

(a) Recognition

Facies Association 3b comprises several facies from Classes C, D and E, and Groups C2, D1, D2, E1 and E2, and dominates sequences up to 20m thick.

Facies Assocation 3b is dominated by very thin- to thin-bedded, tabular sandstone-mudstone couplets (C2.3), structureless siltstones (D1.1), muddy siltstones (D1.2), graded stratified siltstones (D2.1), thick irregularly laminated siltstones and mudstones (D2.2) (Plate 5.19), thin regularly laminated siltstones and mudstones (D2.3), structureless and varicoloured mudstones (E1.1 and E1.2), graded mudstones (E2.1), laminated mudstones (E2.2) and hemipelagites (G2.1) (Fig. 5.20).

(b) Depositional Processes and Environment

It is suggested that these sediments were deposited from high- (D1.1, D1.2, E2.1) and low-density (C2.3, D2.1, D2.2, D2.3, E2.1, E2.2) turbidity currents, and by hemipelagic and pelagic settling (E1.1, E1.2, G1.2).

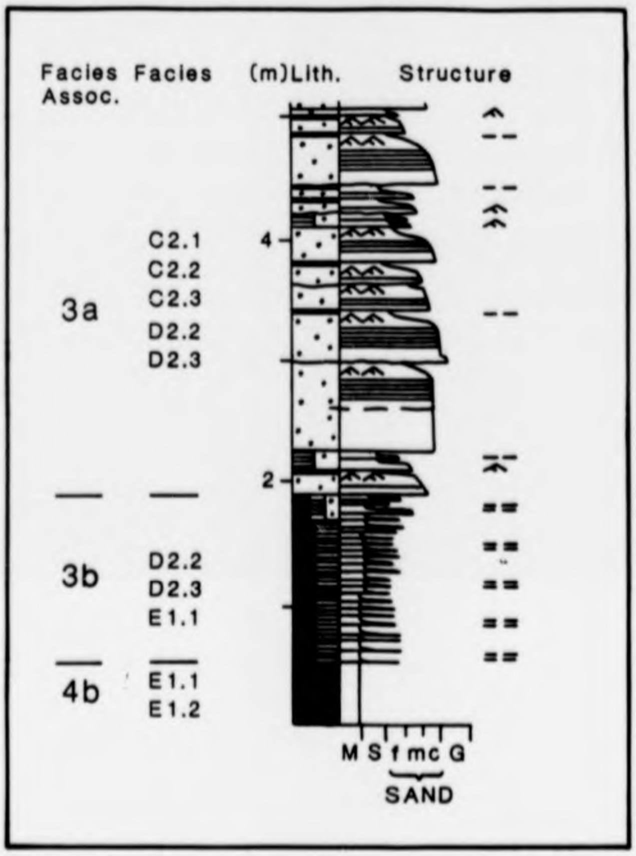


Figure 5.20: Graphic log illustrating an occurrence of Facies Association 3b in the transition zone between Moffat Shales and the Grennan Point Formation. Log from Drumbreddan Bay (NX 0669 4373). Grennan Point Formation. For legend see Figure 5.3.

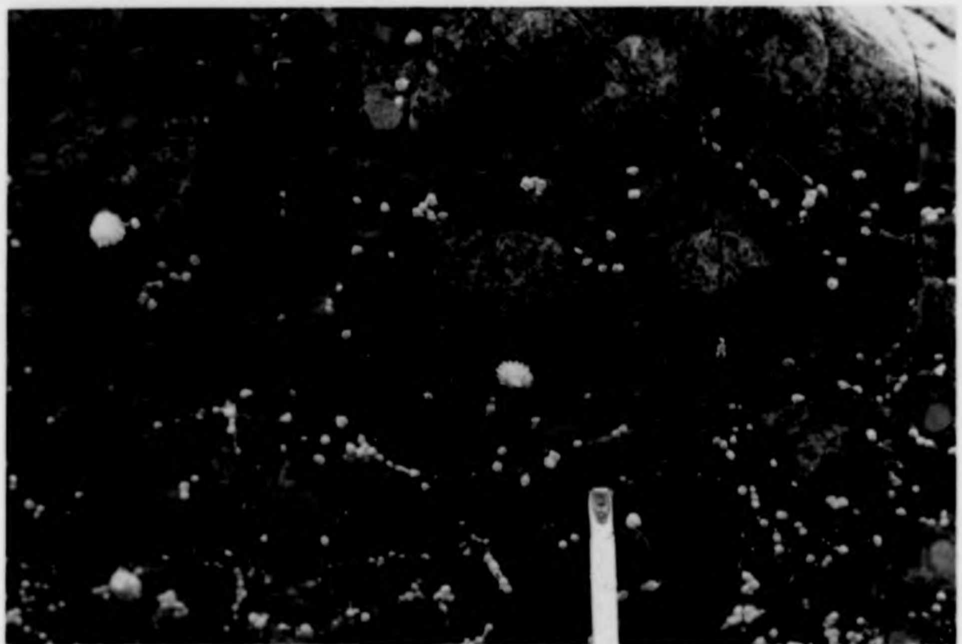


Plate 5.27: Small sand-volcanoes. Mull of Logan Formation (NX 0835 4165). View to southeast. 1.5cm wide rule for scale.


Plate 5.28: Load and flame structures. Portpatrick Formation, Acid-clast Division (NX 0067 5279). Marker pen for scale.

The tabular, thin-bedded and laminated nature of Facies Association 3b sequences is indicative of deposition from sheet-like turbidity currents in a 'featureless' depositional environment. During periods of quiesence, sedimentation from hemipelagic and pelagic fallout was dominant.

5.3.5 Facies Association Group 4 - Pelagic and Hemipelagic Deposits

Facies Association Group 4 includes two facies associations, the salient characteristics of which are listed in Table 5.2. The distribution of each of these facies associations within the major non-pelagic stratigraphical units within the study area is summarised in Tables 2.3 and 5.7. It should be noted that these facies associations are mainly confined to the pelagic sediment dominated Moffat Shales.

5.3.5.1 Facies Association 4a - Pelagic and Hemipelagic Deposits

(a) Recognition

Facies Association 4a is dominated by numerous facies types from Classes E and G, and Groups E1, E2, G1 and G2 (Pickering et al. 1986; Tables 5.1 and 5.7). Because of their fine-grained nature, Facies Association 4a sequences are usually intensely folded, and it is thus difficult to estimate the

FACIES ASSOCIATION GROUP 4

FACIES ASSOCIATION 4a

Mudstones, siltstones and cherts (Facies E1.1, E1.2, G1.1, G1.2 & G2.1)

These sediments may be structureless, or laminated. Varicoloured varieties of mudstone are particularly common, red, green and black varieties occur most frequently. These sediments are frequently fossiliferous, the black mudstones are commonly graptolitic. Radiolarian cherts occur.

FACIES ASSOCIATION 4b

Mudstones and siltstones (Facies E1.1, E1.2, G1.2 & G2.1)

These sediments may be structureless, or laminated. Varicoloured varieties of mudstone are particularly common, red, green and black varieties occur most frequently varieties are particularly common. These sediments are frequently fossiliferous, the black mudstones are commonly graptolitic.

Table 5.7: Summary lithological descriptions of the main facies types included within Facies Associations 4a and 4b, Facies Association Group 4, as they actually occur in the study area.

thicknesses of succession which they form. However, they occupy sections with across-strike widths of up to approximately 300m.

Facies Association 4a comprises structureless mudstones and shales (E1.1), varicoloured mudstones and shales (E1.2), cherts (radiolarian) (G1.1), pelagic, graptolitic shales (G1.2), and massive siltstones and shales (G2.1).

(b) Depositional Processes and Environment

It is suggested that the sediments included within Facies Association 4a were deposited by hemipelagic and pelagic setting (Pickering et al. 1986; Tables 5.1 and 5.7). These sediments were probably deposited in an environment well away from major clastic sources.

5.3.5.2 Facies Association 4b - Pelagic and Hemipelagic Deposits

(a) Recognition

Facies Association 4b is dominated by facies types from Classes E and G, and Groups E1, E2, G1 and G2 (Pickering et al. 1986; Tables 5.1 and 5.7). Facies Association 4b sequences are often intensely deformed, and it is therefore impossible to determine the stratigraphical thicknesses which they dominate.

They occupy sections with across-strike widths of up to approximately 150m.

Facies Association 4b comprises structureless mudstones and shales (E1.1) varicoloured mudstones and shales (E1.2), graptolitic shales (G1.2),m and massive siltstones and shales (G2.1).

(b) Depositional Processes and Environment

It is suggested that the sediments which comprise Facies Association 4b were deposited by hemipelagic and pelagic setting (Pickering et al 1986; Table 5.1). These sediments were probably deposited in an environment well isolated from any major clastic inputs.

5.4. DEPOSITIONAL MODELS

5.4.1 Facies Association Group 1

Facies Association Group 1 includes:

(1) Facies Association 1a; poorly to very irregularly bedded, coarse conglomerates, including clasts up to 15 x 10m in size.

(2) Facies Association 1b; medium- to very thick-bedded, conglomeratic and blocky

sediments; clasts within the conglomerates do not exceed 30 x 15cm.

(3) Facies Association 1c; thin- to medium-bedded sandstones and occasional conglomerates, clasts have a maximum size of 50 x 15cm.

Facies Associations 1a, 1b and 1c often occur within the same stratigraphical sequences. Facies Associations 1a and 1b are demonstrably lateral equivalents. The present-day geographical inter-relationships between Facies Associations 1a, 1b and 1c can be explained in terms of original spatial and temporal variations in local palaeogeography and depositional processes (Fig. 5.21).

Facies Association 1a sediments are considered to have been deposited largely as a result of rockfalls and slides, and from debris flows. Thus these sediments appear to have been deposited on unstable slopes, probably influenced by synsedimentary faults and contemporary tectonic movements (Fig. 5.21). In a process-continuum rockfalls, slides and debris flows can develop into high- and low-density turbidity currents (Stow 1985), processes considered to have been responsible for the deposition of the sediments in Facies Association 1b. These sediments were probably deposited as sheets on relatively

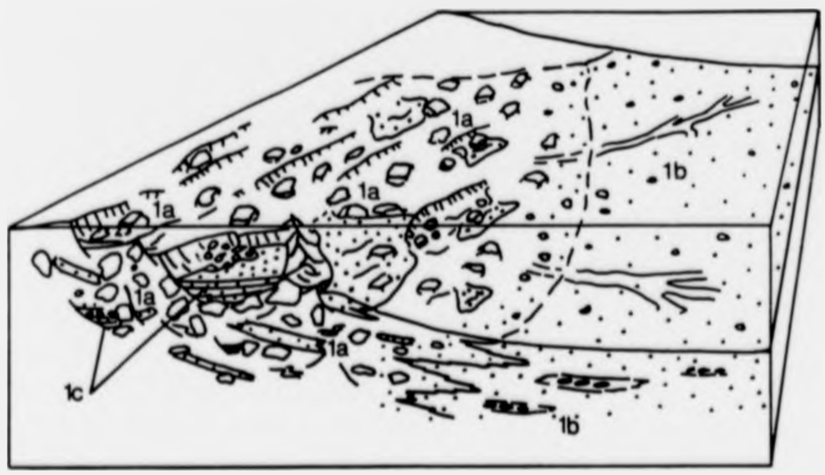


Figure 5.21: Depositional model for Facies Association Group 1 (refer to text for details).

stable, aggrading slopes (Fig. 4.21). It is therefore suggested that Facies Associations 1a and 1b can, respectively, be viewed as 'proximal' and 'distal' equivalents (Fig. 5.21). Rockfalls, slides and debris flows were developed in areas of slope instability. High- to low-density turbidity currents were generated as a consequence of these processes and flowed as sheets away from the localised areas of instability. Conical depositional features may have been formed; Facies Association 1a sediments were deposited nearer the apex, while Association 1b sediments were deposited towards the margins (Fig. 5.21).

Facies Association 1b occasionally occurs within stratigraphical sequences dominated by Facies Association 1a, suggesting that the unstable slopes occasionally became locally more stable. Facies Association 1b sediments often occur as large dislocated clasts within Association 1a sequences, testifying to repeated periods of slope stability and instability.

Facies Association 1c sediments form isolated sequences in stratigraphical sections dominated by Facies Association 1a. They are attributed to deposition from high- to low-density turbidity currents, debris flows, rockfalls and slides. Such sequences could be, and probably were, deposited in small isolated basins, situated upon unstable slopes, and bounded by topographic irregularities such as syn-sedimentary fault scarps and depositional features (Fig. 5.21). The sediments within these basins were probably partly derived from external sources, for example, turbidity currents which 'overtopped' the basin margins. However, the majority of the sediments are considered to have been derived from the unstable margins of these basins as turbid sheet flows, debris flows, slides, slumps and rockfalls (Fig. 5.21). The gradual denudation of the margins of these basins consequently allowed the normal depositional processes active on the unstable slopes to become progressively more important within the basins, resulting in coarsening- and thickening-up of Facies Association 1c sediments and transitional upper stratigraphical contacts with Facies Association 1a (Fig. 5.3).

5.4.2 Facies Association Group 2

Facies Association Group 2 includes:

(1) Facies Association 2a. Thick- to very thick-bedded, conglomeratic and channelised sediments.

(2) Facies Association 2b. Thick- to very thick-bedded sandstones and pebbly

sandstones. These sediments frequently display strongly erosive bases.

(3) Facies Association 2c. Medium- to thick-bedded sandstones and laminated siltstones and sandstones. These sediments are often arranged into thinning- and fining-up cycles.

(4) Facies Association 2d. Thin- to medium-, irregularly bedded sandstones. These sediments usually exhibit good thickening- and coarsening-up cycles.

(5) Facies Association 2e. Medium- to thick-bedded sandstones. Both thinning- and fining-up and thickening- and coarsening-up cycles are displayed.

(6) Facies Association 2f. Laminated siltstones and mudstones and thin-bedded sandstones.

The facies associations listed above are all considered to have been deposited in channel and channel-related environments (Fig. 5.22).

The sediments included within Facies Associations 2a and 2b are considered to represent the deposits of

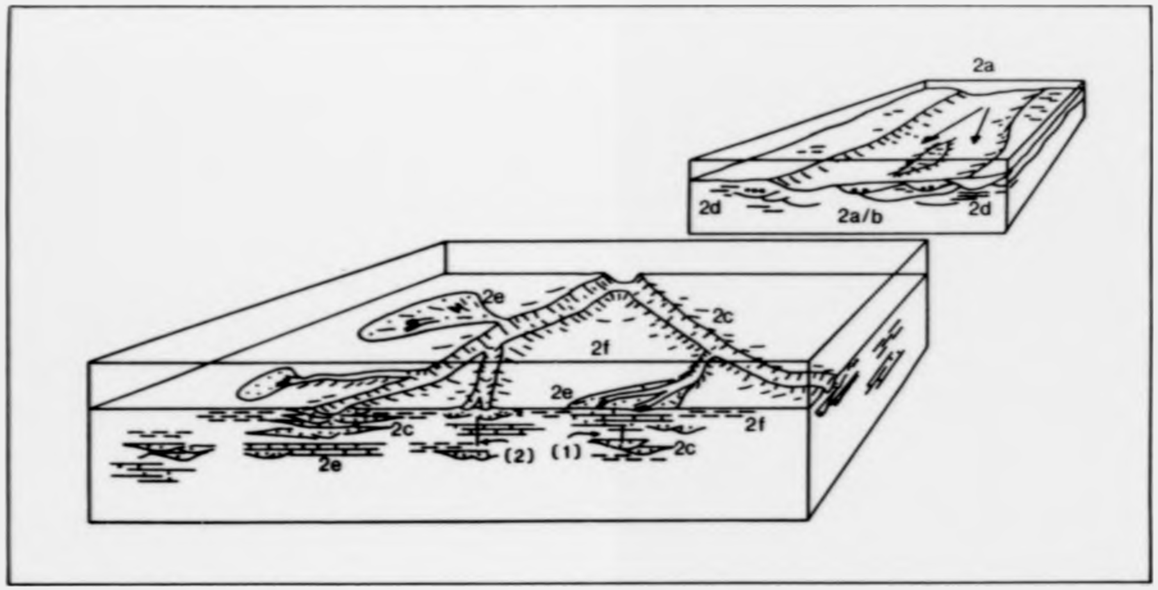


Figure 5.22: Depositional model for Facies Association Group 2 (refer to text for details). The diagram roughly illustrates the types of vertical sequence which might be expected to form as a result of: (1) channel migration out of a depositional area; (2) channel migration into a depositional area.

major channels, equivalent to 'upper-mid-fan' (Walker 1978) channels, while those included within 2c are thought to represent minor channels, equivalent to 'lower-mid-fan' channels. Thus Facies Associations 2a and 2b probably represent upstream equivalents of Facies Association 2c (Fig. 5.22). Sequences representing both stacked and migrating channels have been recognized.

The sediments included within Facies Associations 2d, 2e and 2f are interpreted as channel margin, crevasse splay and interchannel deposits respectively.

The distribution of Facies Associations 2a to 2f within single stratigraphical sequences is a consequence of variations in channel type and location with time. In very general terms, two types of stratigraphical sequence have been recognized:

(1) Channel deposits (Facies Association 2a, 2b or 2c) passing upwards into channel margin or interchannel deposits (Associations 2d, 2e or 2f). These sequences are indicative of channel migration laterally out of the depositional area (Fig. 5.22).

(2) Interchannel and channel margin deposits (Facies Associations 2d, 2e or 2f) pass upwards into channel deposits (Associations

2a, 2b or 2c). These sequences are indicative of channel migration into a particular area (Fig. 5.22). Crevasse splay activity is considered to have been important in some interchannel to channel environment transitions (Fig. 5.22), a process analagous to that proposed by Elliott (1974) for interdistributary bay sequences is thought to have been operative.

5.4.3. Facies Association Group 3

Facies Association Group 3 includes:

(1) Facies Association 3a. Thin- to very thick-bedded sandstones and laminated siltstones and mudstones. Thickening- and coarsening-up cycles are commonly developed.

(2) Facies Association 3b. Very thin- to thin-bedded sandstones and laminated siltstones and mudstones.

The sediments included within Facies Associations 3a and 3b are ascribed to high- to low-density turbidity currents, thought to have been sheet flows. Facies Associations 3a and 3b are probably proximal to

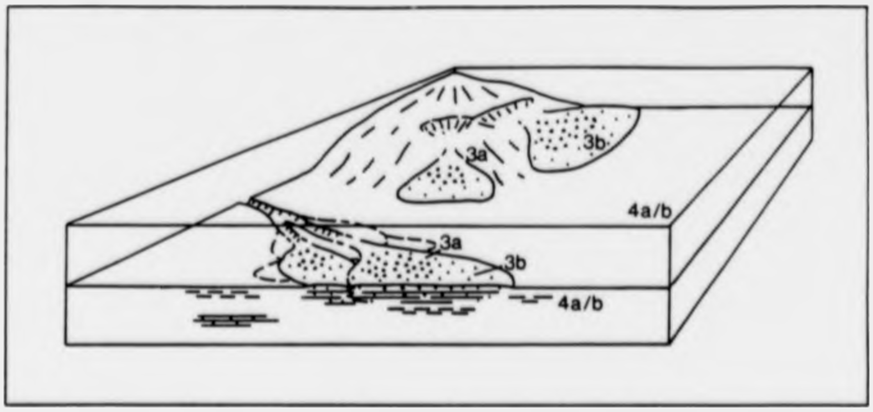


Figure 5.23: Depositional model for Facies Association Groups 3 and 4 (refer to text).

distal lateral equivalents, respectively (Fig. 5.23).

5.4.4. Facies Association Group 4

Facies Association Group 4 includes:

(1) Facies Association 4a. Shales, siltstones and cherts.

(2) Facies Association 4b. Shales and siltstones.

The sediments included within these facies associations are considered to have been deposited by pelagic and hemipelagic settling in environments distant from major clastic sources (Fig. 5.23).

5.5. CONCLUSIONS

The sediments exposed within the study area represent a variety of deep-water depositional environments including:

(1) Unstable slope, 'featureless' slope and perched basin environments; Facies Association Group 1.

(2) Within-channel, channel margin and

interchannel environments; Facies Association Group 2.

(3) Aggrading slope and 'lobe' environments; Facies Association Group 3.

(4) Basin floor environments; Facies Association Group 4.

These depositional environments form elements of larger depositional systems including fans, axial wedges and debris wedges. In order to ascertain the types of depositional system which are represented within the various stratigraphical sequences exposed within the study area, it is essential to assess, in detail, the vertical and lateral distributions of the various facies associations and facies association groups, and to ascertain how these relate to each other. This assessment is undertaken in Chapter 6. Figures 6.2a, 6.3 and 6.4 show how the various Facies Associations and Association Groups, described in this Chapter, probably interrelate on fans, slope aprons and debris wedges and axial wedges, respectively.

CHAPTER 6

DEPOSITIONAL SYSTEMS

6.1 GENERAL

It is generally accepted that the sediments exposed within the Southern Uplands of Scotland, and Longford/Down zone of Ireland, were formed in deep-water sedimentary environments, situated in areas which were either distant from major clastic inputs, or within active and evolving clastic depositional systems (Kelling et al. 1987). The pelagic black shales and associated sediments which constitute the Moffat Shales are thought to have been deposited in areas either topographically isolated or distant from major clastic inputs. The greywackes and associated sediments, which overlie these pelagic deposits, represent the accumulated deposits of a variety of depositional systems. Few previous studies have been concerned with the nature of these depositional systems: Leggett (1980) described a prograding submarine fan sequence from the Stobo area; Hepworth et al. (1982), ascribed sequences in the Abington-Sanquhar area to axially deflected fans; Kelling et al. (1987) described a variety of depositional systems from the Rhinns of Galloway area, and recently Kemp (1987b) attributed sequences in the Kirkcudbright and Hawick areas to axially deflected and large 'passive margin' style fans.

The purpose of this Chapter is to assess the types of depositional system which are represented within the greywacke dominated successions exposed within the study area, as determined from the observed distribution of sedimentary facies, ascertained from the well-exposed sediments on the west coast of the Rhinns of Galloway and to the east of Loch Ryan and Luce Bay. It is, therefore, concluded that the sedimentary environments and depositional systems, in which the greywacke sequences were formed, can be determined from the vertical arrangement of facies, supplemented by data on lateral relationships and palaeoflow patterns. Depositional systems have been assessed in terms of the submarine fan model (as developed by Mutti and Ricci-Lucchi 1972; Walker and Mutti 1973; Mutti 1979; Nelsen 1979), other deep-water depositional regimes (Nelson and Nilsen 1984; Stow 1985), and the trench-fill models of Schweller and Kulm (1978).

In accordance with many previous studies it is assumed that the mid-Ordovician to early-Silurian greywacke successions, exposed within the study area, were deposited on or close to a continental margin representing the northwestern limit of the Iapetus oceanic realm (Leggett 1980; Kelling et al. 1987).

In this Chapter the major stratigraphical units are described in terms of their included facies assocítions. It should be noted that discussions concerning the depositional environmental setting of each facies association represented are presented in Chapter 5.

6.2 TYPES OF DEPOSITIONAL SYSTEM

It must be stressed that present opinions vary as to the true nature of the Southern Uplands 'basin', back-arc basin (Morris 1987; Stone et al. 1987) and fore-arc trench (Leggett 1980) being only two of the options suggested recently. Whatever the geotectonic scenario, the predominant palaeocurrent indicators within the Southern Uplands, which accord with an axial palaeoflow pattern, indicate that the basin was elongate and relatively narrow. Thus a similar array of depositional systems might be expected to develop in any of the proposed geotectonic/basin settings. In modern deep-water settings a variety of depositional systems are recognized (Nelson and Nilsen 1984; Stow 1985); the most important of these include fans, slope aprons, debris wedges and axial wedges (Fig. 6.1).

6.2.1 Submarine Fans

A great variety of fan types exists, ranging from

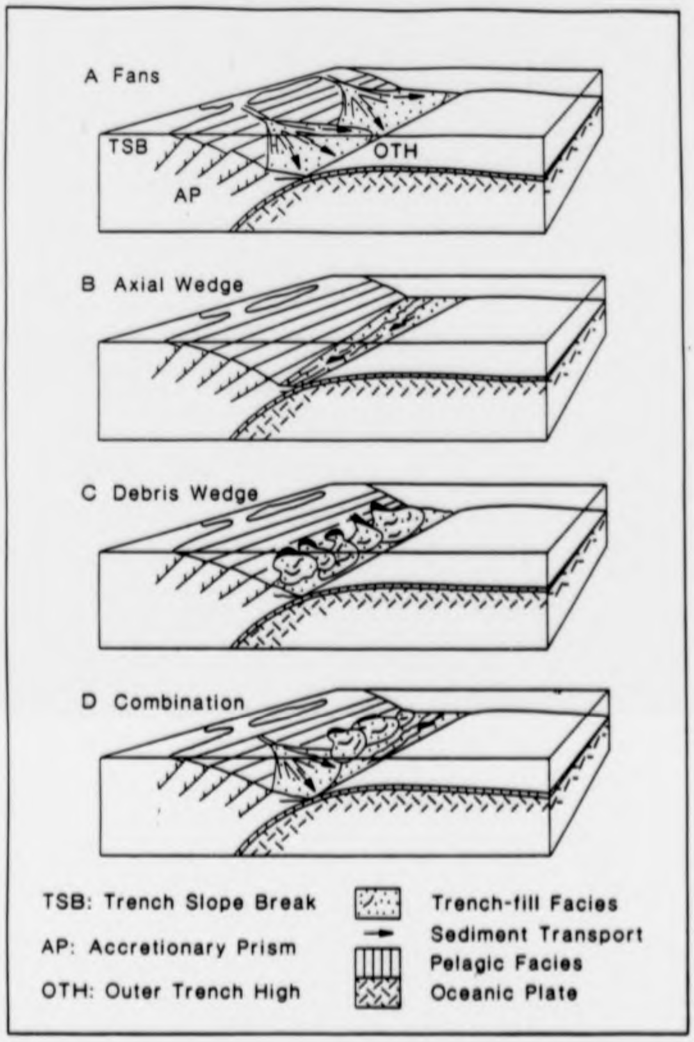


Figure 6.1: Depositional systems associated with trenches on active plate margins: (A) Submarine fans; (B) Axial wedge; (C) Slope derived debris-wedge; (D) Combination of systems (A)-(C).

sand-rich or low-efficiency (Mutti 1979), to mud-rich or high-efficiency (Nilsen 1979) systems, with a variety of intervening mixed-sediment types (Mutti 1979).

Sand-rich systems (Fig. 6.2a) are also referred to as low-efficiency systems since it is envisaged that the sand-laden gravity flows which supply the bulk of the sediment to them are not capable of transporting it over long distances, sediment distribution is thus inefficient. As a result modern sand-rich systems (e.g. the Navy Fan, Normark et al. 1979) tend to be relatively small. Channel environments dominate the fan surface. The channels are mainly relatively shallow, physically and temporally unstable features. Lobes are present but they tend to be poorly developed. These systems are 'immature' since they are small and fan environments are both unstable and poorly developed. In ancient sequences this type of system would be recognized by a predominance of sand-grade sediment and by the presence and predominance of a combination of stacked channel-fill, channel-margin and interchannel deposits (Facies Association Group 2, Table 5.4). Sheet and lobe deposits would probably be recognized as constituting a minor proportion of these sequences (Facies Association Group 3, Table 5.6). Sand-rich system sequences often display abrupt transitions from basin-floor to fan-type facies associations (Nilsen 1979).

Mud-rich systems (Fig. 6.2b) are also referred to as high-efficiency systems since it is envisaged that the mud-laden gravity flows which supply the bulk of the sediment to them are capable of transporting it over long distances, sediment distribution is thus efficient. Modern mud-rich systems display a broad range of sizes often attaining immense dimensions (e.g. the Indus Fan, Kolla et al. 1979). These systems tend to be dominated by large channel/levee complexes which can extend the length of the fan system. These systems are 'mature' in that they are large, sediment is distributed efficiently and depositional environments appear to be relatively stable. In ancient sequences this type of system would be recognized by a predominance of fine grained sediments and by the presence and predominance of well developed channel, levee and interchannel deposits (Facies Association Group 2, Table 5.4). Muddy lobe deposits may be present but of only minor importance.

Mixed-sediment fans (Fig. 6.2c) are intermediate in character between sand-rich and mud-rich systems. They tend to be efficient systems and thus sediment can be transported over considerable distances. Modern mixed-sediment systems (e.g. the Astoria Fan) display well developed channel systems which supply sediment to depositional lobes located at their terminations. Walker's (1978) fan-model is easily applied to this type of fan-system in which the fan can be subdivided into upper, mid and lower fan areas. This type of system is mature in the sense that the depositional environments are well developed and well organized. In ancient sequences this type of system would be recognized by a combination of well developed channel and channel-related facies associations (Facies Association Group 2, Table 5.4) and lobe and sheet-like sequences (Facies Association Group 3, Table 5.6).

It is extremely important to note that the external morphology of any fan system need not be radial and in many modern examples the shape of submarine fans appears to be dictated by basin geometry. Palaeocurrent data from the Southern Uplands sequences (Fig. 6.5) suggests that this was also the case here. Palaeocurrents reflect sediment transport along the east-northeast to west-southwest trending basin rather than directly from the obvious provenance areas to the north.

6.2.2 Slope Aprons and Debris Wedges

Stow (1985) reviewed slope apron and debris wedge systems and recognized four distinct system types: (a) clastic, (b) faulted, (c) ridge-flank and (d) carbonate slope aprons/debris wedges. However the criteria used by Stow (1985) to distinguish between the various system types (the genetic origin of the slope, slope gradient etc.) are not easily applied to ancient, deformed sequences of the scale seen in the Southern Uplands. Because of this Stow's (1985) subdivision has not been employed in this study. The review has been used to make broad generalizations concerning the nature, distribution and types of depositional environment which may have coexisted on ancient depositional systems of this type in the Southern Uplands.

The review (Stow 1985) shows that modern and ancient slope apron/debris wedge systems are composed of a combination of slump, debris flow, turbidite and hemi-pelagic deposits. They typically accumulate in base-of-slope settings and may be incised by channels (Nelson and Nilsen 1984; Stow 1985). The distribution of depositional environments within such systems is generally irregular. The degree of internal organization within ancient sequences is minimal. These may be dominated by the deposits of debris flows, rockfalls, slumps and turbidity currents (Facies Association Group 1, Table 5.3), and by high-density sheet-flow deposits (Facies Association Group 3, Table 5.6) (Surlyk 1978; Nelson and Nilsen 1984) (Fig. 6.3).

6.2.3 Axial Wedges

Modern axial wedge systems have been examined by Schweller and Kulm (1978) and most commonly occur within trenches, along active plate margins. However, similar depositional systems are developed in other narrow elongate basins (Hsu et al. 1980). The axial trench wedges described by Schweller and Kulm (1978) are dominated by long linear channels which are flanked by areas of turbidite deposition. Lobes may be developed at the distal ends of channels.

Ancient sequences representative of an axial wedge system would therefore probably be dominated by Facies Association Group 2 (Table 5.4) and Facies Association Group 3 (Table 5.6) deposits, indicative of channel, channel related, sheet flow and lobe deposits (Fig. 6.4). Owing to the apparent similarity between

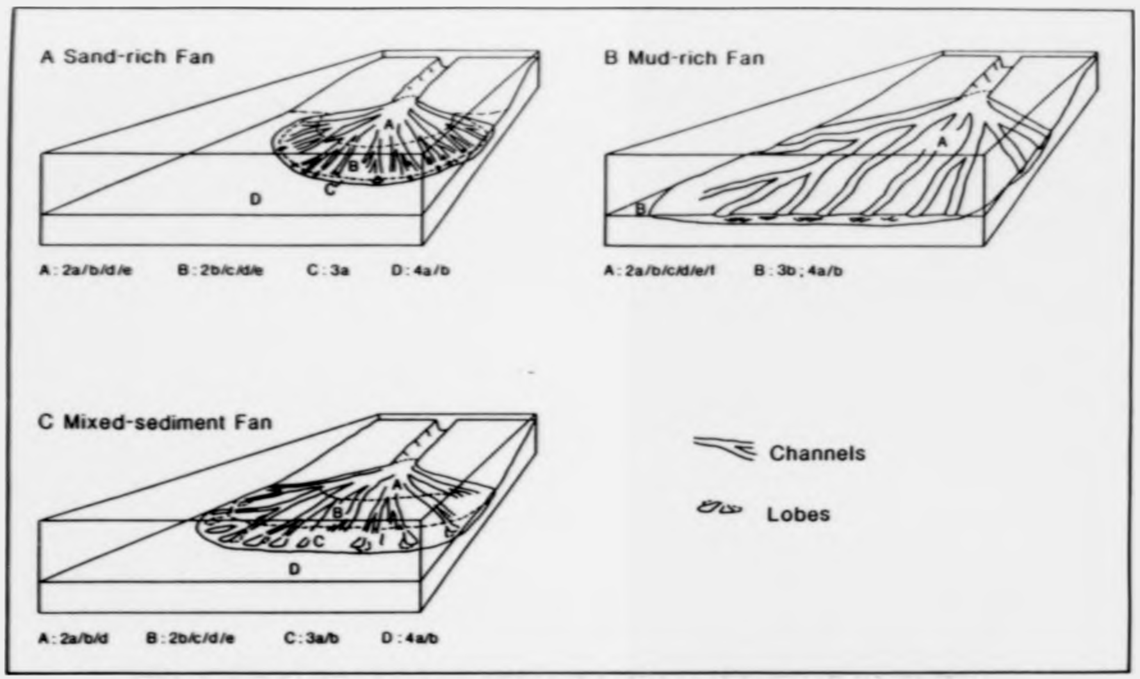


Figure 6.2: Types of submarine fan: (A) Sand-rich fan, dominated by chanels; (B) Mud-rich fan, dominated by channels and broad inter channel areas; (C) Mixed sediment fan, dominated by a combination of channels and lobes. The diagrams indicate the broad areas in which the facies associations described in Chapter 5 might be expected to be deposited.

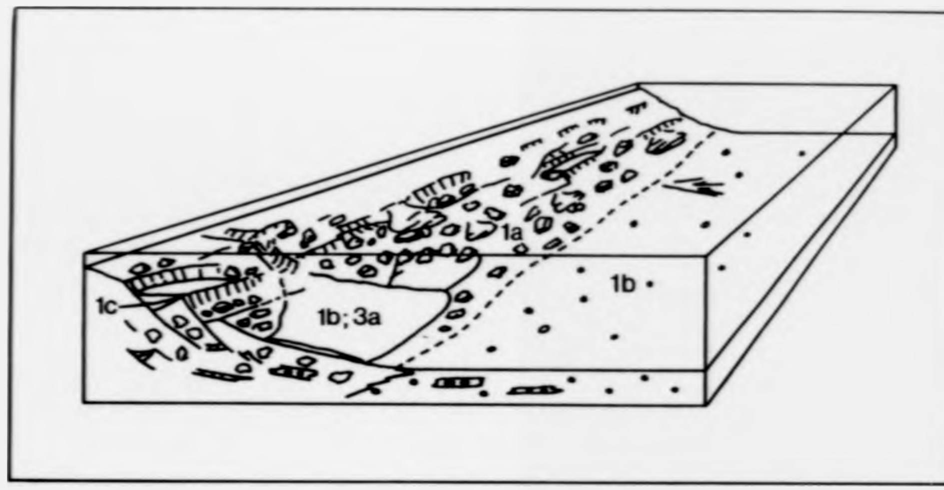


Figure 6.3: Diagram illustrating a typical debris wedge, and the areas in which the facies associations decribed in Chapter 5 might be expected to be deposited.

Figure 6.4: Models of trench or axial wedge development from Schweller and Kulm (1978). The diagrams have been modified to show the broad areas in which the facies associations described in Chapter 5 might be expected to be deposited.

the range of component facies associations within most fan and axial wedge systems, differentiation has to be based largely on regional palaeocurrent studies.

6.3 DEPOSITIONAL SYSTEMS WITHIN THE SOUTHWESTERN SECTOR OF THE SOUTHERN UPLANDS

The purpose of this section is to assess the nature of the depositional systems which are represesented within the greywacke-dominated successions exposed in the study area. It is stressed that within a basin on the scale of the Southern Uplands/Longford-Down zone several types of depositional system may have existed simultaneously. Thus the systems which operated at any one time, (and the preserved and exposed successions which they generated) are not necessarily representative of the entire zone.

Since palaeocurrent data play an important role in the following interpretations it should be noted that, wherever possible, local fold plunge and the dip and strike of bedding are taken into account in the restoration of palaeocurrent indicators. In sequences where folds are absent, or fold plunges are not measurable, palaeocurrent data are obtained by simply rotating about the strike removing dip. The palaeocurrent data collected during the course of this study are listed along with collection

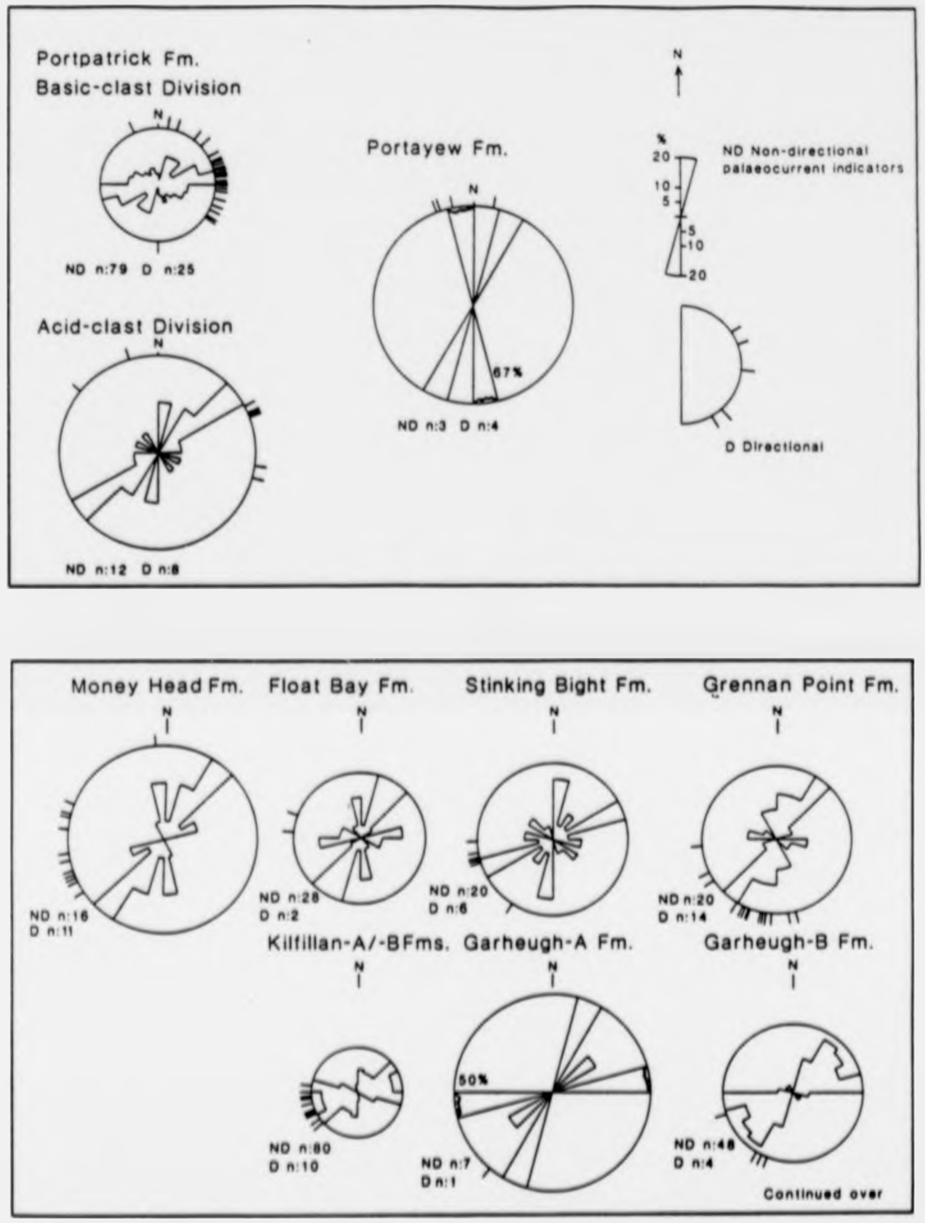


Figure 6.5: Palaeocurrents from the stratigraphical units exposed in the study corridors.

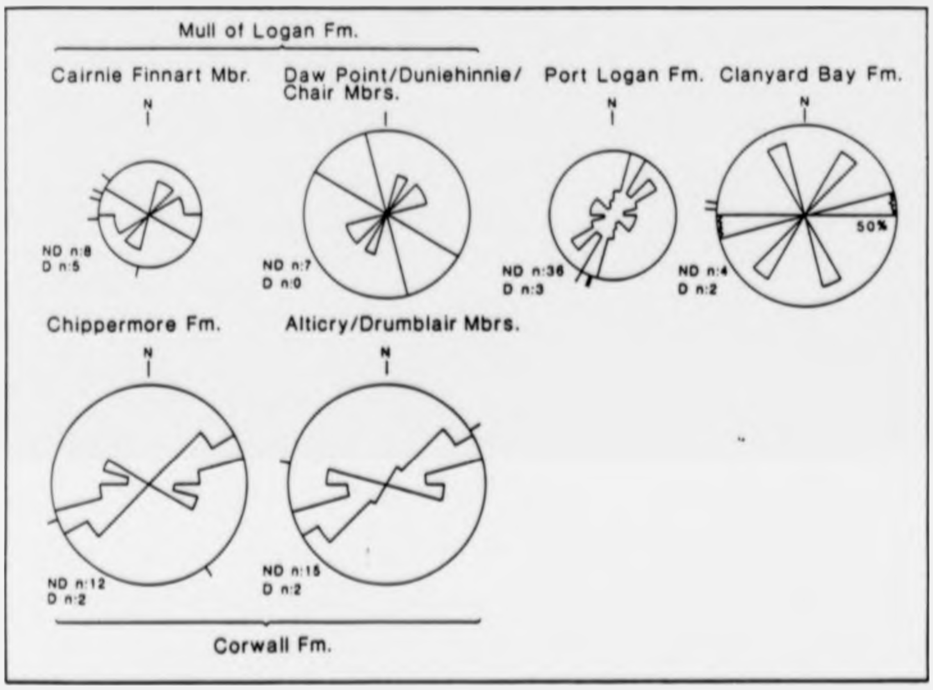


Figure 6.5: Palaeocurrents from the stratigraphical units exposed in the study corridors.

localities and sections in Appendix 3.

In the following sections the sandstone (greywacke) sequences in each of the formations which have been identified in the study area are interpreted in terms of current models to determine the depositional system(s) which they represent. Correlated successions are discussed in conjunction.

6.3.1 The Southern Part of the Northern Belt

6.3.1.1 The Portpatrick and Glenwhan Formations

The Portpatrick Formation is subdivided into the petrographically contrasted Acid- and Basic-clast Divisions (Containing Type A and Type B greywackes respectively, Chapter 4). The entire Glenwhan Formation is , petrographically identical with the Basic-clast Division (both are composed of Type B greywackes, Chapter 4) and contains no apparent equivalent of the Acid-clast Division (Type A greywackes, Chapter 4), which is thus considered to have had an originally limited lateral extent. The Portpatrick Formation, Acid-clast Division is older than the Basic-clast Division and the Glenwhan Formation (Figs.2.2 and 2.3).

(a) The Acid-clast Division

The Acid-clast Division greywackes have a maximum biostratigraphical age which is represented by the wilsoni Zone (Fig. 2.2). The Division is characterised by medium- to very thick-bedded (10cm to 200cm thick) greywackes which most commonly exhibit sheet-like bed-geometries. The sediment sequences (which are mostly acyclic) are occasionally arranged into 3m to 8m thinning-up, and, 2m to 12m thickening-up sequences (Table 2.3)*. The majority of the sediments are ascribed to Facies Associations 3a and 3b (Table 5.6). However, sequences representative of Facies Associations 2c and 2f are also present (Tables 2.3 and 5.4). Palaeocurrent data suggest that these sediments were derived from a source to the south and southwest.

The general sedimentological aspects of the Acid-clast Division greywackes, particularly the predominantly sheet-like nature of the sediments (Facies Association 3a, Table 5.2), suggest that much of the deposition was from high-density, open sheet-flows. The presence of Facies Associations 2c and 2f (Table 5.2) suggest the activity of channelised flows. Thus sediments were deposited in non-channelised slope, channel, interchannel and minor lobe environmental settings (see Chapter 5). The random vertical arrangement of facies associations is

* Appendix 5, L1, L2 & L3.

not typical of fan successions (Mutti and Ricci-Lucchi 1972; Walker and Mutti 1973; Nilsen 1979) and implies a considerable degree of environmental instability, more commonly associated with sandy slope aprons (Stow 1985). The Acid-clast Division greywacke succession is therefore considered to represent a sandy slope apron, situated adjacent to a dissected magmatic arc (Chapter 4) lying to the south and southwest (Kelling et al. 1987). This depositional system appears to have been limited in its original extent, perhaps by palaeotopographical 'highs'.

(b) The Basic-clast Division and Glenwhan Formation

The base of the Basic-clast Division is seen at two localities:

(1) In the vicinity of Catevennan (NW 9947 5429) where it stratigraphically succeeds the Acid-clast Division;

(2) In Port of Spittal Bay (NX 0200 5215) where it directly succeeds Moffat Shales. Greywacke sedimentation appears to have commenced during clingani or linearis Zone times (Fig. 2.2).

The base of the Glenwhan Formation is seen in the vicinity of Gabsnout Burn (NX 1840 6060). Sedimentation of the Glenwhan Formation greywackes appears to have commenced during *linearis* Zone times (Fig. 2.3).

The greywackes of the Basic-clast Division and the Glenwhan Formation are characterised by their medium- to very thick-bedded (0.1m to 8m thick) nature, and tabular and lenticular bed-geometries. The sequences are mainly acyclic, although, some 3m to 15m thickening-up and 4-10m thinning-up sequences are present (Table 2.3)*. Many facies associations are represented, including Associations 2a to 2f inclusive and Associations 3a and 3b (Tables 5.4 and 5.6). Palaeocurrent data (Fig. 6.5) suggest that these sediments were transported from the south and southwest. It is important to note that within the Port of Spittal Bay and Hairyhorroch Members, of the Basic-clast Division, petrographically contrasted siliceous units are occasionally included within the facies associations briefly described above (Type C greywackes, Chapter 4). Palaeocurrent indicators have not been found associated with these units. The siliceous units can be exclusively ascribed to Facies Group C2 (Pickering *et al* 1986).

The general sedimentological characteristics of the Basic-clast Division and Glenwhan Formation greywackes (summarised in Table 2.3) suggest

* Appendix 5, L4, L5 & L6, Fig. 5.9.

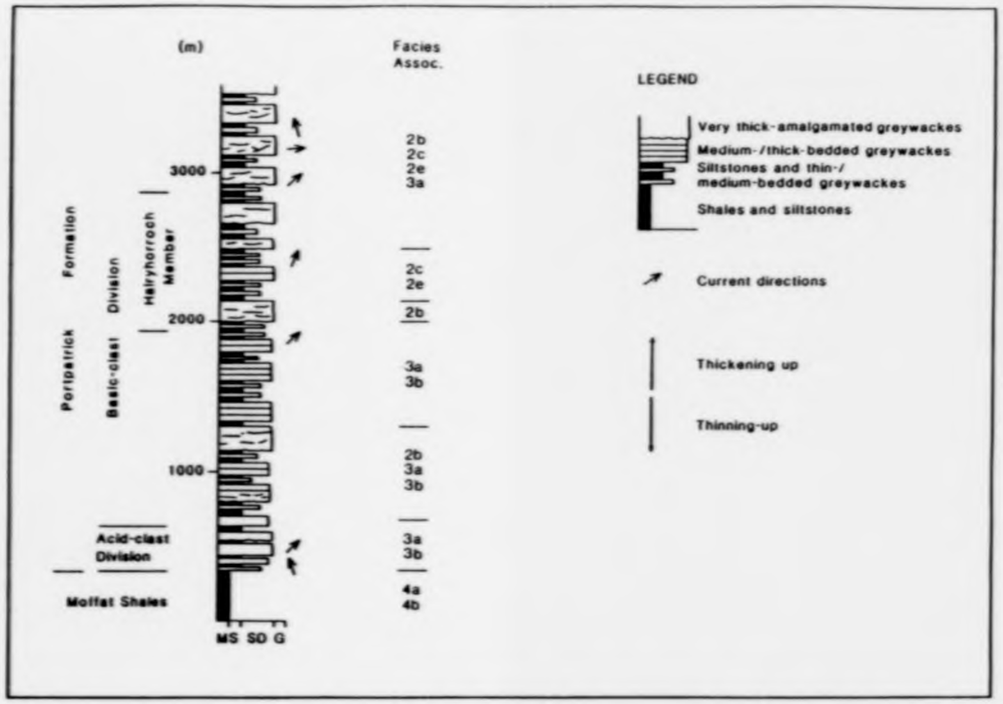


Figure 6.6: Log section through the Portpatrick Formation exposed between Killantringan Bay (NW 9820 5700) and Morroch Bay (NX 0177 5235). Note the increased importance of channel related facies associations (2b/c/e) in the upper part of the section.

that deposition took place in a variety of environmental settings, including in-channel, interchannel, non-channelised slope and lobe. The deposits of minor channels (Facies Association 2c) become conspicuous towards the 'tops' of these successions,*1 succeeding non-channelised slope and lobe sequences,*2 and introducing a degree of vertical organization (Fig. 6.6). Thus the Basic-clast Division and Glenwhan Formation successions are probably representative of immature sandy fans. Judging from the relatively wide lateral extent of this type of succession, represented within stratigraphical units correlated with the Portpatrick Formation, Basic-clast Division and the Glenwhan Formation (e.g. the Scar Formation of Floyd 1982) these immature sandy fans probably coalesced along an extensive slope towards the south and southwest. The siliceous units (Type C greywackes, Chapter 4) which occur within the Port of Spittal Bay and Hairyhorroch Members of the Basic-clast Division are interpreted as the open sheet-flow deposits of depositional systems derived from a source other than that which supplied the Basic-clast Division (Type B greywackes, Chapter 4, Fig. 5.9).

6.3.1.2 The Portayew and Boreland Formations

The maximum biostratigraphical age of the Portayew and Boreland Formations is not well constrained,

*1 Appendix 5, L4-L7. *2 Appendix 5, L8.

being definable only as Hartfell (Fig. 2.2). The formations are characterised by alternations of thick- to very thick-bedded (0.5m to 2.0m), tabular to broadly lenticular greywackes in 5m to 30m thick packets, and, thin- to thick-bedded (5cm to 70cm) tabular greywackes, in 7m thick packets (Table 2.3). Facies Associations 3a, 3b and 2c dominate the former, while Association 3b dominates the latter (Tables 2.3, 5.4 and 5.6). Rare thinning-up (2m to 10m) and thickening-up (3m-10m thick) cycles are present throughout the successions. Palaeocurrent data (Fig. 6.1) suggest that these sediments were derived from a source to the south.

The general sedimentological characteristics of the Portayew and Boreland Formation greywackes are indicative of deposition mainly from low- to high-density open sheet flows (Facies Associations 3a and 3b, Tables 2.3 and 5.6) and subordinate channelised flows (Facies Association 2a, Tables 2.3 and 5.4). The presence of these facies associations suggests that these Formations were deposited on north-or northwest-facing slopes as clastic aprons. The relative paucity of channel deposits (Tables 2.3 and 5.2) indicate that channels were relatively unimportant. The clastic slopes were therefore largely 'featureless' and only occasionally cut by ephemeral channels, a situation analogous to that inferred for the Portpatrick

Formation, Acid-clast Division.

6.3.1.3 The Cairngarroch Formation

The biostratigraphical status of the Cairngarroch Formation remains unclear. The Formation is dominated by thin- to thick-bedded (5cm to 100cm thick) tabular greywackes, arranged in an acyclic manner. Facies Associations 3a and 3b (Table 5.1) dominate the Cairngarroch Formation succession.

The dominance of Facies Associations 3a and 3b within the Cairngarroch Formation suggests that the sediments were mainly deposited from low- to high-density turbidity currents. An apparent lack of internal organization within the Cairngarroch Formation indicates that the component sediments were deposited as a 'clastic slope apron' similar to those inferred for the Portpatrick Formation, Acid-clast Division, and Portayew Formation successions.

6.3.2 The Northern Part of the Central Belt

6.3.2.1 The Money Head Formation

The Money Head Formation greywacke succession appears to have a maximum *atavus* or *acinaces* Zone age (Fig. 2.2). The succession abruptly overlies Moffat Shale lithologies, and is characterised by a wide variety

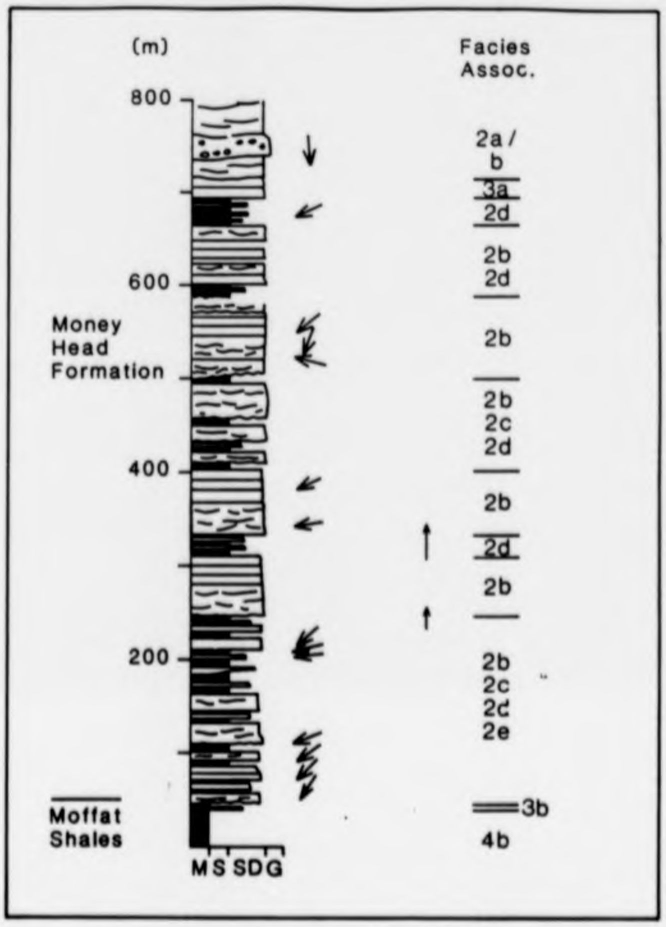


Figure 6.7: Log section through the Money Head Formation between Strand-foot (NX 0515 4815) and Cairngarroch Bay (NX 0464 4905).

of lithologies and Facies Associations (Kelling _et al_. 1987; Tables 2.3 and Plate 5.9).

The succession comprises alternations of the following:

(1) 5m to 30m thick packets of very thick-bedded (1m to 5m thick) lenticular greywackes which are assigned to Facies Association 2b, and are interpreted as deposits formed within relatively large channels (Tables 2.3 and 5.2).

(2) 5m to 35m thick packets of thick- to very thick-bedded (80cm to 200cm) broadly lenticular to tabular greywackes, representative of Facies Assocations 2b and 3a (Table 2.3 and Plate 5.6), and interpreted as within-channel and 'proximal' lobe deposits.

(3) 5m to 25m thick packets of thin- to thick-bedded (2cm to 35cm) tabular to lenticular greywackes which are assigned to Facies Associations 2d, 2e and 2f. These are interpreted as channel-margin, overbank crevasse and inter-channel deposits (Table 2.3 and Fig. 5.10).

Palaeocurrent data (Fig. 6.5) indicate that these sediments were transported from the north and northeast.

The broad sedimentological characteristics of the Money Head Formation greywacke succession (the included facies associations and their vertical arrangement, Fig. 6.7), particularly the abrupt basal transition from a basin floor facies association (Facies Association 4b; the Moffat Shales (Table 5.2)), and the vertical stacking of channel deposits (Fig.6.7), are indicative of deposition on a sand-rich 'fan', corresponding to the 'low-efficiency' type of submarine fan of Mutti (1979). Palaeocurrent evidence (Fig. 6.5) suggests that this was an axially diverted depositional system.

6.3.2.2 The Float Bay and Kilfillan -A and -B Formations

The Float Bay Formation and the Kilfillan -A and -B Formations all appear to have been deposited in the time-interval represented by the *acuminatus* and *leptotheca* Zones. The greywacke successions within all of these stratigraphical units display a similar distinctive array of lithologies and facies associations (Table 2.3, 2.4, 2.5 and 2.6), importantly containing small 0 5m to 10m thick sequences of Facies Association 4b (Table 5.2).

The Float Bay Formation greywacke succession is dominated by medium- to thick-bedded (25cm to 100cm thick), lenticular and tabular greywackes (Table 2.3). These form acyclic sequences and are assigned to Facies Associations 2c, 2e, 3a and 3b (Table 5.2).*1 They are interpreted as minor channel and lobe deposits. Thin-bedded (4cm to 5cm) greywackes, assigned to Facies Associations 3b and 2e are also present, and are interpreted as the deposits of open sheet flows.

The Kilfillan -A and Kilfillan -B Formation greywacke successions, exposed to the north-northeast are generally more thickly bedded. They are dominated by thin- to very thick-bedded (10cm to 200cm) lenticular to tabular greywackes which form mainly acyclic sequences and are assigned to Facies Associations 2c, 2e, 3a and 3b (Tables 2.3, 5.4 and 5.6).*2 These are interpreted as channel and lobe deposits. Associated with these sediments, there are very thick (10m to 100m) packets of very thick-bedded (1m to 4m) lenticular greywackes (Tables 2.3). These sediments are assigned to Facies Association 2b and are interpreted as channel deposits (Table 5.2). Thin- bedded (2cm to 10cm) greywackes also occur, assigned to Facies Association 2e and 3b and interpreted as crevasse splay and lobe deposits also occur.

*1 Appendix 5, L12. *2 Appendix 5, L13 & L14.

Relatively thin (0.5m to 10m) packets of graptolitic black shale and siltstone occur throughout the Float Bay and Kilfillan -A and -B sequences (Table 2.3). These are assigned to Facies Association 4b (Table 5.2) and are interpreted as pelagic and hemipelagic deposits.

Palaeocurrent data yield a dominant north-northeast to south-southwest palaeoflow pattern (Fig. 6.5), explaining the more 'proximal' appearance of the Kilfillan -A and -B greywackes.

The presence within the Float Bay and Kilfillan -A and -B greywacke successions of deposits indicative of a variety of discrete 'fan-type' depositional environmental settings, apparently exhibiting a more 'proximal' style to the east-northeast (more thickly bedded and more intensely channelised), suggests that the successions were deposited within a single elongate 'mixed' sediment fan or (in view of the palaeocurrent data) an axial wedge depositional system.

6.3.2.3 The Stinking Bight and Garheugh -A Formations

The Stinking Bight Formation appears to have a maximum age corresponding to the cyphus/triangulatus

Zone boundary, while the precise biostratigraphical status of the Garheugh -A Formation remains unknown.

The Stinking Bight Formation greywacke succession is dominated by thick- to very thick-bedded (0.5 to 4m) lenticular to tabular, greywackes (Table 2.3).*1 These display 2m to 7m thinning-up cycles and are ascribed to Facies Associations 2c and 3b (Table 5.2). They are interpreted as minor channel and lobe deposits. Associated with these sediments are 1m to 12m thick packets of thin- to thick-bedded (10cm to 50cm) tabular greywackes, representative of Facies Associations 2d and 2e (Tables 2.3). These are interpreted as channel-margin and interchannel deposits.

The Garheugh -A Formation greywacke succession is dominated by acyclic sequences of very thick-bedded (1m to 5m thick) lenticular greywackes which contain lenticular intra- and extra-formational clast conglomeratic bodies (e.g. Barhaskine Conglomerate at NX 2589 5356).*2 These sediments are assigned to Facies Associations 2a and 2b and are interpreted as the deposits of stacked, major channels (Table 2.3 and 5.2).

Palaeocurrent evidence (Fig. 6.5) suggests that the Stinking Bight and Garheugh -A Formation greywackes were transported from east-northeast to west-

*1 Appendix 5, L15. *2 Appendix 5, L16 & Figs. 5.5 & 5.6.

southwest. Taken together with the general sedimentological characteristics noted above, the data are consistent with a scenario in which major channels (represented within the Garheugh -A Formation) perhaps formed within a mid-fan (Walker 1979) environment, funnelled sediment towards the west-southwest in an area of minor channels and lobes (represented within the Stinking Bight Formation) formed in a lower-mid-fan environment. Thus the Stinking Bight and Garheugh -A Formation greywacke successions are considered to have been deposited within a single axially diverted sand-rich 'fan' complex, analogous to the 'low-efficiency' type of submarine fan of Mutti (1979). The suggestion in Kelling et al. 1987) that these successions may represent an axial wedge system is now rejected in view of the rapid along-strike facies transition between the contrasted Stinking Bight and Garheugh -A Formation greywacke successions.

6.3.2.4 The Grennan Point and Garheugh -B Formations

The Grennan Point Formation probably has a maximum *convolutus* Zone age, while the Garheugh -B Formation probably has a maximum *gregarius* Zone age.

The Grennan Point Formation greywacke succession is dominated by thin- to very thick-bedded (10cm to 150cm) tabular to broadly lenticular greywackes

(Table 2.3).[*1] These contain 5m to 15m thickening-up cycles. These sediments are assigned to Facies Associations 2c, 3a and 3b, and are interpreted as lobe, non-channelised slope and minor channel deposits (Tables 5.2).

The Garheugh -B Formation greywacke succession is dominated by thin- to very thick-bedded (10cm to 200cm) tabular to broadly lenticular greywackes. These are occasionally arranged in 3m to 20m, thickening-up sequences (Tables 2.3).[*2] The greywackes are assigned to Facies Associations 2c, 3a and 3b, and are interpreted as non-channelised slope, lobe and minor channel deposits (Table 5.2).

Palaeocurrent evidence implies a predominantly east-northeast to west-southwest palaeoflow pattern (Fig. 6.5). In view of this and the generally more thickly bedded nature of the Garheugh -B Formation greywackes, it appears that the Grennan Point and Garheugh -B Formation successions were probably deposited on the same elongate depositional system. The difference in maximum biostratigraphical age confirms progradation of the system toward the west-southwest. The non-channelised nature of the majority of the sediments within the succession implies that the depositional system was a largely non-channelised sandy 'fan'. Relatively high surface gradients are implied by the often intense slumping

*1 Appendix 5, L17 & Fig. 5.17. *2 Appendix 5, L18 & L19.

associated with these sediments (Fig. 3.6).

6.3.2.5 The Mull of Logan and Corwall Formations

The Mull of Logan Formation comprises four Members, the equivalents of three of which are contained within the Corwall Formation (Table 6.1). Graptolites obtained from within the Cairnie Finnart and Drumblair Members suggest that the Mull of Logan and Corwall Formations may both be assigned to the *turriculatus* Zone.

(a) The Cairnie Finnart and Chippermore Members

The Cairnie Finnart Member succession is dominated by medium- to thick-bedded (25cm to 60cm thick) tabular greywackes which occasionally exhibit 1m to 5m, thickening-up sequences (Table 2.3)*. These sediments are assigned to Facies Associations 3a and 3b and are interpreted as lobe deposits (Table 5.2).

The Chippermore Member succession is dominated by thin-to thick-bedded (5cm-80cm) tabular greywackes, which are occasionally arranged into 1m to 7m, thickening-up and thinning-up sequences (Tables 2.5 2.3). These are assigned to Facies Associations 3a and 3b and are interpreted as lobe deposits (Table 5.2). This succession also includes 15m thick lenticular bodies of intraformational

* Appendix 4, Map D, Log F.

MULL OF LOGAN FM.	CORWALL FM.
Chair Mbr.	Drumblair Mbr.
Duniehinnie Mbr.	Alticry Mbr.
Daw Point Mbr.	---
Cairnie Finnart Mbr.	Chippermore Mbr.

Table 6.1: Suggested correlation of the Members within the Mull of Logan and Corwall Formations; Members are listed in stratigraphical order.

conglomerate, assigned to Facies Association 2a and interpreted as channel-fill deposits (Table 2.3 and 5.2), and poorly exposed developments of thick- to very thick-bedded greywacke (1m to 4m), tentatively assigned to Facies Association 2a and interpreted as channel deposits.

Palaeocurrent data from the Cairnie Finnart and Chippermore Members indicate a very diverse palaeoflow pattern, generally to the south, southwest, west and northwest (Fig. 6.5). Such a dispersal can be explained in terms of flow 'fanning', developed when the transporting current is released from the confines of a channel, for example, on to a suprafan area. This dispersal in palaeoflow pattern may also indicate lobe coalescence. Various lines of evidence which suggest that the Cairnie Finnart and Chippermore Members are 'distal' and 'proximal' counterparts, respectively (Fig. 8): the Chippermore Member turbidites exhibit less well-developed Bouma sequences, are more thickly bedded, display more inter-unit erosional surfaces and slump horizons and include the deposits of, apparently, major channels. The Chippermore and Cairnie Finnart Member greywacke successions are thus considered to represent the mid-fan deposits (Walker 1978) of an axially diverted mixed-sediment fan.

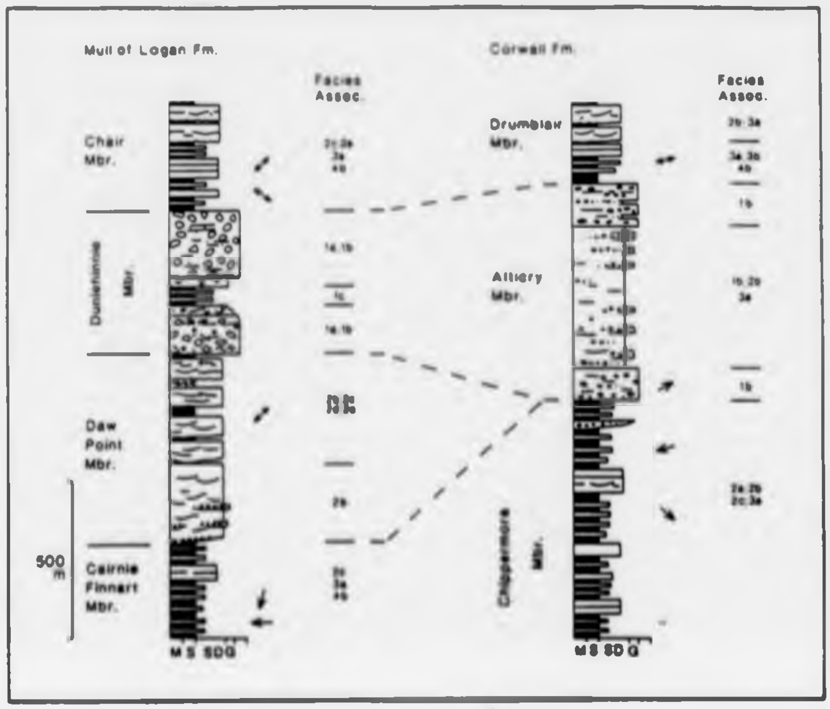


Figure 6.8: Log sections through the Mull of Logan and Corwall Formations, between Port Logan (NX 0963 4091) and Drumbreddan Bay (NX 0780 4350), and Chippermore (NX 2955 4855) and Drumblair (NX 2821 5040), respectively.

(b) The Daw Point Member

The Daw Point Member stratigraphically succeeds the Cairnie Finnart Member. The contact between these successions is deeply scoured and is marked by a thin (20cm to 50cm thick), intra-formational conglomerate.

The Daw Point Member succession may be assigned to two Divisions (Fig. 6.8):

(1) The lowermost division is dominated by very thick-bedded (1m to 8m) amalgamated and lenticular greywackes which are predominantly acyclic, but occasionally displaying 10m to 18m thick, thinning-up sequences (Table 2.3 (c))*. The sediments are assigned to Facies Association 2b and are interpreted as the deposits of major channels (Table 5.2).

(2) The upper division is dominated by thick- to very thick-bedded (70cm to 200cm thick) tabular greywackes (Table 2.3 (a)). These are assigned to Facies Associations 2b and 2c and are interpreted as channel-fill deposits (Table 5.2). Associated with these sediments, but subordinate to them, are 1m to 5m thick packets comprising thin- to thick-bedded

* Appendix 4, Map D, Log E.

(5cm to 35cm) tabular greywackes (Table 2.3 (b)), representative of Facies Association 2d and 2e and interpreted as channel-margin and interchannel deposits (Table 5.2).

The deeply-scoured contact between the Daw Point and Cairnie Finnart Members represents a phase of major channel incision into the mid-fan area. The vertical arrangement of lithologies within the Daw Point Member is indicative of channel migration out of the depositional area. The sediments within the upper part of the Daw Point Member succession are often quite intensely disrupted. This disruption, which takes the form of soft-sediment folding and boudinage, is here attributed to slope steepening associated with tectonic uplift and the initiation of the slope-dominated depositional system represented in the overlying Duniehinnie Member.

(c) Duniehinnie and Alticry Members

The basal contact of the Duniehinnie Member with the Daw Point Member, is not conspicuously erosional but is marked by soft-sediment disruption. The basal contact of the Alticry Member with the Chippermore Member also shows little sign of major erosion. It, therefore, appears that the basal boundaries of the Duniehinnie and Alticry Members are broadly concordant (Fig. 6.8).

In terms of lithology, the Duniehinnie Member succession is relatively homogeneous, being dominated by poorly to irregularly bedded intra-formational conglomerates, containing clasts up to 15m x 10m in size.*1 A few very thick-bedded (1m to 2 5m thick) greywackes occur, but these are generally disrupted and irregularly interbedded with conglomeratic lenses (Table 2.3). The sediments are assigned to Facies Association 1b, and are interpreted as the deposits of a steep, unstable slope (Tables 5.2, Fig. 6.8).

In middle and upper parts the succession contains a 30m thick packet of predominantly thin- to medium-bedded (5cm to 30cm), tabular to broadly lenticular, greywackes, which are interbedded with slumps and intraformational conglomerates.*2 These are ascribed to Facies Association 1c and are interpreted as slope deposits (Table 5.2).

The Alticry Member succession may be assigned to three divisions, the uppermost and lowermost of which are conglomeratic. These intra-formational conglomerate units (1-3m) contain clasts up to 20cm x 20cm in size and are irregularly bedded (Table 2.3). They are assigned to Facies Association 1b and are interpreted as impersistent sheet, debris

*1 Plates 5.1 & 5.2. *2 Appendix 4, Map D, Log D.

flow lobe and channel deposits (Tables 5.2). The central division is dominated by very thick-bedded (>1m) greywackes (Tables 2.3). These are ascribed to Facies Associations 1b, 2b and 3a and are interpreted as the deposits of high-density sheet-flows and channels (Table 5.2).

Clast size variation suggests that the Duniehinnie and Alticry Members are probably proximal and distal counterparts and this suggestion also accords with palaeocurrent evidence (Fig. 6.5). The Duniehinnie Member conglomerates appear to have been deposited mainly from sediment slides, slumps and rockfalls on a very unstable slope. It is clear from the magnitude of many of the blocks, that some of these formative events must have involved very substantial forces. These events also were most probably responsible for generation of the high-density sheet-flows which were responsible for Alticry Member deposition. The sequence dominated by thin- to medium-bedded greywackes within the middle and upper parts of the Duniehinnie Member is interpreted as the infill of a small isolated basin which developed on a very irregular slope surface (Section 5.4.1). The conglomeratic clasts are intraformational and are considered to have been locally derived from the sequences within the Mull of Logan and Corwall Formations.

(d) The Chair and Drumblair Members

The Chair and Drumblair Members overlie the Duniehinnie and Alticry Members, respectively. The transitions are sharp.

The Chair Member is dominated by thick- to very thick-bedded (0.5m to 4m), tabular to broadly lenticular greywackes*, which are occasionally arranged into 3m to 10m, thickening-up sequences (Table 2.3). The sediments are ascribed to Facies Associations 3a and 2c and are interpreted as high-density sheet-flow and channel deposits (Table 2.3). Packets, up to 3m in thickness, of varicoloured shales and siltstones are associated with the sediments described above (Table 2.3). These lutites are assigned to Facies Associations 3b and 4b and are interpreted as the deposits of low-density open sheet-flows and pelagic and hemipelagic fallout (Table 5.2).

The Drumblair Member succession is dominated by medium-to very thick-bedded (15cm to >100cm) tabular and lenticular greywackes (Table 2.3). Thickening-up sequences (1m to 3m thick) are commonly associated with the more thinly bedded units. The sediments are assigned to Facies Associations 2b, 2c and 3a, and are interpreted as lobe and channel

* Appendix 4, Map D, Log C.

deposits (Tables 5.2). Packets ranging in thickness between 1m and 10m, of varicoloured mudstones and siltstones are interbedded with the above sediments. These lutites are assigned to Facies Associations 3b and 4b and are interpreted as the deposits of low-density open sheet-flows and pelagic and hemipelagic fallout (Table 5.2).

The Drumblair Member appears to be a more proximal equivalent of the Chair Member (Fig. 6.8). This suggestion is supported by palaeocurrent data which indicate a palaeoflow pattern to the west-southwest. The general sedimentological characteristics of these units suggest that they are the 'mid-fan' (Walker 1978) deposits of an axially, west-southwest prograding mixed-sediment fan system.

6.3.2.6 The Port Logan and Clanyard Bay Formations

It is important to note that the Port Logan and Clanyard Bay Formations are considered to be 'across-strike' stratigraphical equivalents: they exhibit closely similar arrays of lithologies and facies associations, comparable petrographical characteristics and overlapping ages. The Port Logan Formation appears to be of *crispus* Zone age, while the Clanyard Bay Formation is, at least partly, of *crispus* or *griestoniensis* Zone age (Fig. 2.2).

The Port Logan and Clanyard Bay Formations comprise alternations of:

(1) 10m to 15m thick packets of very thick-bedded (1m to 3m), lenticular greywackes, which are predominantly acyclic (Tables 2.3 and 5.2). These are assigned to Facies Associations 2b and 2c and are interpreted as channel-fills (Table 5.2)*.

(2) 5m to 20m thick packets of thin to thick-bedded (>5cm to 40cm) tabular to lenticular greywackes and siltstones. These are mainly acyclic, but some (1m to 5m thick) thickening-up sequences are developed (Table 2.3 and Fig. 5.12). These sediments are assigned to Facies Associations 2d, 2e and 2f, and are interpreted as channel-margin and interchannel deposits (Table 5.2)*.

(3) 20m to 100m thick acyclic packets of very thin- to thin-bedded (>5cm) greywackes and siltstones and mudstones (Table 2.3). These sediments are assigned to Facies Associations 3b and 4b and are interpreted as the deposits of open sheet-flows and pelagic and hemipelagic fallout (Table 5.2 and Plates 5.14 and 5.15).

* Appendix 4, Map E, Log A.

Palaeocurrent data suggest that the sediments were derived from the northeast. The sedimentological characteristics of the Port Logan and Clanyard Bay successions (particularly the absence of good lobe-type sequences, and the mud-rich nature of the successions), suggest that they represent the deposits of an axially diverted mud-rich fan or perhaps even an axial wedge type system.

6.4 SUMMARY

It appears that within the area covered by the present study:

(1) The sediments exposed within the southern part of the Northern Belt mainly represent the deposits of clastic, north-facing slopes and immature, axially diverted, east-northeast prograding sand-rich 'fan' systems. The occurrence of petrographically distinct siliceous (Type C greywackes, Chapter 4), turbiditic greywacke units within the Port of Spittal Bay and Hairyhorroch Members (Basic-clast Division (Type B greywackes, Chapter 4)) suggests that a second source was supplying some sediment, in open sheet-flows, to the depositional area, implying interaction between depositional systems

within these Members.

(2) The sediments exposed within the northern part of the Central Belt represent the deposits of a variety of depositional systems, including: sand-rich channelised and non-channelised fans, mixed-sediment fans, mud-rich fans (?), probable axial wedges and a debris wedge/cone. Palaeo-current evidence suggests that these fan and axial wedge systems were exclusively derived from sources to the north and northeast. The debris wedge/cone system (Duniehinnie and Alticry Members) appears to have been developed as a consequence of slope instability in the southwest.

The evolution of the depositional systems described above and the geotectonic controls on their evolution and development, are discussed in the next Chapter.

CHAPTER 7

THE EVOLUTION OF DEPOSITIONAL SYSTEMS AND GEOTECTONIC CONTROLS

7.1 GENERAL

The evolution of the depositional systems represented within the greywacke successions exposed within the Southern Uplands/Longford-Down zone has rarely been discussed in detail. Notable exceptions include Leggett (1980), who described the evolution of a prograding fan system from the Stobo area, and Kemp (1987b) who has described the evolution of axially diverted and large passive margin style fans from the Kirkcudbright and Hawick areas.

In this Chapter the evolutionary characteristics of the depositional systems and sediment sources represented within the successions exposed in the study area are assessed, together with probable geotectonic controls and influences on their development. Where appropriate information is available from adjacent areas of the Southern Uplands/Longford-Down zone it has been incorporated into the following discussions and interpretations.

The sediments which are exposed within the study area were deposited within an elongate basin trending east-northeast to west-southwest. The majority of the palaeocurrents within the study area record axial (along the basin) sediment transport paths. It is extremely important to note that those flowing axially to the east-northeast are associated with lateral palaeocurrents which indicate an ultimate sediment source to the south. In contrast those flowing to the west-southwest are usually associated with lateral palaeocurrents which indicate an ultimate sediment derivation from sources to the north. Thus both northerly and southerly sources supplied sediment to the Southern Uplands Basin. Southerly sources were particularly important during the upper Ordovician times when they supplied immense quantities of volcanilithic-rich sediment to the basin. Northerly sources a variety of sediment types to the basin during both upper Ordovician and lower Silurian times. Palaeocurrents then reveal that during upper Ordovician times the basin was fed by two opposed source terrains, the southerly one was a volcanic terrain. It is therefore clear that a simple fore-arc situation, in the sense of Leggett (1980), did not exist during upper Ordovician times. Leggett's (1980) model can, however be applied to the Llandovery sequences.

The basin evolved continuously throughout the Llandeilo to late Llandovery time interval as a result of the development of major thrust and strike-slip fault systems and as a result of changes in convergence rate and direction. The consequent continual changes in basin geometry had a direct influence on the development and geometries of the contemporaneosly active depositional systems. These nature and timing of these changes are addressed in this Chapter.

Relative rates of plate convergence and deposition at subduction margins are known to affect the development of deep-water systems in these settings, and to dictate the types of system which will operate (Schweller an Kulm 1978). Certain system types are stable in certain conditions, for example when convergence rates are low and rates of deposition are high large fan-systems are stable, at the other extreme when convergence rates are high and rates of deposition are low depositional systems are rarely sustained (Fig. 7.4) (Schweller and Kulm 1978). The evolutionary trends occurring during the Llandovery can be partially explained using rates of convergence _versus_ rates of deposition relationships.

7.2 THE SOUTHERN PART OF THE NORTHERN BELT

Stratigraphical evidence (Chapter 2, Sections 2.3.3 and 2.5.1) indicates that the onset of greywacke sedimentation within this part of the study area was probably diachronous in both an across-strike direction (becoming younger towards the northwest) (Fig. 2.4), and in an along-strike direction, (becoming younger towards the northeast) (Fig. 2.4). The lithologically comparable Cairngarroch and Portayew Formation greywacke sequences probably share a lower wilsoni Zone age (Fig. 2.2) and represent the development of a southerly derived clastic slope apron. (Chapter 6, Sections 6.3.1.2 and 6.3.1.3). During linearis Zone times this type of depositional system began to operate within the Glenluce area, to the northeast, forming the Boreland Formation (Chapter 2, Section 2.3.2.2). In the laterally equivalent parts of the central Southern Uplands, for example, west Nithsdale (Floyd 1982) the onset of greywacke sedimentation could also be interpreted as being diachronous towards the northwest (both the Shinnel and Scar Formations have maximum linearis Zone ages). The available biostratigraphical data allow this interpretation since the Moffat Shales which underlie the Scar Formation, the equivalent of the Basic-clast Division of the Portpatrick Formation, and Glenwhan Formation, have a minimum linearis Zone age, coeval with the 'basal' turbidites of the Shinnel Formation, the equivalent of the Portayew and Boreland Formations. Available sedimentological information indicates that the Shinnel Formation sequences were probably formed within a clastic slope apron (Kelling, pers. com., 1987).

Petrographical evidence (Chapter 4, Section 4.5) indicates that the southerly source area, against which these aprons abutted, was probably a strongly dissected volcanic terrain (Fig. 7.1).

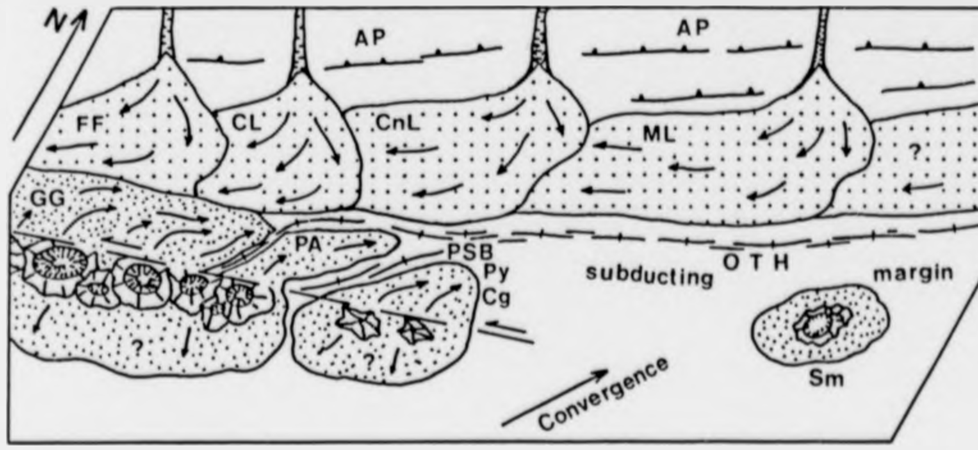
The deposition of the Portayew and Boreland Formations, probably commenced during lower _wilsoni_ and _linearis_ Zone times, respectively (Chapter 2). The Formations comprises sequences which are representative of southerly derived, rarely channelised clastic slope apron (Chapter 6, Section 6.3.1.2). In the Rhinns of Galloway, the Portayew Formation was probably overstepped by the Acid-clast Division of the Portpatrick Formation which was then deposited onto pelagic sediments (Moffat Shales) accumulating to the north. The absence of a petrographical equivalent of the Acid-clast Division within the Glenwhan Formation, and the northeasterly diachronism, apparently displayed by the Portpatrick Formation (Fig. 2.4), suggests that the later spread of the clastic aprons probably controlled by basin highs, such as, tectonic ridges, or perhaps by the

Figure 7.1: Schematic diagram depicting the palaeogeographic and geotectonic evolution of the soutwest Southern Uplands/Longford-Down zone during the later Ordovician (see text). AL, Afton "Lobe"; AP, Accretionary Prism; Bd, Boreland Formation; Bk, Ballymacormick Block; CL, Corsewall "Lobe"; Cn, Carsphairn "Lobe"; FF, Finnalaghta Formation; GG, Gowna Group; Gn, Glenwhan Formation; LF, Lackan Formation; ML, Marchburn "Lobe"; PA, Portpatrick Formation, Acid-clast Division; PB, Basic-clast Division; PL, Portslogan "Lobe" (Kirkolm Group); PSB, Port of Spittal Bay High; Py, Portayew Formation; Sc, Scar Formation; Sh, Shinnel Formation; Sm, Seamount. Modified after Kelling et al. (1987).

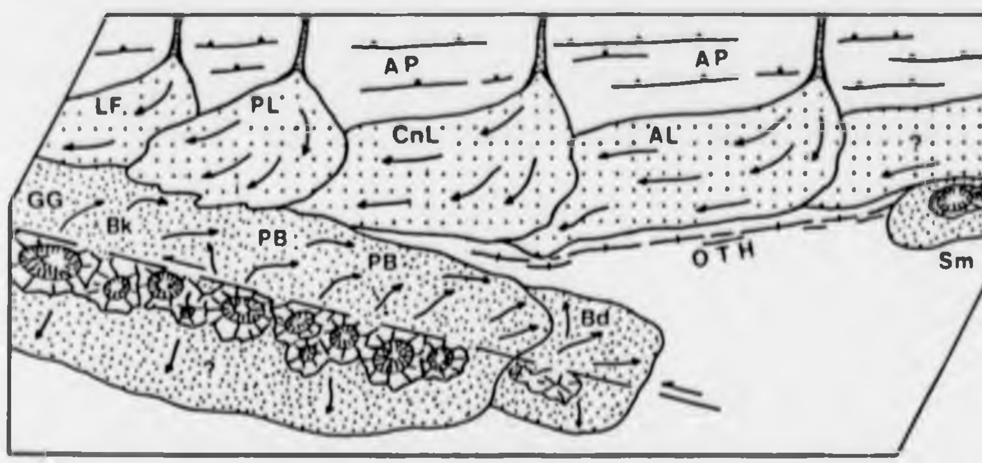
Legend

relatively quartzose coarse clastic sediments
volcanilithic-rich coarse clastic sediments
pelagic sediments
palaeoflow patterns
volcanic edifice
strongly dissected volcanic edifice
major strike-slip fracture zone
thrusts
bathymetric highs

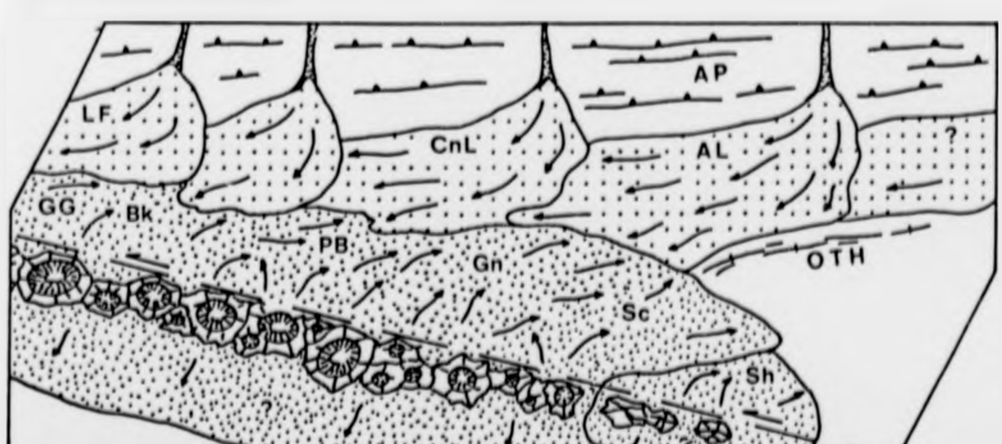
A. gracilis - clingani



B. clingani - linearis



C. linearis - anceps



limited extent of the source terrain. A petrographical comparison of the Acid-clast Division and Portayew Formation greywackes (Type A and D greywackes respectively, Chapter 4), suggests that during the wilsoni to linearis time interval the southerly volcanic source terrain became progressively more active (see Chapter 4, Section 4.5).

The Acid-clast Division is stratigraphically overlain by the Basic-clast Division in the vicinity of Catevennan (NW 9947 5212). To the southeast, however, in Port of Spittal Bay (NX 0200 5212), greywackes representative of the Acid-clast Division are absent from a sequence in which Basic-clast Division sediments directly succeed Moffat Shale pelagics. Since the Port of Spittal Bay site appears to lie south of the main depocentre of the southerly derived Acid-clast Division greywackes (Figs. 2.2 and 6.5), their absence from this location appears anomalous, unless recourse is made to as-yet-unrecognized major strike faulting. However, the absence of the Acid-clast Division can be explained if the Moffat Shales and associated sediments within Port of Spittal Bay (NX 0200 5212) formed part of a topographical high which was not over-topped by sediments of the Acid-clast Division succession. The 'high' might have originated as part of a tectonic ridge or perhaps a very large slump lobe. Indirect evidence for this high is also found within the Moffat Shales and associated sediments which underlie the Basic-clast Division greywackes in Port of Spittal Bay (NX 0200 5215). These sediments exhibit a range of soft-sediment deformation and dewatering features attributed to slumping and creep on the flanks of the high (Fig. 7.2).

The Basic-clast Division greywackes in Port of Spittal Bay (NX 0200 5212) probably have a maximum clingani Zone age, indicating that the 'Port of Spittal Bay High' had been overwhelmed by clingani Zone times. The age of the transition between the Acid- and Basic-clast divisions, evident in the vicinity of Catevennan (NW 9947 5429), has not been biostratigraphically determined. However, it is considered to be of a comparable to the onset of Basic-clast Division sedimentation in Port of Spittal Bay (Chapter 2, Section 2.3.1.1). The petrographically and lithologically correlated Glenwhan Formation greywacke sequence appears to have a maximum linearis Zone age (Figs. 2.2 and 2.3).

It therefore appears that during clingani Zone times a series of immature, coalescing, axially diverted fans began to develop from a source to the south and southwest, in the Rhinns area (Chapter 6, Section 6.3.1.1). By linearis Zone times this type of depositional system was probably being developed in

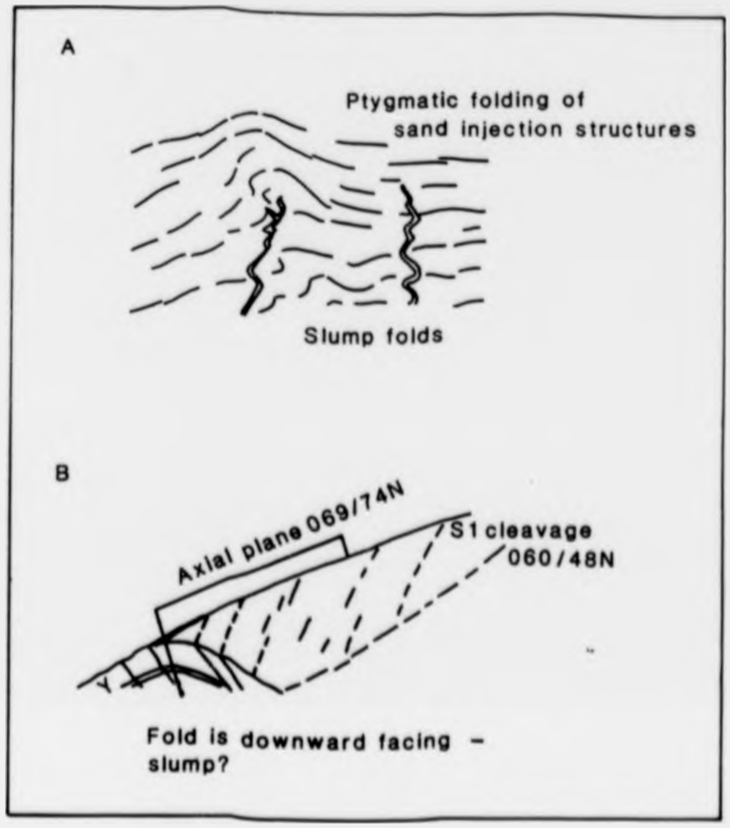


Figure 7.2: Slump structures from Port of Spittal Bay. (A) Slump folds cut by dewatering conduits, developed in Moffat Shale; (B) Downward facing slump fold in a greywacke/siltstone sequence.

both the Rhinns and Glenluce areas, forming the Portpatrick Formation, Basic-clast Division and the Glenwhan Formation (Fig. 7.1). This local diachronism towards the east-northeast appears to be part of a regional trend (Fig. 2.4). Petrographical (Chapter 4) and sedimentological (Chapter 6, Section 6.3.1.1) evidence from the Basic-clast Division, the Glenwhan Formation and the lateral equivalents of these stratigraphical units suggest that the sequences they contain were deposited in areas proximal to, and north of, a contemporaneously active volcanic terrain (see discussions of Type B greywackes, Chapter 4 and Kelling et al. 1987). Thus the lateral diachronism probably reflects migration of the source terrain rather than the simple progradation of a depositional system (Kelling et al. 1987) (Fig. 7.1).

The presence of quartzose units (Type C greywackes, Chapter 4) within the Basic-clast Division, Port of Spittal Bay and Hairyhorroch Members is evidence that the immature sand-rich fans which were actively developing within the Rhinns area interacted with depositional systems derived from a different (probably-recycled orogen) terrain. Kelling et al. (1987) suggested that the quartzose units may be related in provenance to the Kirkolm Group (Kelling 1961), which represents an axially diverted medium-sized fan system, derived from a north and northeasterly source. Thus the quartzose units were probably also derived from a northern margin. It is suggested that they were deposited from high- to low-density sheet-flows which impinged from time to time on the Port of Spittal Bay and Hairyhorroch depositional areas (Chapter 6, Section 6.3.1.1) (Fig. 7.1). Similar quartzose (Type C, greywackes) units have been identified within the Scar Formation, a lateral equivalent of the Basic-clast Division situated in Nithsdale (Floyd 1982, his Fig. 4b).

The majority of the greywackes which constitute the stratigraphical units, exposed within the southern part of the Northern Belt in the study area, and their lateral equivalents in Ireland and Scotland, display petrographical and sedimentological features which indicate that they were deposited to the north of an evolving volcanic terrain (Morris 1987; Stone et al. 1987). As Kelling et al. (1987) recognize "the nature of this volcanic terrain is of great importance in determining the precise geotectonic status of this sector of the Southern Uplands/Longford-Down Zone active margin during the late Ordovician". There appear to be three main possibilities (Kelling et al 1987):

(1) Volcanic edifices sited on oceanic crust transported to the active margin by plate convergence (seamount chain of Kelling et

al. (1987), p. 801). The remains of such volcanic edifices* have been identified elsewhere in the Southern Uplands (Tweedale lavas; Bail Hill Volcanic Complex), and sedimentary aprons are associated with these (Kiln Formation, McMurtry 1980; Hepworth et al. 1982). However, a number of observations seem to render this explanation unlikely for the Portayew and Portpatrick Formations, and their correlatives: (i) the petrographical and geochemical nature of the highly volcanilithic sequences (Type B greywackes, Chapter 4) (Basic-clast Division, Glenwhan Formation) implies a derivation from a calc-alkaline volcanic terrain (Kelling 1961, 1962; Sanders and Morris 1978), (ii) the large volumes of sediment produced and the relative longevity of the volcanic source (?late Llanvirn to Ashgill) and (iii) "the occurrence of arc-derived detritus of 'continental' and subduction-complex origin (e.g. quartz-mica schists and blueschists)" (Chapter 4, Sections 4.4.1.1 and 4.4.1.2) (Kelling et al. 1987, p.801).

(2) An "in situ" volcanic arc, produced as a direct result of subduction to the south of

* These are broadly contemporaneous with the Portpatrick and Portayew Formation sequences.

the present Southern Uplands/Longford-Down zone. The generation of such an arc is considered (Morris 1987; Stone et al. 1987) to have led to the formation of a deep marine back-arc basin into which both south-derived volcanilithic-rich and north-derived quartzose sediments were transported. This model accounts for most of the sedimentological and petrographical data but, as Kelling et al. (1987) have pointed out, it does not by itself explain the along-strike (northeastwards) diachronism of the south and southwest, arc-derived sequences. The presence of 'continental' and blueschist detritus in the supposed arc derived sequences of the Portayew and Portpatrick Formations, and their correlatives, also favours a continental margin arc rather than an oceanic island arc. In view of this it is surprising that there is no evidence of early rift related sedimentation (Kelling et al. 1987).

(3) A tectonically displaced continental margin arc. As a result of major sinistral, strike-or oblique-slip displacements it is envisaged that a continental margin arc was introduced into a fore-arc geotectonic

setting. This model accounts for the diachronous onset of arc-derived greywacke sedimentation evident within the Portayew, Portpatrick and correlative formations (Table 2.7, Fig. 2.4). Petrographical data and stratigraphical evidence suggest that the volcanic arc evolved from a strongly dissected, sporadically active arc (represented in the Portayew Formation and its equivalents and the Portpatrick Formation, Acid-clast Division, Types D and A greywackes respectively, Chapter 4, Sections 4.4.1.4 and 4.4.1.1) into an intensely active arc (Portpatrick Formation, Basic-clast Division, Type B greywackes, Chapter 4, Section 4.4.1.2), at least within the Scottish sector. Repeated tectonic displacement of the arc along a fracture system is envisaged to have been responsible for the dissection of the laterally advancing arc and the consequent deposition of the diachronous Portayew and its correlative sequences. Subsequent evolution of the arc gave rise to the sediments included within the Portpatrick Formation and its along-strike correlatives. This model also accounts for the interbedding of volcanilithic and quartzose greywackes in the Port of Spittal

Bay and Hairyhorroch Members of the Portpatrick Formation. The northeasterly extent of the tectonically displaced arc, and its associated fracture system, must have been limited at any one time, enabling the incorporation of seamount remnants (Tweedale lavas; Bail Hill Volcanic Complex) in the more northeasterly Northern Belt sequences, an occurrence not so readily explained by the '*in situ*' back-arc basin model (Morris 1987; Stone *et al*. 1987).

This model, therefore, envisages sinistral displacement of a continental margin arc and trench, along a fracture system lying oblique to the trend of the margin. McKerrow (1983) has postulated late Caradoc-Silurian major sinistral transform motions between the British Isles and North America. These products of oblique convergence, have trends and inferred displacements which are consistent with the displaced arc model. The tectonic elements responsible for the juxtaposition of the continental arc and trench are presumably now concealed within or below later formed structures (Kelling *et al*. 1987). Cole and Lewis (1981) have recognized a broadly comparable situation from the Miocene of the Taupo-Hikurangi system of New Zealand.

For the reasons outlined above, the volcanic terrain is considered to have been a tectonically displaced continental margin arc. It is important to note that since the vast majority of the Llandovery sediments were derived from a north and northwesterly source, they were probably not deposited on the continental side of the arc. The Northern Belt sequences and the arc were deformed during the Ashgill-Landovery interval, prior to the deposition of the predominantly north and northwest derived Llandovery sediments (Fig. 6.5). However, petrographical evidence from the Llandovery sequences, suggests that the arc may not have been entirely removed prior to the initiation of Llandovery sedimentation.

Thus Caradoc-Ashgill sedimentation in the southern part of the Northern Belt was dominated by north and northwest building clastic slope aprons and immature, axially diverted sand-rich fans (Fig. 7.1). These depositional systems were developed on the northern flanks of a laterally advancing, tectonically displaced, continental margin arc. The 'continental' margin to the north supplied quartzose sediment to south and southwest prograding medium-sized fans (Kirkolm Group, Kelling 1961), which occasionally operated in the same depositional area as the arc aprons and are derived immature sand-rich fans. Interaction of Ordovician depositional systems derived from the 'continental' and 'arc' margins is recorded by the interbedding of volcanilithic-rich and quartzose sediments in the Basic-clast Division (Fig. 5.9) and by the concordant passage between stratigraphical units which are dominated by quartzose sediments and those dominated by volcanilithic-rich sediments, for example the Kirkolm and Galdenoch Groups (Kelling 1961).

7.3 THE NORTHERN PART OF THE CENTRAL BELT

The time-stratigraphical diagrams which have been constructed for the rocks exposed in the study area (Figs. 2.2 and 2.3) show that there is an unusually large step in the ages of the greywacke sequences across the Cairngarroch Fault, which separates the Northern and Central Belts. Anderson and Oliver (1986) commented on this and suggested that it may be a result of:

(1) a long pause in sedimentation and accretion.

(2) erosive subduction of all the 'missing' tracts.

(3) excision by post-accretionary strike-slip faulting.

The contrasting palaeogoegraphical interpretations invoked for the rocks exposed in the Northern and

Central Belts suggests that the apparent hiatus is a result of fault excision. Anderson and Oliver (1986) show that the movement on the Cairngarroch Fault was sinistral strike-slip and that it was very substantial and probably post-accretionary. The Cairngarroch Fault may have played a major part in the excision of the 'arc-sliver' which supplied sediment to the Portpatrick Formation and related greywacke sequences. Sinitral displacements are invoked for both the fault system which introduced the arc into the Southern Uplands region and for the Cairngarroch Fault. It is a distinct possibility that these are related structures. Petrographical evidence suggests that the Northern Belt sequences were deformed during the apparent hiatus (Chapter 4, Section 4.5).

Palaeocurrent evidence (Fig. 6.5) indicates that throughout most of the Llandovery, greywackes were derived from a margin to the north and northeast. Petrographical evidence suggests that the source may have lain within the deformed Northern Belt sequences. The (relatively) volcanilithic nature of acuminatus to turriculatus Zone greywackes indicates that the displaced continental margin arc, so important as a source during the Caradoc-Ashgill, although probably deformed and inactive, may have continued to supply sediment to the south well into the Llandovery.

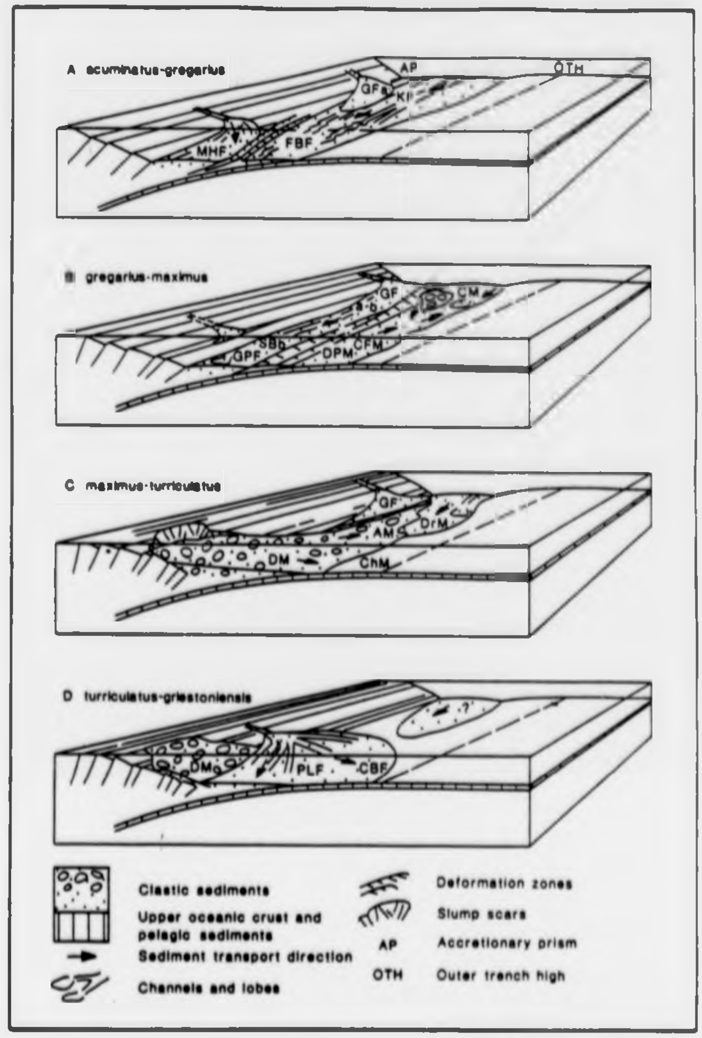
The Llandovery sediments are here considered to have been deposited within a trench, developed at a convergent margin, for two main reasons:

(1) the predominance of axial palaeocurrents (Fig. 6.5).

(2) the apparent diachronism of the depositional systems towards the southeast perpendicular to the axial progradation directions of the majority of the depositional systems, a feature most readily explained in terms of plate convergence.

The Float Bay and Kilfillan -A and -B Formation sequences represent the earliest Llandovery depositional systems developed (atavus to leptotheca? Zone) (Figs. 2.2 and 2.3). These sequences are representative of either an axially diverted fan or an axial wedge depositional system (Chapter 6, Section 6.3.2.2). Palaeocurrent data suggest a predominant palaeoflow pattern towards the southwest (Figs. 6.5 and 7.3).

The Money Head Formation sequence, which is exposed to the northwest of the Float Bay Formation, directly overlies pelagic deposits (Moffat Shales). Furthermore, the component greywackes are petrographically distinctive, often containing substantial amounts of detrital pyroxene (Type E



AM, Alticry Member; CM, Chippermore Member; ChM, Chair Member; CFM, Cairnie Finnart Member; DM, Duniehinnie Member; DPM, Daw Point Member; DrM, Drumblair Member; FBF, Float Bay Member; GF, Garheugh Formation (with A and B Formations); GPF, Grennan Point Formation; KF, Kilfillan Formation; MHF, Money Head Formation; PLF, Port Logan Formation; SBb, Stinking Bight beds

Figure 7.3: Schematic diagram depicting the palaeogeographic and geotectonic evolution of the southwest Southern Uplands during the early Silurian. Modified after Kelling <u>et al.</u> (1987).

greywacke, Chapter 4, Section 4.4.2.1). The sedimentological characteristics of the Money Head Formation suggest an origin as an axially diverted sand-rich fan complex (Chapter 6, Section 6.3.2.1), while, palaeocurrent data suggest a predominant palaeoflow pattern towards the southwest (Fig. 6.5 and 7.3). The acinaces to cyphus? Zone age of this formation suggests that the sand-rich fan complex developed during the same time interval as part of the Float Bay/Kilfillan -A and -B fan or axial wedge system (Fig. 7.3). The differing depositional styles and petrography, but parallel palaeoflow patterns of these contemporaneous systems are difficult to reconcile with simultaneous deposition within a single trench basin and an intervening structural barrier is therefore postulated. However, Kelling et al. (1987, p.803) have argued that 'it is possible that the two systems were bathymetrically separated, the Money Head system perhaps being developed in a lower slope basin, rather than the open trench floor' (Fig. 7.3).

The Stinking Bight and Garheugh -A Formation sequences appear to be representative of an axially diverted sand-rich fan (Chapter 6, Section 6.3.2.3). Palaeocurrent data indicate palaeoflow towards the southwest. This axially diverted sand-rich fan system has a cyphus/triangulatus Zone boundary to leptotheca? Zone age and may therefore have coexisted, in part, with the Float Bay/Kilfillan -A and -B depositional system. This suggests that small, axially diverted sand-rich fans began to prograde over the elongate mixed-sediment fan or axial wedge during the cyphus to leptotheca time interval (Fig. 7.3).

The Grennan Point and Garheugh -B Formation sequences are probably products of a very immature, axially diverted, non-channelised, sand-rich fan (Chapter 6, Section 6.3.2.4). Palaeocurrent data (Fig. 6.5) again indicate a predominant transport to the southwest. The leptotheca? to sedgwickii? Zone age of the formations thus suggests continued development of the type of depositional system initiated earlier and represented within the Stinking Bight and Garheugh -A Formation sequences (Fig. 7.3).

The Mull of Logan and Corwall Formations are of maximus? to terriculatus Zone age. The Cairnie Finnart and Chippermore Member sequences appear to be the mid-fan deposits (Walker 1978) of an axially diverted, mixed-sediment system (Chapter 6, Section 6.3.2.5) (Fig. 7.3). The Daw Point Member probably represents a major channel/channel complex forming part of the mixed-sediment fan sequence. Palaeocurrent data (Fig. 6.5) reveal a palaeoflow pattern which is predominantly towards the southwest. The development of mixed-sediment fans suggests an evolutionary trend towards fan maturity. This trend was interrupted by the deposition of the Duniehinnie and Alticry Member sequences which record growth and development of a major debris-cone (Chapter 6, Section 6.3.2.5) (Fig. 7.3), deposited as a result of repeated major slope-failure events. The succeeding Chair and Drumblair Member sequences comprise the deposits of an axially diverted mixed-sediment fan (Chapter 6, Section 6.3.2.5) (Fig. 7.5). Palaeocurrent data (Fig. 6.5) indicate palaeoflow predominantly towards the southwest. The Chair/Drumblair Member system marks a return to mixed-sediment fan deposition.

The Port Logan and Clanyard Bay Formations are here considered to be across-strike equivalents. The sequences contained within these crispus to ?griestoniensis Zone age sequences apparently represent a large, axially diverted mud-rich fan or axial wedge (Chapter 6, Section 6.3.2.6, Fig. 7.3.

The types of depositional system represented by the Llandovery sequences are consistent with their developement within a trench at a convergent margin. The trench was probably supplied with detritus derived from the (?accreted) Northern Belt rocks and remnant continental margin arc situated to the north.

Deposition within the trench evidently commenced with the development of an axial wedge system (Float Bay and Kilfillan -A and -B Formations). Sand-rich systems prograded southeastwards over this depositional system (Stinking Bight and Garheugh -A, and Grennan Point/ Garheugh -B Formations (Fig. 7.3)). Certain of these systems appear to have been bathymetrically or tectonically isolated (Money Head Formation) (Fig. 7.3). These depositional systems appear to have evolved into mixed-sediment fans (Cairnie Finnart, Daw Point, Chippermore, Chair and Drumblair Members). Localised major slope failure produced debris-cones (Drumblair and Alticry Members) which interrupted deposition from mixed-sediment fans, possibly diverting these. The development of a mud-rich fan/axial wedge complex (Port Logan and Clanyard Bay Formations) (Fig. 7.3) marks the final stage of deposition in the study area. Evidence from the Kirkcudbright area (Kemp 1987b) suggests that large axially diverted fans continued to develop until the uppermost Llandovery. The Wenlock rocks exposed in this area appear to have been deposited in large 'passive-margin-type' fans.

7.4 SUMMARY

The Caradoc to Llandovery sequences exposed within the study area are, in accordance with Leggett (1980), interpreted as representatives of depositional systems developed within a fore-arc plate tectonic setting. Plate convergence has been invoked to explain the discrepency between the general southeasterly decrease in the maximum age of greywacke sedimentation and the inferred axial progradation directions, shown by the majority of the depositional systems (Leggett et al. 1979). Accretion processes would explain these stratigraphical features, in addition to many of the structural features and are thus here considered to have operated throughout the Caradoc to Llandovery time interval.

The Caradoc to Ashgill sequences, exposed within the study area, predominantly represent clastic slope aprons and immature sand-rich fans which developed on the northern flank of a tectonically displaced, laterally migrating, continental margin arc. These systems were occasionally covered by deposits of depositional systems sourced to the north. Sinistral displacement and tectonic migration of the arc relative to the fore-arc, along an oblique-slip fracture zone, allows for the diachronous introduction of arc-related sedimentation from the southwest to the northeast. This model also permits the continuous development of thick pelagic and ocean-floor sequences beyond the limits of active clastic sedimentation on the subducting oceanic plate.

Figure 7.4: The developing relationships between convergence rate and sediment supply, in the southwest Southern Uplands through the Llandovery. Base diagram from Schweller and Kulm (1978).

During the Llandovery depositional systems, mainly fans, prograding from a margin to the north and northwest, accumulated within a trench, while pelagic deposits accumulated on the subducting plate to the southeast. Deformation and uplift of the Ordovician sediments and the tectonic disruption and perhaps partial removal of the continental margin arc were probably accomplished by the earliest Llandovery. This scenario would explain the relatively volcanilithic nature of the majority of the Llandovery sequences and, in particular, the pyroxenous nature of the Money Head Formation.

The Llandovery depositional systems in southwestern Scotland evolved from an axial wedge through southwest prograding axially diverted, sand-rich fans and mixed-sediment fans to mud-rich fans. This evolutionary sequence was broken by the development of a debris cone in the upper Llandovery. Information from the Wenlock rocks of Kirkcudbright suggests that the large axially diverted, mud-rich fan systems, developed in latest Llandovery times, were succeeded by large 'passive-margin-style' fans (Kemp 1987b). The evolutionary sequence, outlined here, is indicative of either an increase in sediment supply and/or an increase in convergence rate (Schweller and Kulm 1978) during the Llandovery and into the Wenlock (Fig. 7.4).

CHAPTER 8

CONCLUDING SUMMARY

This thesis has been concerned with the stratigraphy, sedimentology, petrography and structure of the rocks exposed within two 0.2km to 1.5km wide, across-strike 'corridors' exposed in extreme southwestern Southern Uplands of Scotland:

(1) West of Luce Bay; Killantringan Bay (NW 9820 5700 and Clanyard Bay (NX 1010 3800) on the Rhinns of Galloway (Fig. 1.1)..

(2) East of Luce Bay; Little Larg (NX 1612 6612) and Port William (NX 3370 4355) in the Glenluce area (Fig. 1.1).

Structural, stratigraphical, sedimentological and petrographical data, collected during the present study, confirm the results of previous studies undertaken in southwestern Scotland (Kelling 1961; Gordan 1962; Welsh 1964) which have concluded that the rocks exposed here are cut by a series of major strike-faults and that these act as boundaries to tracts which distinctive sedimentological sequences and/or petrographical suites. Correlation of major faults and fault-bounded tracts, between the two study corridors has been achieved by comparing the relative structural positions of structural features within their respective profiles. Distinctive lithological and petrographical associations have been used as marker horizons.

Two major fault structures have been identified within the study area in amongst the ten or so major strike faults which have been identified (Chapter 3). These are:

(1) The Cairngarroch Fault, which is considered to form the Northern-Central Belt boundary (Anderson and Oliver 1986).

(2) The Port Logan Fault which occurs within the Central Belt on the Rhinns of Galloway (Barnes et al. 1987). This Fault separates two structurallly contrasted zones. To the north of the Fault the sediments young predominantly northwestwards and most of the F1 folds verge southeastwards, while to the south of the Fault the sediments young predominantly southeastwards and the F1 folds verge northwestwards. Barnes et al. (1987) have identified the continuation of the Port Logan Fault on the east side of Luce Bay. It should be noted, however, that southwards younging is less well developed in this area.

	WEST OF LUCE BAY	EAST OF LUCE BAY
NORTHERN BELT	Portpatrick Fm.	Glenwhan Fm.
	Portayew Fm.	Boreland Fm.
	Cairngarroch Fm.	-
	Money Head Fm.	-
	Float Bay Fm.	Kilfillan - A Fm. Kilfillan - B Fm.
CENTRAL BELT	Stinking Bight Fm.	Garheugh -A Fm.
	Grennan Point Fm.	Garheugh -B Fm.
	Mull of Logan Fm.	Corwall Fm.
	Port Logan Fm.	(not identified)
	Clanyard Bay Fm.	(not identified)

Table 8.1: The major stratigraphical units identified within the study area. Units are listed in order from north (top) to south (bottom) and correlated units are listed next to each other. Portpatrick Fm. after Kelling (1961), Portayew Fm. after Floyd (1982), Glenwhan and Boreland Fms. after Welsh (1964), undivided Kilfillan and Garheugh Fms. after Gordon (1962).

Throughout most of the study area, the sequences preserved within the fault-bounded tracts young predominantly towards the northwest. Only those sequences preserved within tracts exposed to the south of the Port Logan Fault in the southern part of the study area contain predominantly southeastwards younging sequences.

Structural analysis of the rocks exposed within the study area has recognized three broad groups of deformation structures and a simple sequence of deformation events (based on field data and the conclusions presented in Knipe and Needham 1986). The deformation 'events' and the structures they produced are listed below (Chapter 3):

(1) Pre-D1; early deformation structures. These structures were formed as a result of sediment failure on slopes related to depositional features or tectonic uplift.

(2) D1; main deformation structures. These structures were formed in response to thrusting and include major strike-faults and gently- plunging folds which, in the Cental Belt, commonly display a non-axial-planar cleavage (S1).

(3) Post-D1; late deformation structures. These structures, which include minor thrusts, wrench faults and gently-plunging folds were formed after the rotation of the D1 structures.

The structures produced during each of the 'phases' listed above are considered to have been formed within a specific structural sub-environment in an evolving thrust-stack (Knipe and Needham 1986). The three sub-environments are: (1) outboard of the thrust-stack, (2) the toe of the thrust-stack, and (3) within the thrust stack. During the evolution of the thrust-stack, individual rock units would have encountered these sub-environments sequentially giving rise to the deformation sequence observed within the study area.

Using the lithostratigraphical procedure proposed by Holland et al. (1978) a stratigraphical scheme has been proposed for each of the study corridors (Chapter 2). These schemes include the, where necesarily, modified stratigraphies originally proposed by Kelling (1961), Welsh (1964) and Gordon (1962) and a new stratigraphy, which is here proposed for the Central Belt on the Rhinns of Galloway (see Chapter 2 and Table 8.1). Correlation between the corridors has been achieved by comparing the relative structural positions of the stratigraphical units, within their respective profiles and by using distinctive petrographical and lithological associations as marker horizons. It should be noted that, although most stratigraphical units can be traced from one study corridor to the next some, for example the Money Head Formation, cannot. There are two main possible reasons for this:

(1) Original limited lateral extent of deposition of the greywackes included within such a stratigraphical unit.
(2) Along-strike excision by faulting.

An analysis of biostratigraphical data, derived from published (e.g. Peach and Horne 1899) and unpublished sources (listed in Appendix 1), indicates that:

(1) In the Northern Belt, the maximum age of greywacke sedimentation possibly becomes progressively younger towards northwest and that the onset of greywacke sedimentation in the Portpatrick/ Glenwhan and Portayew/Boreland Formations (Table 8.1) is probably diachronous becoming younger from the southwest to the northeast.

(2) In the Central Belt the maximum age of greywacke sedimentation becomes progressively younger from the northwest to the southeast.

Regional correlations have been made with the sediments exposed within the Northern Belt study area:

(1) Floyd (1982) correlated stratigraphical units exposed in the Northern Belt in West Nithsdale with those described by Kelling (1961) and Welsh (1964) in the study area.

(2) Morris (1983) provided stratigraphical data from the rocks exposed in the western parts of the Longford-Down inlier and correlated the units exposed here with those defined by Kelling (1961), Welsh (1964) and Floyd (1982), in the study area and West Nithsdale.

(3) Craig (1984) described the stratigraphical units exposed in North Down and attempted to incorporate these into the regional framework established from the work of Kelling (1961), Welsh (1964), Floyd (1982) and Morris (1983).

The correlations made by Floyd (1982) and Morris (1983) are accepted. However, those made by Craig (1984) with the Rhinns of Galloway are here considered to be erroneous. Craig (1984) correlates the Portpatrick Formation (Portpatrick Group of Kelling 1961) with the Rockport and Grey Point Formations which are included within the northernmost tract (the Ballygrot Block) exposed on the North Down coast, occupying a structural position clearly not comparable with the Portpatrick

Formation. A close examination of the tectono-stratigraphical scheme proposed by Craig (1984 her Fig.4) and the petrographical data summarised in her Tables 2 and 3 indicates that the Ballymacormick Block is more likely to be the lateral equivalent of the Portpatrick Formation since:

(1) It occupies a similar structural position within the North Down section to that of the Portpatrick Formation in the Rhinns section.

(2) The greywackes exposed within the Ballymacormick Block are petrographically very similar to those included within the Portpatrick Formation, containing abundant andesite fragments, pyroxenes and amphiboles (including minor amounts of glaucophane).

It is thus proposed here that the Ballymacormick Block represents the equivalent of the Portpatrick Formation. The Orlock Block, which is situated immediately to the north of the Orlock Bridge Fault (the Northern/Central Belt boundary), probably represents the lateral equivalent of either the Portayew or the Cairngarroch Formation.

Regional correlations (Floyd 1982; Morris 1983) have shown that the statigraphical units which are exposed within the southern part of the Northern Belt are diachronous, becoming younger to the northeast regionally (the Portpatrick and Portayew Formations and their along-strike equivalents).

Regional correlations have only recently been made with stratigraphical units exposed within the Central Belt study area. Barnes et al. (1987) have correlated between the Ards Peninsular exposed in County Down and the extreme southwestern parts of Galloway (see their Fig. 6).

Petrographical variation occurs throughout the study area and individual stratigraphical units often display distinctive petrographical characteristics (Chapter 4). The present study has identified eight petrographical groups within the study area. These are listed in Table 8.2, along with their stratigraphical occurrences.

Petrographical changes have been noted on a bed scale in parts of the Portpatrick Formation, Basic-clast Division (within the Port of Spittal Bay and Hairyhorroch Members). These changes involve the interbedding of units exhibiting Type B and Type C petrographies (Table 8.2).

The sediments included within the study area can be assigned to four principal "facies association groups" which represent a variety of deep-water depositional environments (Chapter 5):

(1) Facies Association Group 1. This Group includes three facies associations (Section 5.4.1) which comprise poorly to irregularly bedded coarse conglomerates (clasts up to 15 x 10m in size) and thin- to very thick-bedded often 'blocky' sandstones. These sediments are here considered to have been deposited in unstable slope, 'featureless' slope and perched basin environmental settings.

(2) Facies Association Group 2. This group includes six facies associations (Section 5.4.2) which comprise thick organized and disorganized conglomerates, amalgamated sandstones, thin- to thick-bedded sandstones and laminated siltstones and shales. These sediments probably represent within-channel, channel margin and a variety of interchannel environmental settings.

(3) Facies Association Group 3. This Group includes two facies associations (Section 5.4.3) which comprise thin- to very thick-bedded commonly sheet-like greywackes. These sediments were probably deposited in aggrading slope and lobe type environmental settings.

(4) Facies Association Group 4. This Group includes two facies associations (Section 5.4.4) which comprise laminated and homogeneous shales and siltstones. These were probably deposited in areas well isolated from major clastic inputs.

An analysis of the vertical and lateral distribution of these facies association groups, present within individual sand-bodies in the study area, has enabled the identification of specific types of depositional system (Chapter 6). The sand-bodies, or major stratigraphical units, identified within the Northern Belt appear to be representative of:

(1) Clastic slope aprons (Portpatrick Formation, Acid-clast Division, Portayew/Boreland and Cairngarroch Formations.

(2) Immature, sand-rich fans (the Portpatrick Formation, Basic-clast Division/Glenwhan Formation).

The sand-bodies, or major stratigraphical units, identified within the Central Belt appear to be representative of:

(1) An axial-wedge (Float Bay/Kilfillan -A and -

B Formations).

(2) Sand-rich fans (Money Head, Stinking Bight/ Garheugh -A, Grennan Point/ Garheugh -B Formations.

(3) A debris wedge (Duniehinnie and Alticry Members of the Mull of Logan and Corwall Formations).

(4) Mixed sediment to mud-rich fans (the Cairnie Finnart/Chippermore, Daw Point, Chair/Drumblair Members of the Mull of Logan and Corwall Formations and the Port Logan and Clanyard Bay Formations).

Anderson and Oliver (1986) conclude that the Cairngarroch Fault is a major structural feature with a possible displacement of up to 200km, but changes in the structural, sedimentological and petrographical nature of the rocks across the fault, are minimal. For this reason the Northern and Central belts cannot be viewed independently of each other when making geotectonic reconstructions.

In aggregate the palaeocurrent data from throughout the Southern Uplands demonstrate that depositional systems were predominantly sourced from a northwestern margin. In addition, biostratigraphical data indicate that while clastic depositional systems operated along a northwestern margin, pelagic sediments accumulated towards the southeast. The characteristics are indicative of sedimentation within an asymmetrical basin, analogous to those formed in modern fore-arc regions (Kelling et al. 1987).

Examination of the sedimentological, stratigraphical, petrographical and structural characteristics of the sediments exposed within the study area provides vital details concerning the evolution and provenance of depositional systems and the geotectonic framework in which they developed (Chapter 7).

Sedimentological and petrographical data from the Northern Belt sequences included within the study area (see Table 8.1) indicate that clastic slope-aprons and immature sand-rich fans (see above) prograded broadly northwards from a volcanic terrain. Regional along-strike diachronism, towards the northwest, is displayed by these stratigraphical sequences and their correlatives. The petrographical and sedimentological characteristics of the sediments included within these stratigraphical units indicate that deposition occurred close to the source. Diachronism can best be explained in terms of relative, sinistral, oblique-slip displacement of a sporadically active arc terrain with respect to its fore-arc, rather than extended progradation of depositional systems (for which there

	Type A:	Volcanilithic greywackes (Portpatrick Fm., Acid-clast Div.)
	Type B:	Volcanilithic and ferromagnesian mineral-rich greywackes (Portpatrick Fm., Basic-clast Div.; Glenwhan Fm.)
NORTHERN BELT	Type C:	Quartz metalithic and acid volcanilithic-rich greywackes (Alternation on bed scale with Type B in Portpatrick Fm., Basic-clast Div., Hairyhorroch and Port of Spittal Bay Mbrs.)
	Type D:	Quartz-rich greywackes with a minor ferromagnesian mineral content (Portayew Fm.; Boreland Fm.; Cairngarroch Fm.)
	Type E:	Quartz and volcanilithic-rich, occasionally pyroxenous greywackes (Money Head Fm.)
CENTRAL BELT	Type F:	Quartz-rich greywackes (Float Bay Fm.; Kilfillan -A and -B Fms.; Stinking Bight Fm.; Garheugh -A Fm.; Grennan Point Fm.; Garheugh -B Fm.)
	Type G:	Quartz and acid volcanilithic-rich grey-wacke (Mull of Logan Fm.; Corwall Fm.)
	Type H:	Micaceous, quartz and metalithic-rich greywackes (Port Logan Fm.; Clanyard Bay Fm.)

Table 8.2: The main petrographical groups identified within the study area and their stratigraphical occurrences.

is no evidence). This scenario explains the south and southwest derivation of volcanilithic-rich greywackes (Types A, B and D) and the interbedding of volcanilithic- and ferromagnesian-rich greywackes (Type B) and subordinate siliceous greywackes (Type C) in the Hairyhorroch and Port of Spittal Bay Members (Portpatrick Formation, Basic-clast Division) (see above and Chapter 4). Petrographical data suggest that the arc was probably a continental margin arc (see Chapter 4).

Deformation of the Ordovician greywacke sequences and the continental margin arc probably occurred prior to the development of the first of the Central Belt (Llandovery) sequences.

The Central Belt sequences, exposed within the study area, appear to represent a range of depositional system types. Palaeocurrent data suggest that these were derived consistently from the north and northeast. Biostratigraphical data indicate that, while these systems were developing along a northwestern margin, pelagic sediments were accumulating to the southeast, a situation typical of many modern forearcs. Depositional systems display a clear evolutionary trend from trench wedge, to sand-rich fan, mixed-sediment fan and finally mud-rich fan probably indicative of reduced convergence rates or increased sediment supply (Schweller and Kulm, 1978) (see above and Chapter 7).

Most of the fan systems appear to have been axially diverted, indicating strong morphological constraint within a trench system. Petrographical evidence (Chapter 4) suggests that these depositional systems were mainly sourced in recycled orogen terrains. The deformed Ordovician sedimentary sequences and perhaps 'arc remnants', probably formed the provenance of the Llandovery sequences.

It is therefore concluded that the various depositional systems represented by the sediments exposed within the study area were deposited within a fore-arc region which was temporarily disrupted, during the late Ordovician and placed behind a tectonically displaced continental margin arc. The broad structural characteristics of the sediments included within the study area are consistent with their deformation and inclusion within a thrust-stack. This is, in view of its 'fore-arc location', the 'trench' affinities of its component sediments and their structural and stratigraphical characteristics, here considered to represent an accretion complex.

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APPENDIX 1

BIOSTRATIGRAPHICAL DATA

Graptolites have been collected from several localities by the author during the course of the present study. Collections made from five localities have yielded valuable biostratigraphical information:

(1) South side of Float Bay (NX 0616 4725). Graptolites collected from thick laminated siltstone horizon, interbedded with greywackes. The collection includes (identified by B.R. Rickards):

- (a) Climacograptus cf. rectangularis (McCoy)
- (b) Rhaphidograptus toernquisti (Elles and Wood)
- (c) Glyptograptus sp.
- (d) Monograptus revolutus (Kurck sl.)
- (e) Dimorphograptus sp.

In clustre these are representative of the atavus-cyphus Zone interval.

(2) Drumbreddan Bay, north shore (NX 9774 4374) (B.G.S. Palaeontology Division specimen numbers 11E 8183-90). Collected from Moffat Shales 4-5m below the transition to greywacke. The collection includes (identified by A.W.A. Rushton):

(a) Climacograptus sp.

(b) Glyptograptus cf. enodis (Packham)

(c) Monograptus triangulatus cf. fimbriatus (Nicholson)

(d) Rastrites peregrinus (Barrande)

This collection is representative of the gregarius Zone; if the specimen of M.t. fimbriatus is correctly identified, the middle Subzone of Diplograptus magnus is represented.

(3) Drumbreddan Bay, north shore (grid reference as for (2)) (B.G.S. Palaeontology Division specimen numbers 11E 8191-8200). Collected from Moffat Shales 4 3m below high-water mark. The collection includes (identified by A.W.A. Rushton):

(a) Atavograptus atavus (Jones)?

(b) Monograptus austerus (Törnquist)? (group)

(c) Orthograptus cf. cyperoides (Törnquist) (fragment)

(d) Rhaphidograptus (fragments)

(e) Pseudoclimacograptus (fragments)

This collection is representative of the cyphus or gregarius Zone.

(4) Locality as above but 1 8m below high-tide mark. (B.G.S. Palaeontology Division specimen numbers 11E 8201-4). The collection includes (identified by A.W.A. Rushton):

(a) Climacograptus?

(b) Petalograptus palmeus cf. latus (Barrande) (fragment)

(c) Rastrites peregrinus

The collection represents the gregarius Zone, possibly the magnus Subzone.

(5) Grennan Bay (NX 0478 4381) (B.G.S. Palaeontology Division specimen numbers 11E 8205-17). The collection includes (identified by A.W.A. Rushton):

(a) Climacograptus normalis (Lapworth)

(2) Climacograptus rectangularis (McCoy)

These specimens probably represent the atavus or acinaces Zone.

The samples from each of the above localities are in the possession of the B.G.S. and are kept at Murchison House, Edinburgh. The collections made from localities (2) to (5) form the subject of B.G.S. Palaeontology Division report 86/230.

In addition to the biostratigraphical information yielded by the above collections, information contained within a number of unpublished B.G.S. Palaeontology Division Reports has been used and referred to throughout this thesis. These reports are listed below:

RUSHTON, A.W.A. "Report on graptolites from the Camrie area 2 5km N. of Glenluce. Dumfries and Galloway Region, 1" Sheet, Scotland 4(W)". PD 82/41.

RUSHTON, A.W.A. "Report on graptolites from the area of Culroy and Gillespie Burn, near Glenluce". PD 83/29.

RUSHTON, A.W.A. "Report on graptolites near Garheugh, Glenluce (Scottish 1:50,000 Sheet 4)". PD 84/23.

RUSHTON, A.W.A. "Report on graptolites from Gabsnout Burn, 3km NNW of Glenluce, Galloway (Scottish 1:50,000 Sheet 5". PD 84/25.

RUSHTON, A.W.A. "Report on fossils from Drumbreddan Bay". PD 86/230.

RUSHTON, A.W.A. "Report on collections of fossils from Loch Ryan and the Rhinns of Galloway". PD 87/46.

RUSHTON, A.W.A. "Report on recent collections of fossils from the area of the Mull of Galloway (Scotland 1:50,000 Sheet 3)". PD 87/47.

RUSHTON, A.W.A. "Report on the old Survey collections of fossils from the area of the Rhinns of Galloway and Cairn Ryan (Scotland 1:50,000 Sheet 3)". PD 87/50.

RUSHTON, A.W.A. & WHITE, D.E. "Preliminary report on fossils collected from localities on the Rhinns of Galloway, March, 1986". PD 86/160.

TUNNICLIFF, S.P. "Graptolites from the foreshore south of Glenluce. Dumfries and Galloway Region, 1" Sheet, Scotland 4(W)". PD 83/4.

WHITE, D.E. "Late Llandovery and early Wenlock graptolite faunas of the Whithorn Peninsula (Scottish Geological Survey, Sheets 2 and 4)". PD 84/52.

APPENDIX 2

POINT COUNT ANALYSES

The results of 148 point count analyses are presented within this Appendix. The analyses are of samples collected within the study area.

Point counts have been carried out exclusively on samples of medium to coarse sand grade. A total of 1000 points was counted for each analysed sample (for further details see Chapter 4, Section 4.3). Explanations of abbreviations used in the Tables are given in Table 4.1 (Chapter 4).

The samples were, with the exceptions of Z32, Z261 and el (from the Portayew Formation), all collected by the author during the course of the present study. The thin sections of samples Z32, Z26 and el derive from Professor Kelling's collection.

The samples collected by the author each have: (1) a prefix, 'R' or 'GL', which signifies the broad geographical area from which the sample was collected, the 'Rhinns' or the 'Glenluce' section; and (2) a suffix which relates to the season and in some cases the part of that season in which the sample was collected, for example, E-83 signifies the easter of 1983. Thus, for example, the seventh sample collected on the Rhinns of Galloway in the summer of 1984 would have the sample number R7-S-84.

It should be noted that in each of the following Tables samples are listed in order of collection from northwest (top) to southeast (bottom).

KILLANTRINGAN BAY (NW 9820 5700) TO CLANYARD BAY (NX 1010 3800)

Portpatrick Formation, Acid-clast Division

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R1-83 NW 9993 5389	5.7	4.5	8.5	14.1	0.7	40.9	14.6	2.4	0.8	7.8
R17-84 NX 0006 5377	15.0	4.0	14.3	4.5	1.0	28.8	7.6	3.3	1.4	20.1
R11-84 NX 0020 5358	7.5	4.5	8.5	24.1	0.3	34.9	7.0	0.5	1.1	11.6
R3-83 NX 0043 5329	12.4	4.2	13.0	0.5	1.2	17.6	2.3	7.6	2.4	38.8
R7-84 NX 0056 5295	15.1	3.8	16.9	0.6	0.5	28.6	4.5	5.1	2.2	22.7
R8-84 NX 0058 5291	13.1	2.7	8.4	6.2	0.1	42.8	6.5	2.0	1.4	16.6
R5-83 NX 0063 5286	15.3	4.5	12.1	1.1	1.3	22.2	2.1	6.0	2.2	33.2
R12-84 NX 0082 5270	13.9	2.8	17.8	1.2	0.5	30.2	3.8	5.8	2.6	21.4
R9-84 NX 0098 5277	11.3	3.8	15.7	0.7	4.1	20.0	2.5	6.7	1.6	33.6

Portpatrick Formation, Basic-clast Division

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R5b-84 NW 9822 5608	22.2	15.3	7.2	1.5	10.2	15.5	4.4	3.4	1.7	18.3
R5c-84 NW 9822 5608	23.3	14.2	10.4	1.9	8.9	11.6	2.7	6.6	2.6	17.8
R6-84 NW 9820 5604	7.8	0.6	11.9	3.1	0.7	41.1	0.9	3.6	2.8	27.5
R1-84 NW 9820 5604	7.5	0.6	9.3	3.6	0.2	36.7	3.2	6.8	2.5	29.6
R2-84 NW 9820 5601	5.6	0.6	7.9	4.6	0.3	45.4	6.2	6.3	1.6	21.5
R95-S-84 NW 9846 5569	9.4	1.2	12.7	1.7	1.0	21.0	0.5	6.0	2.3	44.2
R94-S-84 NW 9849 5565	34.2	9.2	8.9	1.6	8.4	2.6	1.1	10.9	2.8	20.3
R92-S-84 NW 9849 5565	4.2	0.9	4.4	13.1	0.3	55.1	0.3	2.2	2.6	16.9
R3-84 NW 9850 5563	4.8	3.8	8.6	11.3	0.1	43.9	6.3	4.8	1.4	15.0
R86-S-84 NW 9850 5554	6.5	1.9	8.6	8.3	0.6	35.6	2.6.	6.5	0.9	28.5
R85-S-84 NW 9848 5552	16.3	13.8	16.7	1.6	6.2	7.4	1.7	8.6	2.7	25.0
R84-S-84 NW 9848 5552	8.2	3.1	10.7	2.6	0.9	31.7	0.4	8.6	1.1	32.7
R83-S-84 NW 9848 5552	28.3	18.6	8.8	0.3	11.2	5.1	1.3	5.5	1.3	19.6
R7-83 Nw 9853 5548	14.4	6.7	11.2	1.9	3.0	16.2	1.7	5.2	3.1	36.6
R4-84 NW 9879 5513	4.2	2.1	11.4	1.0	1.6	35.8	1.6	10.2	1.4	30.7
R12-83 NX 1095 5220	4.4	0.5	8.1	6.7	0.7	40.4	2.0	7.0	3.2	27.0

Portayew Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
Z32 NX 0206 5194	16.9	5.7	17.1	1.6	2.6	17.9	6.1	3.1	1.1	27.1
Z261 NX 0208 5177	27.8	5.3	17.4	3.7	3.0	9.0	1.7	3.9	3.2	25.0
R16-83 NX 0217 5164	17.2	2.1	15.8	1.0	1.8	14.2	0.5	5.1	3.4	38.9
e1 NX 0252 5111	11.5	5.8	8.9	6.6	3.8	34.2	8.2	3.0	1.6	16.4
R19-83 NX 0263 5100	21.3	5.3	11.8	1.1	4.2	10.2	1.8	6.6	3.3	34.4

Money Head Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R376-S-84 NX 0456 4875	22.4	9.4	17.8	2.6	3.0	17.8	2.8	2.2	2.4	19.6
R373-S-84 NX 0450 4856	23.5	7.8	19.0	0.7	1.7	18.5	0.5	2.8	1.0	24.5
R369-S-84 NX 0449 4847	24.3	6.9	13.4	0.6	1.7	17.0	3.0	3.0	1.6	28.5
R367-S-84 NX 0449 4841	21.7	4.2	16.7	1.8	1.8	24.4	2.2	2.6	2.4	22.2
R364-S-84 NX 0451 4839	24.8	8.9	9.7	1.7	1.4	19.5	1.8	2.6	2.1	27.5
R366-S-84 NX 0451 4839	18.7	4.5	20.2	1.7	2.9	25.5	2.2	5.4	1.8	17.1
R363-S-84 NX 0458 4834	29.8	3.9	10.8	0.3	0.7	18.3	2.1	2.7	1.8	29.6
R362-S-84 NX 0464 4828	16.3	3.8	16.0	0.2	5.0	22.8	2.0	7.3	2.1	24.5
R361-S-84 NX 0467 4824	18.0	9.4	19.8	2.2	3.2	21.9	1.1	3.3	0.8	19.6
R360-S-84 NX 0484 4834	25.5	6.5	14.2	1.2	4.6	24.2	2.2	4.4	1.7	15.5
R359-S-84 NX 0484 4832	20.7	7.2	15.4	0.4	4.6	17.8	0.4	3.4	2.0	28.1
R357-S-84 NX 0488 4828	22.5	6.2	16.6	0.5	5.4	15.4	2.1	2.8	1.8	26.7
R354-S-84 NX 0488 4826	22.3	4.2	14.7	0.6	4.2	15.6	0.2	3.9	2.1	33.2
R355-S-84 NX 0488 4826	22.1	10.2	11.1	2.1	4.0	20.2	2.0	3.1	2.1	23.1
R353-S-84 NX 0489 4826	22.0	7.7	15.9	0.5	2.9	21.5	1.3	2.0	2.1	24.1
R349-S-84 NX 0489 4823	19.8	5.6	14.5	0.3	2.8	17.4	0.6	3.0	3.0	33.0
R348-5-84 NX 0491 4825	19.0	8.6	11.7	0.9	2.5	23.5	0.2	2.4	2.0	27.4
R347-S-84 NX 0498 4821	24.4	4.2	10.3	1.3	4.0	10.9	0.4	3.1	2.0	39.4

Float Bay Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R294-S-84 NX 0635 4705	18.3	9. 5	13.4	8.1	6.8	13.1	4.0	2.1	1.3	23.4
R284-S-84 NX 0649 4682	23.4	8.3	15.9	3.8	4.4	5.8	4.8	1.1	3.1	29.4
R277-S-84 NX 0656 4674	21.8	7.5	19.0	5.2	5.0	9.9	3.4	2.5	0.3	25.4
R272-S-84 NX 0671 4659	22.6	12.1	10.7	2.4	5.9	7.5	1.9	4.8	3.2	28.9
R266-S-84 NX 0669 4650	26.2	10.5	11.8	5.0	4.0	12.6	2.3	2.3	2.2	23.1
R265-S-84 NX 0670 4644	28.6	5.5	15.4	3.4	3.5	9.6	2.0	6.1	2.3	23.6
R32-83 NX 0673 4639	20.0	7.2	7.2	6.2	6.7	22.9	4.2	3.8	4.6	17.3
R260-S-84 NX 0682 4632	29.4	6.0	15.3	3.5	4.1	7.2	2.3	6.0	1.8	24.4

Stinking Bight Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R30-83 NX 0710 4604	24.1	8.4	17.6	9.4	6.1	15.6	3.8	1.0	1.4	12.6
R401-S-84 NX 0706 4601	47.2	3.7	10.5	2.8	3.1	16.0	0.9	1.5	0.4	13.9
R389-5-84 NX 0705 4584	44.1	2.5	10.4	0.5	1.1	11.0.	0.4	5.5	2.8	21.5
R253-S-84 NX 0710 4538	45.5	4.4	8.7	0.4	1.6	14.4	0.5	1.2	1.2	22.1
R129-S-84 NX 0669 4493	29.1	7.0	9.4	4.7	4.6	17.2	2.1	5.3	1.4	19.2

Grennan Point Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R218-S-84 NX 0750 4377	31.6	6.4	11.5	0.7	3.0	11.2	0.5	5.4	1.8	27.9
R223-S-84 NX 0767 4374	28.6	10.4	11.1	1.1	5.9	8.0	1.7	4.1	3.5	25.1

Mull of Logan Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R325-S-84 NX 0776 4333	26.1	3.1	17.1	0.6	3.6	22.7	0.8	4.4	3.5	18.1
R160-S-84 NX 0756 4255	21.0	7.9	17.3	2.9	2.7	17.1	1.5	3.8	1.6	24.2
R519-S-84 NX 0757 4254	10.4	2.7	14.4	28.4	1.3	5.7	0.6	1.0	0.0	35.5
R158-5-84(c) NX 0757 4254	20.4	7.0	11.0	4.2	2.6	15.7	0.4	3.7	1.9	33.1
R156-5-84(c) NX 0757 4250	28.1	3.0	13.0	1.9	4.7	15.8	1.4	6.5	1.6	24.0
R157-S-84 NX 0756 4248	17.2	7.3	8.0	26.6	2.8	7.5	1.1	1.6	1.2	26.7
R155-S-84 NX 0759 4245	14.2	2.5	13.7	0.5	5.7	27.7	3.0	5.3	9.2	18.2
R153-S-84 NX 0756 4234	15.2	8.8	22.7	17.9	1.8	14.8	6.9	2.4	0.8	8.7
R152-S-84 NX 0756 4234	18.2	6.9	22.6	6.7	2.0	19.7	7.1	3.2	1.4	12.2
R150-S-84(c) NX 0755 4229	14.2	3.7	18.5	2.8	1.0	27.2	5.7	2.8	1.1	23.0
R149-S-84 NX 0755 4229	19.5	4.8	17.8	8.7	4.4	21.7	3.1	5.7	0.9	13.4
R148-S-84 NX 0755 4229	18.5	4.2	17.8	12.3	3.5	21.0	0.7	4.0	1.0	17.0
R147-S-84 NX 0755 4229	15.8	6.8	20.9	1.2	2.1	23.4	4.0	4.8	0.8	20.2
R146-5-84 NX 0755 4229	17.9	9.3	20.2	8.5	2.3	18.9	3.9	2.1	3.5	13.4
R145-S-84 NX 0757 4227	10.5	4.8	23.3	8.7	4.4	24.7	6.6	2.1	1.4	13.5
R182-S-84 NX 0752 4222	16.7	6.1	13.9	14.2	2.4	12.9	1.0	2.3	0.3	30.1

/Mull of Logan Fm. cont'd.....

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R176-S-84 NX 0745 4212	15.6	10.7	17.4	16.2	1.8	14.9	4.8	1.4	1.4	15.8
R199-S-84 NX 0855 4456	41.5	4.5	11.2	1.1	0.4	11.2	0.3	3.7	0.5	25.6

(c) sampled clasts from Duniehinnie Member

Port Logan and Clanyard Bay Formations

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
R411-5-84 NX 0904 3987	48.0	3.6	5.7	1.5	8.5	8.0	1.1	2.8	1.2	19.6
R237-S-84 NX 0931 3966	48.9	6.8	10.8	1.2	2.4	3.8	0.4	3.2	0.5	22.0
R234-S-84 NX 0945 3927	44.9	7.2	12.3	0.7	6.2	5.2	0.9	6.0	1.7	14.9
R233-S-84 NX 0944 3899	34.3	6.1	7.5	0.4	6.7	2.0	0.1	10.4	2.5	30.0
R245-S-84 NX 0954 3863	39.2	8.1	6.8	1.5	8.0	1.8	1.2	5.7	1.7	26.0

LITTLE LARG (NX 1612 6612) TO PORT WILLIAM (NX 3370 4355)

Glenwhan Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
GL55-S-85 NX 1792 6223	5.7	0.8	13.4	2.4	1.7	33.5	1.9	10.2	1.5	28.9
GL56-S-85 NX 1792 6231	5.0	1.1	9.1	1.5	2.6	38.7	0.5	9.5	0.7	31.3
GL57-S-85 NX 1816 6212	7.8	23.0	10.9	1.8	3.1	33.1	1.2	12.1	1.4	26.6
GL58-S-85 NX 1808 6245	10.0	2.2	11.8	0.2	1.4	17.8	1.4	18.8	2.4	34.0
GL59-5-85 NX 1822 6251	8.4	1.7	10.8	0.2	2.1	37.5	0.9	5.6	1.1	31.7
GL60-S-85 NX 1844 6259	11.1	2.2	13.1	1.7	3.5	24.4	1.1	6.7	1.3	34.9
GL61-S-85 NX 1844 6259	8.3	1.7	10.9	0.5	3.0	33.7	1.6	11.0	0.8	28.5
GL62-S-85 NX 1837 6241	7.6	2.4	12.4	0.4	1.8	33.6	0.8	9.0	1.9	30.1
GL63-S-85 NX 1842 6260	8.0	2.4	9.4	4.2	3.1	26.8	1.7	10.5	1.6	32.3
GL65-S-85 NX 1843 6270	6.4	2.4	9.5	4.4	1.9	32.6	0.9	7.9	1.2	32.8

Killfillan -A Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
GL47-S-85 NX 2017 5431	28.7	5.1	13.5	1.3	3.8	7.2	1.5	4.1	3.9	30.9
GL48-S-85 NX 2017 5431	26.0	7.7	17.9	2.1	4.0	11.1	1.2	4.0	2.2	23.8
GL46-S-85 NX 2017 5430	25.3	4.8	11.9	1.5	7.0	9.1	2.0	5.6	2.6	30.2
GL52-S-85 NX 2025 5431	22.9	5.2	14.2	0.7	7.1	8.6	0.4	10.0	2.4	28.5
GL53-S-85 NX 2025 5431	26.4	4.1	14.8	1.3	2.2	10.6	1.4	5.7	2.4	31.1
GL54-S-85 NX 2025 5431	28.0	4.4	16.0	0.6	4.9	9.9	1.5	4.9	3.0	26.0
GL45-S-85 NX 2016 5422	26.7	7.1	9.9	5.0	4.4	17.0	2.8	4.0	2.1	21.0
GL44-S-85 NX 2022 5412	23.5	4.4	9.9	1.6	6.3	7.4	1.4	7.8	3.9	33.8
GL43-S-85 NX 2025 5407	21.8	5.7	11.5	3.2	3.9	9.5	1.2	5.7	2.4	35.1
GL42-S-85 NX 2027 5405	27.5	8.5	14.3	4.3	3.3	13.4	1.9	4.6	1.6	20.6
GL40-S-85 NX 2032 5403	27.2	3.0	11.0	2.2	4.8	87.6	0.2	3.2	2.0	38.2
GL6-5-85 NX 2058 5386	23.2	6.8	17.2	6.0	2.2	15.6	0.8	2.6	2.2	23.4

Kilfillan -B Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
GL9-S-85 NX 2085 5363	23.4	6.2	11.6	2.8	3.4	12.6	0.2	8.0	3.2	28.6
GL50-S-85 NX 2263 5156	27.6	7.8	10.7	2.6	5.5	9.7	0.7	6.6	2.6	26.2
GL51-S-85 NX 2273 5157	22.0	9.7	12.9	1.3	5.6	6.4	0.6	8.7	2.7	30.1
GL49-S-85 NX 2275 5154	25.6	5.8	15.0	1.7	7.3	13.2	0.7	6.1	2.1	22.5
GL130-S-85 NX 2559 5426	23.8	3.0	12.0	2.4	4.4	12.4	1.0	8.0	3.6	29.4
GL128-S-85 NX 2580 5417	28.8	10.2	13.3	2.8	3.8	10.6	2.6	4.2	2.0	21.2
GL137-S-85 NX 2610 5417	27.6	5.2	15.8	2.0	6.6	7.8	0.6	7.4	4.8	22.2
GL135-S-85 NX 2618 5419	22.6	6.0	15.2	2.4	2.6	8.4	0.8	11.0	2.2	28.8
GL138-S-85 NX 2622 5413	20.2	6.8	13.0	2.0	3.4	13.2	0.8	4.2	3.8	32.6

GL9/50/51/49-S-85 are from coastal section.

GL130/128/137/135/138-S-85 are from inland section.

Garheugh -A Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
GL136-S-85 NX 2620 5401	17.6	5.8	21.6	1.8	5.8	9.2	2.4	2.6	3.8	29.4
GL160-S-85 NX 2593 5343	28.1	6.1	15.7	3.7	6.4	10.2	3.6	2.0	3.0	21.2
GL154-S-85 NX 2581 5214	32.9	7.6	10.6	2.4	3.3	7.2	2.2	4.5	1.7	27.6
GL153-S-85 NX 2577 5217	29.4	3.7	13.7	0.8	6.3	8.7	2.7	6.0	1.3	27.4
GL147-S-85 NX 2576 5180	31.8	6.4	17.7	2.5	4.4	10.7	2.5	3.7	1.9	18.5
GL146-S-85 NX 2583 5171	35.0	4.8	11.1	0.8	4.7	9.5	1.8	4.8	1.9	25.6
GL30-S-85 NX 2630 5186	25.6	6.8	14.2	6.0	3.6	8.8	1.2	4.8	1.2	27.8
GL29-S-85 NX 2627 5184	22.8	4.2	11.2	6.2	8.8	9.0	2.8	3.4	4.2	27.4
GL144-S-85 NX 2602 5158	31.9	1.7	13.9	0.4	4.4	9.0	2.2	7.6	1.9	27.0
GL27-S-85 NX 2632 5171	24.8	5.4	10.6	3.2	3.0	13.0	3.6	4.8	2.8	28.8
GL141-S-85 NX 2601 5145	31.1	8.7	14.3	1.3	3.5	12.1	17.1	1.9	2.1	23.3
GL142-S-85 NX 2601 5145	29.0	8.3	13.6	5.3	4.4	11.4	1.4	1.4	2.6	22.6
GL26-S-85 NX 2650 5148	23.7	3.6	14.5	5.2	5.9	6.3	1.8	5.8	2.0	31.2
GL15-E-85 NX 2594 5112	19.4	2.8	7.2	2.2	4.6	7.8	1.0	9.0	2.6	43.4

Garheugh -B Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
GL14-E-85 NX2614 5101	21.1	5.8	17.3	4.7	6.2	6.8	1.3	4.9	1.0	30.9
GL24-S-85 NX 2668 5094	26.8	3.6	9.2	1.6	6.2	7.6	0.8	4.8	1.2	38.2
GL23-S-85 NX 2652 5080	25.0	6.8	14.2	1.6	5.8	7.6	2.6	2.6	1.7	32.1
GL22-S-85 NX 2681 5085	21.1	3.5	10.8	6.0	8.9	11.9	2.0	1.8	2.0	32.0
GL7-E-85 NX 2652 5049	23.4	5.1	9.8	1.5	4.1	11.6	3.1	7.8	2.1	31.5
GL1-E-85 NX 2654 5040	30.8	3.6	9.8	1.4	3.5	8.1	1.7	6.7	2.8	31.6
GL20-S-85 NX 2687 5058	26.2	5.4	8.2	1.1	7.1	11.0	2.0	2.3	2.1	34.6
GL70-S-85 NX 2668 5023	21.3	9.9	7.3	6.0	6.9	14.3	5.9	2.7	0.4	25.3
GL18-S-85 NX 2684 5037	25.4	5.9	15.5	2.0	4.7	19.1	1.4	4.7	3.9	17.4
GL66-S-85 NX 2678 5017	23.4	4.0	12.8	1.1	7.7	4.6	1.0	12.7	1.9	30.8
GL17-S-85 NX 2716 5020	26.2	6.5	12.2	2.4	4.7	19.8	3.0	6.1	1.6	20.2

Corwall Formation

Sample No./ Grid Ref.	Qm	Qp	F	Ls	Lm	Lv	Li	Hm	Mis	M
GL82-S-85 NX 2970 5088	18.5	7.4	20.4	1.5	3.4	18.3	0.7	3.8	2.8	23.2
GL76-S-85 NX 2928 4997	25.6	3.4	22.2	0.4	0.9	6.0	0.7	9.8	5.6	25.3
GL91-S-85 NX 2905 4978	15.4	1.8	11.5	3.8	1.2	18.0	1.6	4.0	0.5	42.2
GL86-S-85 NX 2914 4984	21.9	5.0	11.3	0.7	3.2	19.7	3.8	5.8	1.7	26.9
GL74-S-85 NX 2925 4987	14.8	8.1	20.2	0.4	0.9	16.7	1.7	2.5	7.0	32.7
GL73-S-85 NX 2927 4989	20.1	10.0	17.0	7.4	2.0	14.8	2.8	5.0	11.0	19.8

APPENDIX 3

PALAEOCURRENT DATA

Palaeocurrent data collected during this study are presented in this Appendix.

The following abbreviations are used:

(1) Fl; Flute cast

(2) G; Groove

(3) LR; Longitudinal ridges and furrows

(4) R; Ripples

Portpatrick Formation, Acid-clast Division

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0080 5270	Fl	72°W	to E	032/44NW	NW
NX 0062 5292	Fl	34°W	to E	039/88NW	NW
	Fl	38°W	to E	026/57NW	NW
	G	30°W,26°W	-	"	NW
	G	32°W,29°W	-	"	NW
NX 0067 5279	G	Plunge to 036°	-	037/22SE	SE
NX 0040 5338	G	11°E,19°E	-	032/83NW	NW
NX 0092 5271	G	25°W	-	050/90	NW
	Fl	15°W to E		"	NW
NX 0003 5334	G	70°W,45°W	-	040/85N	NW
	Fl	35°W	to E	"	NW
	G	50°E	-	040/75SE	SE
NX 0057 5296	R	55°W	to E	040/40SE	SE
NX 0050 5303	F	85°E	to N	035/85SE	SE
NX 0010 5265	G	5°E	-	050%80NW	NW
	Fl	30°W	to E	050/75NW	NW

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NW 9852 5549	G	30°E	-	072/76S	N
to	G	20°E	-	"	N
NW 9842 5620	Fl	41°E	-	079/87N	N
	G	46°E	-	"	N
	G	34°E	-	077/75S	N
	G	60°W	-	088/82N	N
	Fl	89°W	to W	080/85N	N
	G	25°E	-	"	N
	Fl	35°E	to E	"	N
	Fl	55°	to E	"	N
NW 9860 5538	G	55°E,45°E	-	070/70S	N
	Fl	50°E	-	"	N
NW 9837 5586	Fl	5°E	to E	073/90	N
NX 0195 5218	G	8°W,48°W	-	057/85S	NW
	Fl	18°W	to E	"	NW
	G	80°E	-	060/85N	NW
	G	47°W,70°W	-	055/90	NW
	Fl	80°E	to E	"	NW

Portpatrick Formation, Basic-clast Division

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NW 9810 5672	G	58°W	-	085/77°S	N
NW 9810 5669	Fl	20°E,30°E, 40°E	to E	083/64°S	N
NW 9812 5679	Fl	71°W	to E	086/77°S	N
NW 9852 5549	G	68°W	-	067/88°S	NW
		83°E	?	"	NW
NW 9821 5608	R	30°W	-	085/63S	N
NW 9802 5647	R	10°W	-	078/78S	N
	R	8°W	-	"	N
	G	20°E	-	"	N
	G	35°E	-	"	N
	G	40°E	-	"	N
NW 9821 5600	G	63°E	-	088/80S	N
	G	16°E	-	"	N
NW 9845 5585	G	7°E	-	083/85S	N
	G	6°E	-	"	N
NW 9824 5617	G	50°E	-	085/90	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NW 9820 5604	G	38°E,46°E	-	090/79S	N
NW 9821 5606	G	44°,72°E, 12°E,62°E	-	09079S	N
	Fl	62°E	to E	090/70S	N
NN 9809 5631	P	82°W	to W	085/77S	N
	G	47°E	-	"	N
to	G	83°E	-	084/66°S	N
NW 9911 5674	G	71°E	-	"	N
	G	44°E	-	088/75S	N
	G	14°E	-	"	N
	Fl	14°E,44°E	to E	"	N
	G	17°E	-	"	N
	G	28°E,51°W	-	084/80S	N
	G	19°W,8°E	-	082/84S	N
	Fl	28°E	to E	"	N
	G	10°E,40°E	-	090/69-S	N
	G	9°E,26°E	-	"	N
	G	9°W	-	"	N
	Fl	9°W	to E	"	N
	Fl	23°E	to E	090/64S	N
	G	34°E,21°E	-	"	N
	G	50°W,90°, 62°W	-	087/82S	N
	G	50°E	-	092/80S	N

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
	G	55°W	-	055/78S	N
	G	46°E	-	075/75S	N
	G	52°W	-	090/66S	N
	Fl	7°E	to E	086/70S	N
	G	4°W,20°E	-	"	N
	G	69°E	-	"	N
	Fl	35°E	to E	"	N
	Fl	20°E,22°E	to E	086/69S	N
	G	30°E	-	"	N
	G	20°E	-	088/68S	N
	Fl	33°E	to E	090/70S	N
	G	40°	-	083/64S	N
	G	83°W	-	085/62S	N
	G	33°E,38°	-	104/70S	N
	G	17°E	-	087/82S	N
	G	72°E,24°E	-	081/80S	N
	G	67°E	-	081/79S	N
	G	42°E	-	082/73S	N
	Fl	3°W	to E	083/76S	N
	Gr	12°W,52°E	-	"	N
	Fl	85°E	?	080/90	N
	Gr	40°E,65°E	-	095/80S	N
	Fl	10°W	to E	"	N
	Gr	35°W	-	090/80S	N
	Fl	0°	to E	"	N

Portayew Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0254 5160	Fl	67°E	to E	055/65N	N
NX 0299 5079	Gr	80°E	-	045/85N	N
	Gr	72°E,81°E	-	"	N
	Fl	89°E,81°E	-	"	N
	Fl	76°E	to E	"	N
	Fl	89°W	to W	"	N
	R	41°E	-	"	N

Money Head Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0460 4895	G	50°E	-	065/72N	N
NX 0460 4884	G	67°E	-	065/44N	N
NX 0456 4874	G	12°E	-	078/37N	N
NX 0449 4859	G	23°E	-	053/73N	N
NX 0452 4856	Fl	23°W,38°W	to W	072/67N	N
	Fl	32°W,30°W	to W	"	N
NX 0485 4833	Fl	8°W,6°W,1°W	to W	061/72N	N
NX 0466 4828	Fl	23°E	to W	058/62N	N
NX 0449 4859	G	25°E	-	053/73N	N
to	Fl	12°W	to W	"	N
NX 0452 4856	G	28°E	-	"	N
NX 0484 4832	Fl	16°W,12°W	to W	064/68N	N
	LR	14°E,48°W	-	058/59N	N
	G	76°E	-	062/70N	N
NX 0500 4820	G	20°E,52°E	-	064/59N	N
to	G	28°E	-	"	N
NX 0489 4829	G	10°E,20°E,60°W	-	"	N

Float Bay Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0684 4627	Fl	47°	to W	048/79S	S
NX 0669 4640	G	2°W,28°E	-	055/79N	N
	G	30°W	-	"	N
	LR	1°E	-	"	N
NX 0639 4715	G	46°E,48°E	-	038/68S	N
	G	45°E,36°E	-	"	N
NX 0640 4696	G	25°E,35°E	-	052/74S	N
	G	14°E	-	050/59S	N
	G	50°W,60°E	_	052/74S	N
NX 0639 4733	G	68°W	-	042/59N	N
	LR	68°W	-		
NX 0617 4720	G	14°E	-	050/85S	N
NX 0617 4722	G	12°E,8°E	-	050/85S	N
NX 0633 4704	G	25°E	-	041/66S	N
NX 0634 4729	G	82°W	-	077/86N	N

/ cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0523 4812	G	75°E	-	035/72S	N
	G	45°W	-	064/64S	N
to	G	47°W	-	071/83S	N
NX 0680 4634	G	88°E	-	033/83S	S
	G	15°E	-	045/51S	N
	G	20°E	-	051/75S	N
	G	31°W	-	"	N
	G	40°W	-	060/80S	N
	G	23°E	-	046/78S	N

Stinking Bight Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0716 4554	LR	3°N	-	036/72S	N
	G	40°E	-	"	N
	G	3°E	-	060/70S	N
NX 0714 4579	G	7°E	-	054/45S	N
NX 0715 4579	Fl(?)	26°E	to E	055/78S	N
	G	14°°E	-	"	N
NX 0668 4499	G	8°E	-	028/08S	N
NX 0667 4491	G	20°E	-	064/14S	N
NX 0664 4483	Fl	6°W	to W	046/55S	N
	Fl	12°W	to W	"	N
NX 0678 4467	G	0°,8°W	-	040/43S	N
	Fl	6°W	to W	"	N
NX 0678 4461	G	11°E,16°E 27°E	-	049/48S	N
NX 0667 4487	G	11°W	-	038/32S	N
	G	15°E	-	050/25S	N
	Fl	21°E	to W	057/27S	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
	Fl	13°E	to W	038/28S	N
	G	25°E	-	041/54S	N
	G	60°E	-	053/20S	N
	G	16°E	-	063/21S	N
	G	33°E	-	049/17S	N
	Fl	24°E	to W	056/23S	N
NX 0667 4491	G	23°E	-	064/14S	N

Grennan Point Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0748 4368	G	18°E	-	064/58S	N
	G	1°E	-	067/69S	N
to					
	G	15°E	-	063/58S	N
NX 0746 4371					
NX 0763 4367	G	6°W	-	066/82S	N
to	G	55°E,15°E, 41°W	-	064/79S	N
NX 0661 4370	Fl	23°W	to W	064/82S	N
	Fl	39°E	to W	060/76S	N
	Fl	25°E	to W	063/75S	N
	Fl	31°E	to W	064/71S	N
	G	26°E	-	"	N
	G	22°E	-	060/84S	N
	G	28°E	-	060/75S	N
	G	76°E	-	061/76S	N
	Fl	29°E	to W	061/77S	N
	Fl	28°E	to W	063/80S	N
	G	49°E	-	"	N
	G	79°E	-	064/83S	N
	G	85°E	-	061/85S	N
NX 0669 4373	G	3°E	-	054/82S	N
	G	27°E	-	054/68S	N
	Fl	39°E	to W	055/72S	N
	Fl	30°E	to W	056/73S	N
	Fl	36°E	to W	058/77S	N

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0767 4361	G	15°W	-	056/73S	N
	G	39°E	-	061/80S	N
to	G	38°E	-	041/78S	N
NX 0685 4450	G	43°E	to W	"	N
	Fl	48°E	to W	051/78S	N
	Fl	30°E	to W	061/68S	N
	G	31°E	-	"	N
	R	12°E	to W	075/73S	N
	Fl	1°W	to W	055/69S	N

Mull of Logan Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0760 4261	G	78°W	-	058/63S	N
	G	35°E	-	064/69S	N
to					
	G	83°W	-	045/65S	N
NX 0779 4350					
NX 0763 4307	G	10°E	-	065/75S	S
NX 0743 to NX 0760 4261	R	69°E	-	037/89S	N
NX 0747 4193	G	35°W	-	083/63S	N
NX 0843 4165	G	22°E	-	043/80S	N
	Fl	62°E	to W	080/72S	S
	Fl	38°E	to E	"	S
	Fl	55°W	to W	"	S
NX 0825 4169	G	58°E,29°W	-	043/60S	N
	Fl	38°W	to W	"	N
	G	22°W	-	"	N
NX 0941 4125	G	67°E	-	047/72S	S
	G	62°E	-	040/61S	S
to					
	Fl	60°W	to W	"	S
NX 0817 4171	R	35°W	-	044(65S	N
	G	1°E	-	"	N

Port Logan Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0950 4060	G	58°W	-	148/33N	N
	R	37°W	-	038/82N	S
to	G	18°E	-	079/83N	N
NX 0956 3870	R	46°E	-	100/49N	N
	G	6°W	-	067/79N	N
NX 0948 3929	G	21°E	-	071/76S	N
	G	77°E,8°W	-	077/80S	N
	G	62°E	-	090/92N	N
NX 0922 4032	G	59°E	-	096/41N	N
	R	9°W,40°E	-	"	N
	G	65°E	-	103/41N	N
	LR	58°E	-	100/41N	N
	R	11°W	-	"	N
	G	34°W	-	106/52N	N
	G	62°E	-	097/52N	N
	G	81°E	-	093/46N	N
	G	55°E	-	103/44N	N
	Fl	71°E,81°E	to W	103/42N	N
	G	67°E	-	092/33N	N
	R	28°E	-	"	N
	G	72°E	-	102/60N	N
	R	30°E	-	091/49N	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0910 4016	G	011°	-	084/57N	N
	G	335°	-	084/57N	N
to	G	005°	-	090/48N	N
NX 0914 4021	LR	349°	-	"	N
	R	306°	-	090/48N	N
	R	6°W,1°W	-	"	N
	G	005°	-	119/46N	N
	R	16°E	-	104/39N	N
	G	015°	-	"	N
	G	016°	-	"	N
	G	013°	-	"	N
	Fl	028	up plunge	"	N
	LR	017°	-	"	N

Clanyard Bay Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 0957 3875	G	12°	-	081/76N	N
	G	58°E	-	082/76N	N
to	G	56°W	-	076/56N	S
NX 1000 3814	LR	50°E	-	084/72N	S
	Fl	41°E,46°E	to E	"	S

Kilfillan -A Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2025 5406	G	20°W	-	059/87N	N
	Fl	26°W	to W	"	N
NX 2021 5412	G	23°W	-	063/83S	N
	G	14°W	-	"	N
NX 2033 5402	G	60°E	-	075/82N	N
NX 2027 5433	G	45°W	-	078/85S	N
	G	35°W	-	"	N
	G	42°W	-	"	N
NX 2015 5437	G	6°E	-	066/85N	N
	G	12°W	-	073/88S	N
to	G	46°W	-	075/82S	N
NX 2067 5382	G	30°W	-	"	N
	Fl	24°W	to W	073/82S	N
	G	23°W	-	067/83S	N
	G	20°W	-	070/80S	N
	G	20°W	-	073/82N	N
	G	32°W	-	080/80S	N
	G	34°W	-	073/86S	N
	G	80°E	-	024/32S	N

Kilfillan -B Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2080 5375 to NX 2282 5155	G	22°W	-	076/84N	N
	G	2°W	-	091/60S	N
	G	25°W	-	"	N
	G	12°W	-	086/72S	N
	Fl	12°W	to W	078/65S	N
	LR	3°W	-	"	M
	LR	8°E	-	"	N
	LR	61°E	-	080/81S	N
	G	36°E	-	"	N
	LR	56°E	-	083/58S	N
	LR	86°E	-	076/67S	N
	Fl	14°E	to W	080/60S	N
	LR	8°E	-	101/78S	N
	LR	3°E	-	099/58S	N
	LR	8°E	-	098/62S	N
	R	12°W	to W	076/54S	S
	F	24°W	to W	076/34S	S
	LR	84°W	-	096/69S	S
	LR	64°W	-	069/53S	S
	LR	75°E	-	067/27S	N
	F	63°E	to W	075/36S	N
	G	52°E	-	"	N
	G	3°W	-	074/71S	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2124 5247	LR	20°E	-	086/76S	N
	LR	22°E	-	098/72S	N
	LR	12°W	-	"	N
NX 2126 5245	LR	21°W	-	094/66S	N
	LR	6°W	-	"	N
	LR	0°	-	098/69S	N
	LR	1°E	-	"	N
	G	12°W	-	"	N
	LR	17°W	-	"	N
	LR	17°W	-	"	N
NX 2144 5224	G	44°E	-	086/70S	N
	LR	27°E	-	"	N
	LR	10°E	-	"	N
	LR	24°E	-	"	N
NX 2131 5238	LR	2°W	-	092/66S	N
	G	64°E	-	"	N
	LR	4°W	-	092/64S	N
	LR	26°W	-	"	N
	Fl	46°E	to W	094/58S	N
	LR	5°E	-	102/62S	N
	Fl	20°E	to W	104/61S	N
	LR	18°E	-	104/62S	N
	G	53°E	-	098/67S	N
	LR	24°E	-	100/70S	N
	LR	24°E	-		N

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2136 5233	G	30°E,1°E	-	089/58S	N
	G	31°E,15°E	-	"	N
	G	29°E	-	"	N
NX 2137 5232	G	3°E	-	086/71S	N
	G	6°E	-	"	N
NX 2144 5224	G	53°W	-	082/40S	S
	G	65°W	-	078/36S	S
	G	76°W	-	080/32S	S
	Fl	68°W	to W	"	S
	R	38°W	-	"	S
	R	52°W	-	"	S
NX 2167 5212	G	14°W	-	074/84N	N
	G	12°E	-	"	N
	G	22°E	-	"	N
	LR	9°W	-	086/67N	N
	LR	10°W	-	090/84N	N
	Fl	14°E	to W	082/80N	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
	G	24°E	-	082/80N	N
	G	13°W	-	"	N
	LR	13°E,20°E	-	"	N
	G	69°E	-	"	N
	LR	36°E	-	"	N
	G	44°E	-	081/86N	N
	LR	34°E	-	"	N
NX 2145 5224	LR	56°W	-	071/43S	S
	G	30°W	-	060/44S	S
	LR	63°W	-	072/46S	S
	LR	43°W	-	"	S
	LR	80°E	-	024/32SE	N

Garheugh -A Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2594 5113	G	33°E	-	045/58S	N
	Fl	8°E	to W	047/51S	N
to	G	44°W	-	045/58S	N
NX 2589 5114	G	11°E	-	060/52S	N
NX 2628 5184	G	30°W	-	060/63S	S
	G	10°E	-	067/66S	S
NX 2579 5251	G	12°E	-	068/90S	N

Garheugh -B Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2656 5040	G	6°E	-	056/74S	N
NX 2657 5041	G	8°E	-	061/80S	N
	G	6°W	-	066/84S	N
NX 2656 5042	G 9	38°E	-	068/82S	N
	G	8°W	-	065/75S	N
NX 2645 5048	G	45°W	-	068/79S	N
NX 2648 5050	G	10°W	-	065/78S	N
NX 2645 5052	G	3°E	-	068/85S	N
NX 2658 5046	G	8°E	-	068/74S	N
NX 2655 5047	G	11°E	-	067/88S	N
NX 2654 5048	G	15°E	-	063/82S	N
NX 2653 5050	G	46°W	-	064/76S	N
	G	6°W	-	"	N
NX 2651 5052	F	4°E	to W	068/68S	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2649 5054	G	15°W	-	065/83S	N
NX 2648 5054	G	9°W	-	068/86S	N
NX 2646 5060	G	9°E	-	060/45S	S
NX 2636 5075	G	078°	-	168/18E	E
NX 2635 5076	G	046°	-	044/33S	S
NX 2629 5083	G	9°E	-	055/68S	N
NX 2612 5000	G	10°E	-	062/73S	N
NX 2658 5031	G	1°W	-	054/87S	N
NX 2656 5036	Fl	22°E	to W	054/87S	N
NX 2661 5027	Fl	20°E	to W	058/76S	N
NX 2663 5028	Fl	20°E	to W	063/75S	N
	G	26°E, 5°E, 20°E	-	"	N
NX 2670 5020	G	39°E	-	063/75S	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2689 5010	G	16°E,1°W	-	058/69S	N
NX 2687 5012	G	11°-E,5°-W	-	058/69S	N
NX 2690 5009	G	28°E	-	055/66S	N
NX 2694 5007	G	10°W	-	055/66S	N
NX 2691 5008	G	42°W	-	055/66S	N
NX 2679 5612	G	15°W	-	058/63S	N
	G	29°W	-	047/65S	N
NX 2677 5017	G	38°E	-	060/64S	N
NX 2671 5021	G	82°W	-	059/79S	N
	G	20°E	-	"	N
NX 2670 5021	G	18°W	-	058/76S	N
	G	26°E	-	"	N

Corwall Formation

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2889 4918	G	18°W	-	061/80N	N
NX 2886 4902	G	63°E	-	068/81N	S
NX 2886 4901	R	10°E	-	068/81N	S
NX 2897 4888	G	14°E	-	062/86N	N
NX 2925 4872	Fl	17°E	to W	076/73N	N
NX 2939 4902	G	26°E	-	057/79S	S
NX 2943 4902	G	53°E	-	063/84N	S
NX 2969 4917	G	40°E	-	072/86S	N
NX 2970 4911	R	10°W	-	072/84S	S
NX 2927 4883	G	30°E	-	073/73S	N
NX 2993 4841	G	10°W	-	078/77S	N

/ Cont'd.....

Grid Ref.	Structure	Pitch	Flow Direction	Bedding	Younging Direction
NX 2808 4007	G	6°E	-	072/75N	N
NX 2887 4947	Fl	81°W	to E	073/78N	N
NX 2911 4994	G	9°W	-	062/74S	
	G	24°E	-	"	N
	G	29°E	-	062/70S	N
	G	19°W	-	"	N
	Fl	19°W	to W	"	N
	G	22°W	-	"	N
	G	5°W	-	"	N
NX 2923 4990	G	26°W	-	070/79S	N
NX 2864 4954	Fl	8°E	to E	066/70N	N
NX 2977 5087	G	42°E	-	059/76S	N
NX 2972 5089	G	12°E	-	058/90S	N
NX 2962 5081	G	22°E	-	061/71S	N
NX 2956 5077	G	17°E	-	060/85S	N
NX 2972 5089	G	12°W	-	058/90S	N

APPENDIX 4

1:10,000 SCALE MAPS OF THE KILLANTRINGAN BAY (NW 9820 5700) TO CLANYARD BAY (NX 1010 3800) STUDY CORRIDOR

The five maps (A to E) presented within this Appendix were originally produced as part of a contract for the B.G.S. They include stratigraphical, sedimentological and structural information relating to the Killantringan Bay (NW 9820 5700) to Clanyard Bay (NX 1010 3800) study corridor.

Similar maps relating to the Little Larg (NX 1612 6612) to Port William (NX 3370 4355) study corridor have been produced by the Southern Uplands Division of the B.G.S. as part of their regional remapping programme. These are stored at Murchison House, Edinburgh.

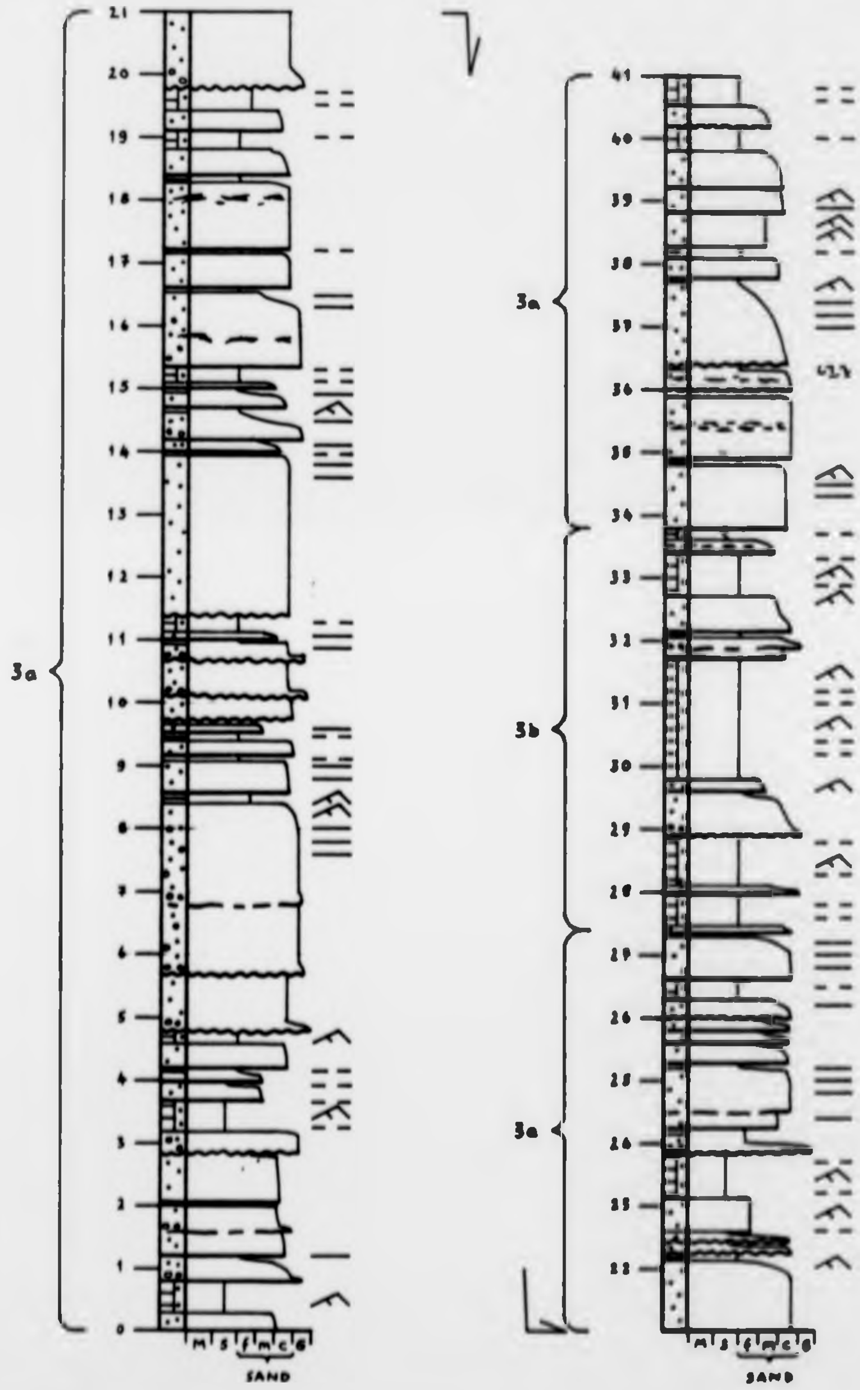
APPENDIX 5

SUPPLEMENTARY LOG SECTIONS

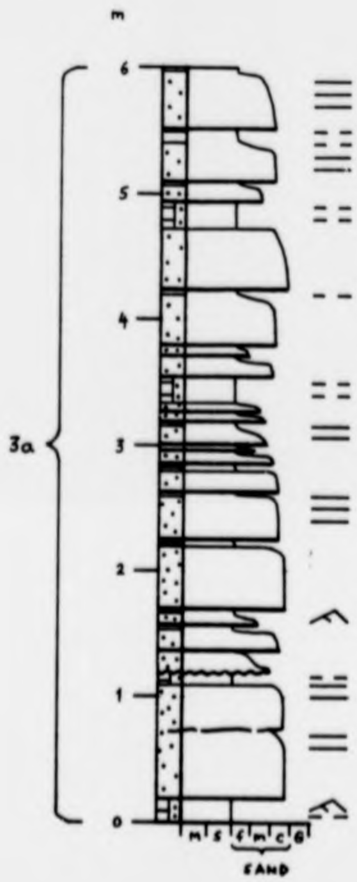
The log sections included within this Appendix are intended to supplement those within the body of the thesis. They illustrate many of the facies associations described within text.

Together with the logs presented in the body of the thesis and those included on the pull-out maps (Appendix 4) all of the stratigraphical units described in the text are illustrated.

L1 **Locality:** Quarry south of Portpatrick (NX 0003 5371)
Stratigraphical Unit: Portpatrick Formation, Acid-clast Division
Probable Age: Caradoc



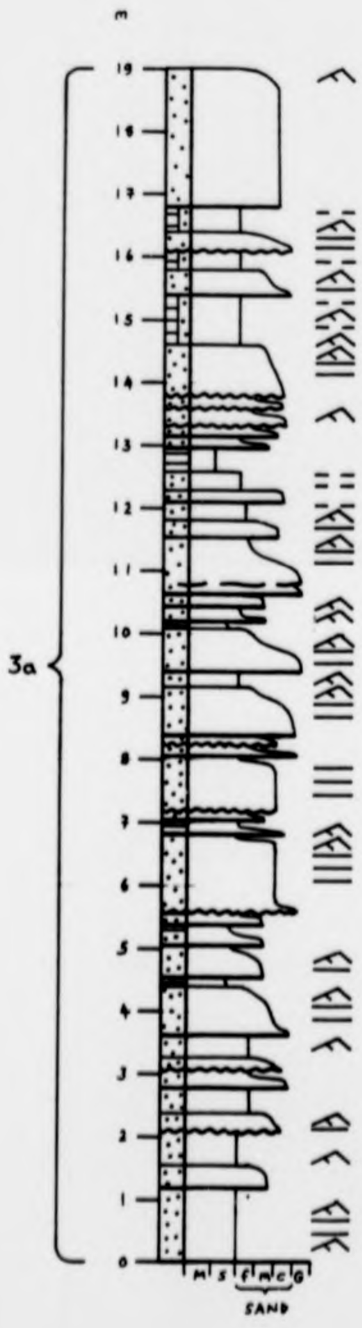
L2 **Locality:** 1km south of Portpatrick (NX 0048 5310)
Stratigraphical Unit: Portpatrick Formation, Acid-clast Division
Probable Age: Caradoc



L3 **Locality:** 1.2km south of Portpatrick (NX 0060 5289)

Stratigraphical Unit: Portpatrick Formation, Acid-clast Division

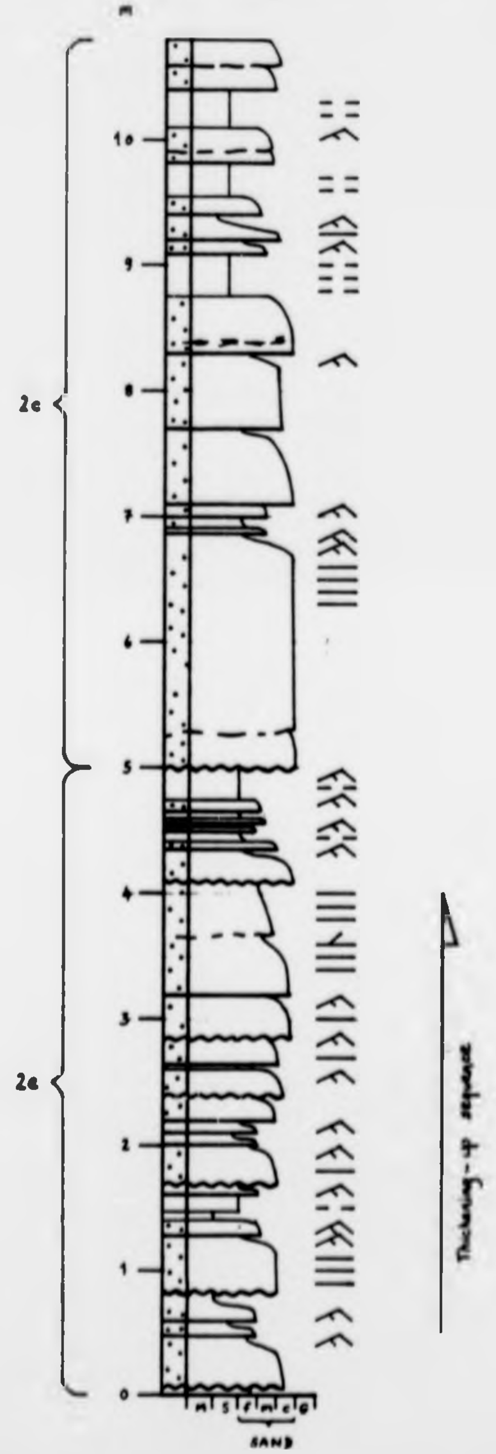
Probable Age: Caradoc



L4 **Locality:** Black Head (NW 9803 5652)

Stratigraphical Unit: Portpatrick Formation, Basic-clast Division

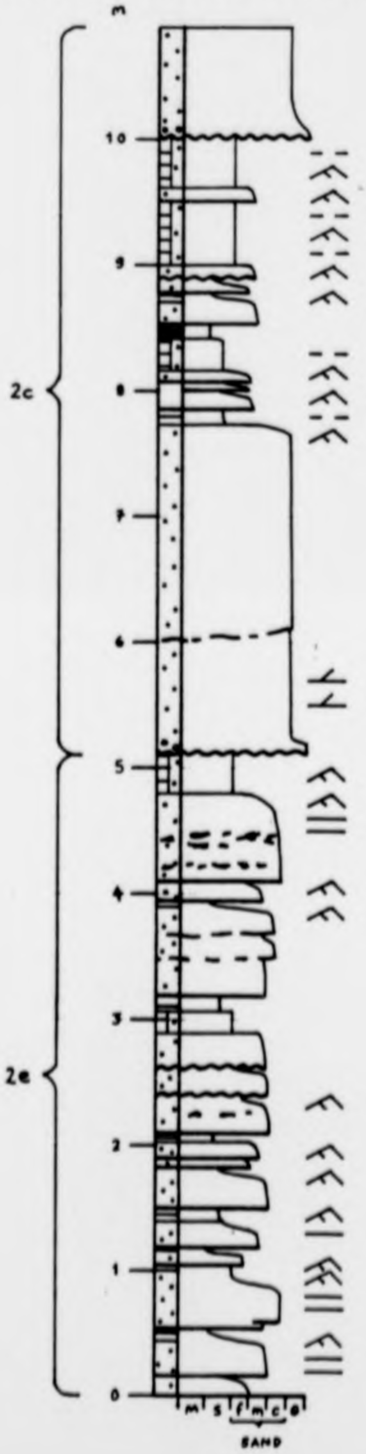
Probable Age: Ashgill



L5 **Locality:** Hairyhorroch (NW 9852 5549)

Stratigraphical Unit: Portpatrick Formation, Basic-clast Division, Hairyhorroch Member

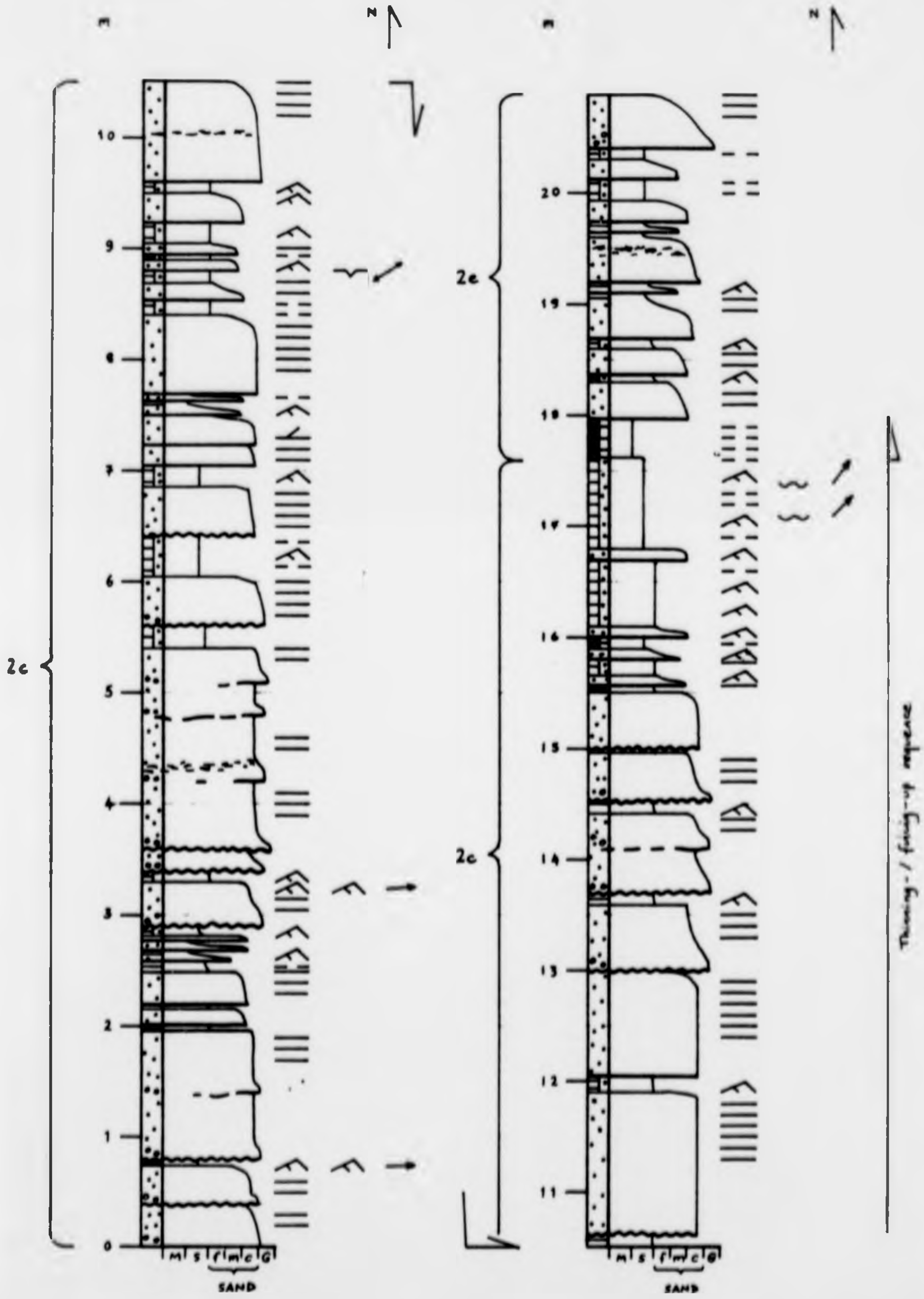
Probable Age: Caradoc/Ashgill



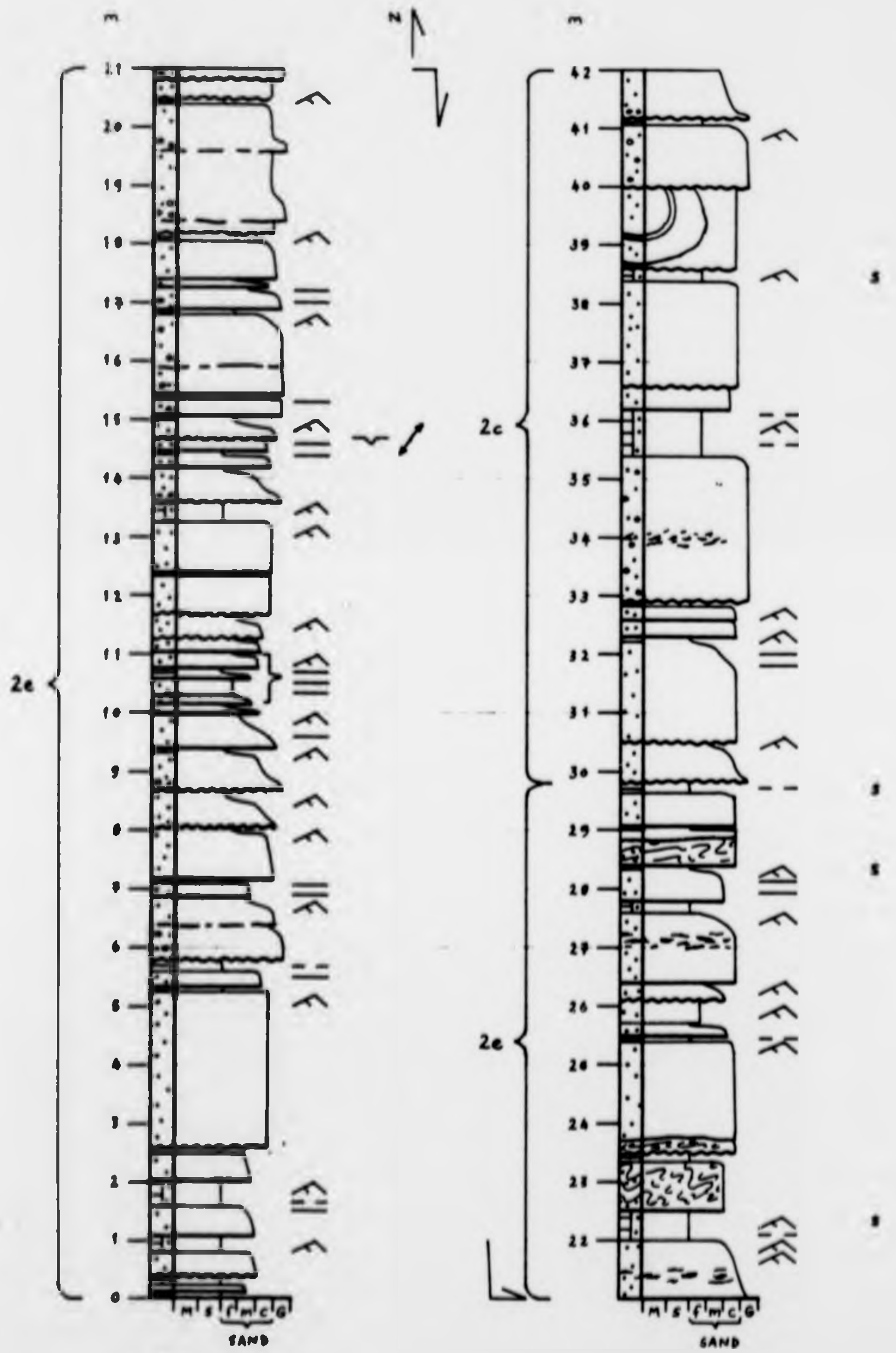
L6 **Locality:** Black Head (NW 9802 5646)

Stratigraphical Unit: Portpatrick Formation, Basic-clast Division, Hairyhorroch Member

Probable Age: Caradoc/Ashgill

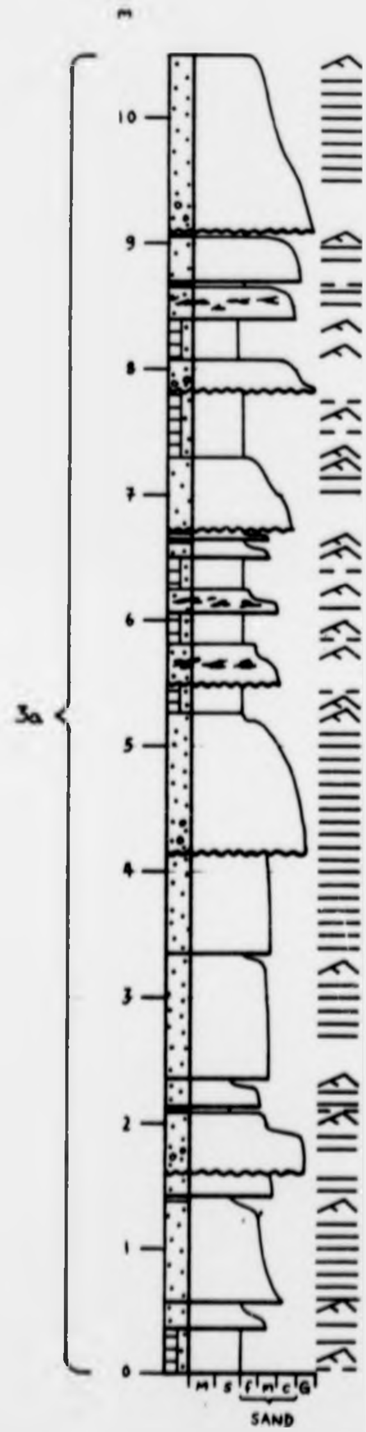


L7 **Locality:** Portamaggie (NW 9820 5615)
Stratigraphical Unit: Portpatrick Formation, Basic-clast Division, Hairyhorroch Member
Probable Age: Caradoc/Ashgill

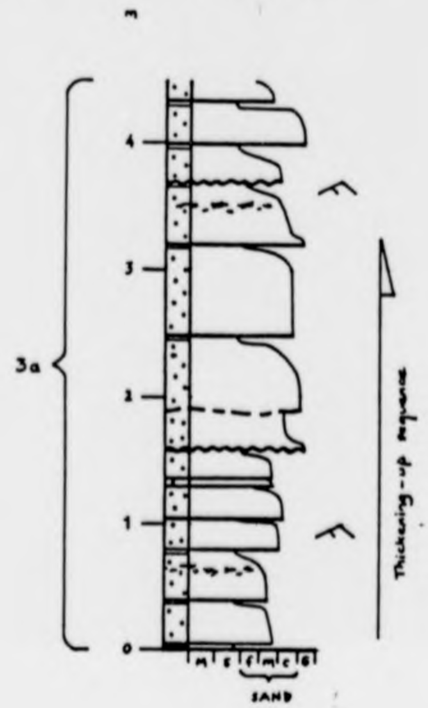


S = Siliceous Units

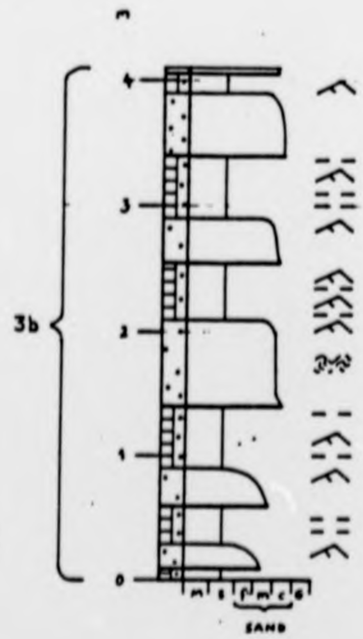
L8 **Locality:** 50m north of Hairyhorroch (NW 9850 5565)
Stratigraphical Unit: Portpatrick Formation, Basic-clast Division, Hairyhorroch Member
Probable Age: Caradoc/Ashgill



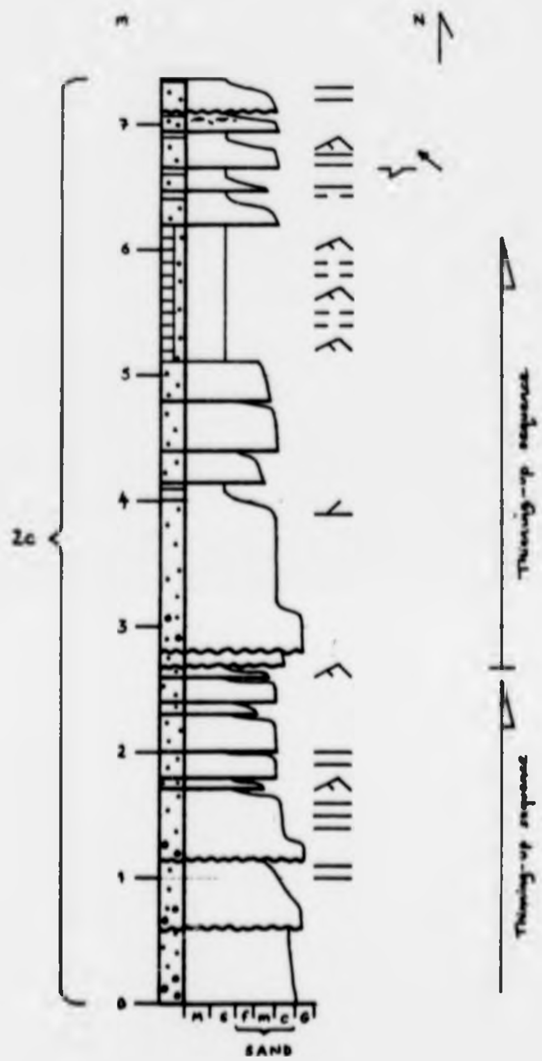
L9 Locality: Finlock Bay (NX 0260 5150)
Stratigraphical Unit: Portayew Formation
Probable Age: Caradoc



15 m Break



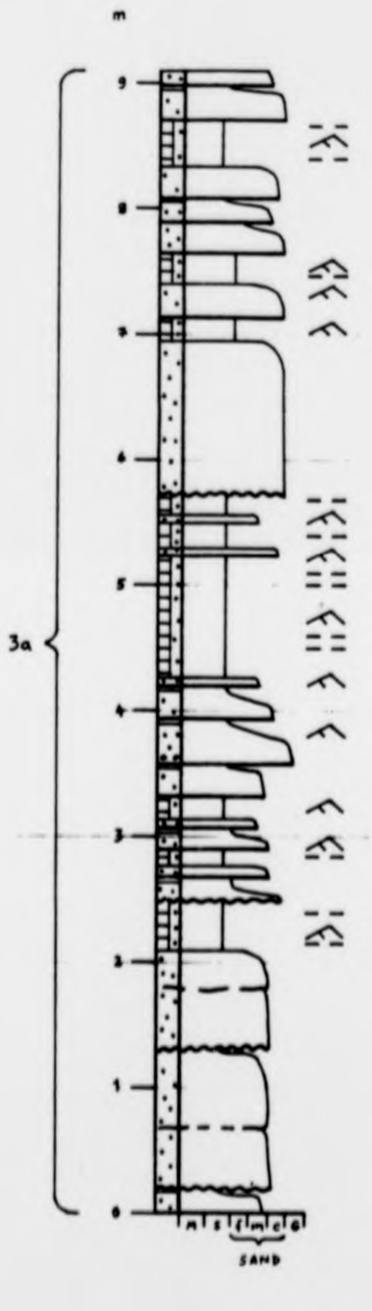
L10 **Locality:** Dunanrea Bay (NX 0299 5079)
Stratigraphical Unit: Portayew Formation
Probable Age: Caradoc



L11 **Locality:** 550m south of Port of Spittal Bay (NX 0225 5142)

Stratigraphical Unit: Portayew Formation

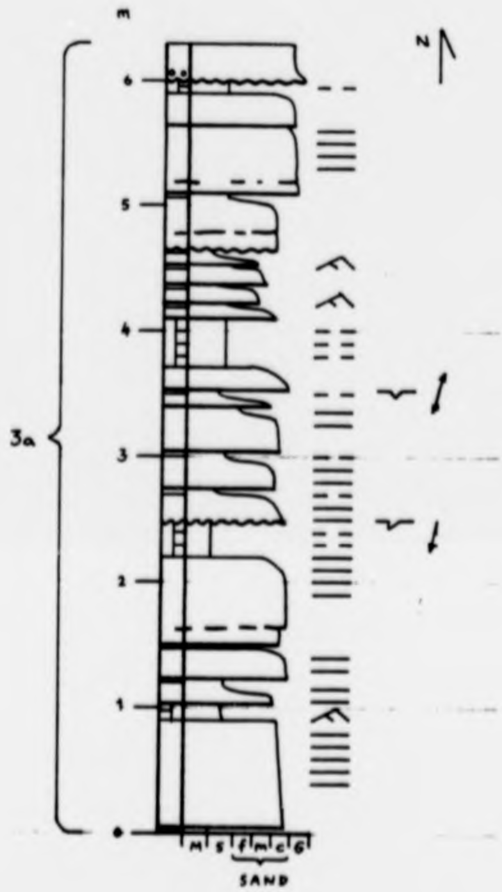
Probable Age: Caradoc



<u>L12</u> **Locality:** South side of Float Bay (NX 0633 4704)

Stratigraphical Unit: Float Bay Formation

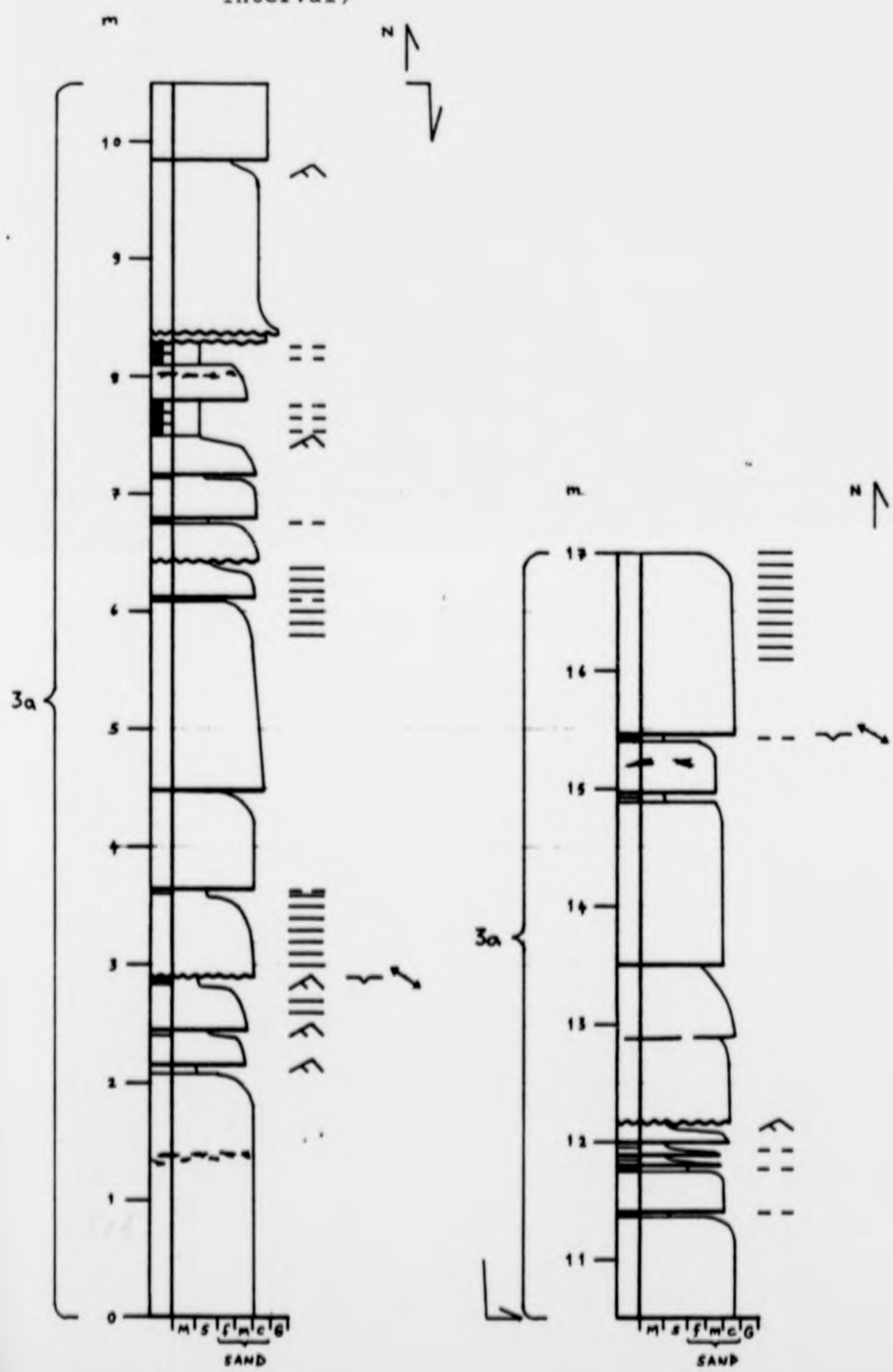
Probable Age: Llandovery (<u>atavus</u>-<u>leptotheca</u> Zone interval)



__L13__ **Locality:** Small roadside quarry 1.2km north-northwest of Stairhaven (NX 2027 5433)

Stratigraphical Unit: Kilfillan-A Formation

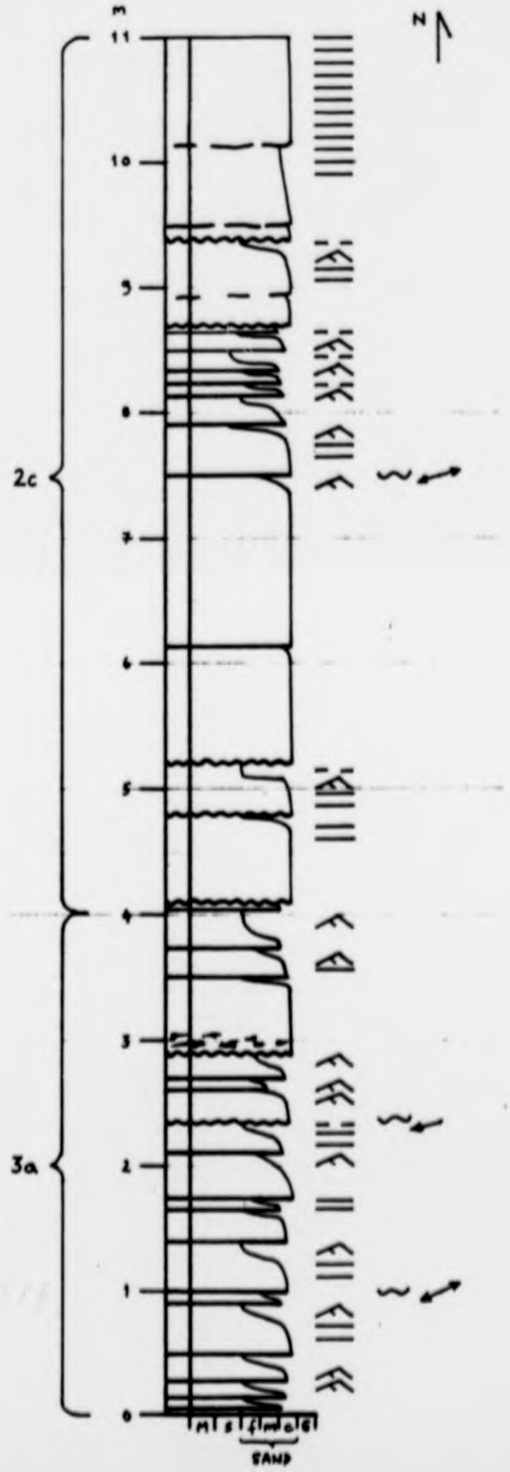
Probable Age: Llandovery (__acuminatus__-__cyphus__ Zone interval)



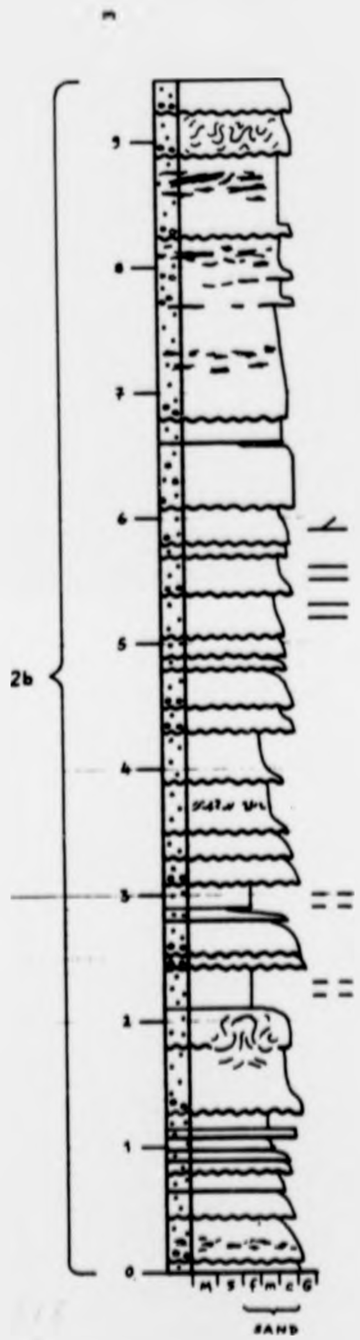
<u>L14</u> **Locality:** On the coast 500m due west of Laigh Sinniness (NX 2124 5247)

Stratigraphical Unit: Kilfillan-B Formation

Probable Age: Llandovery (<u>acuminatus</u> to <u>leptotheca</u> Zone interval)



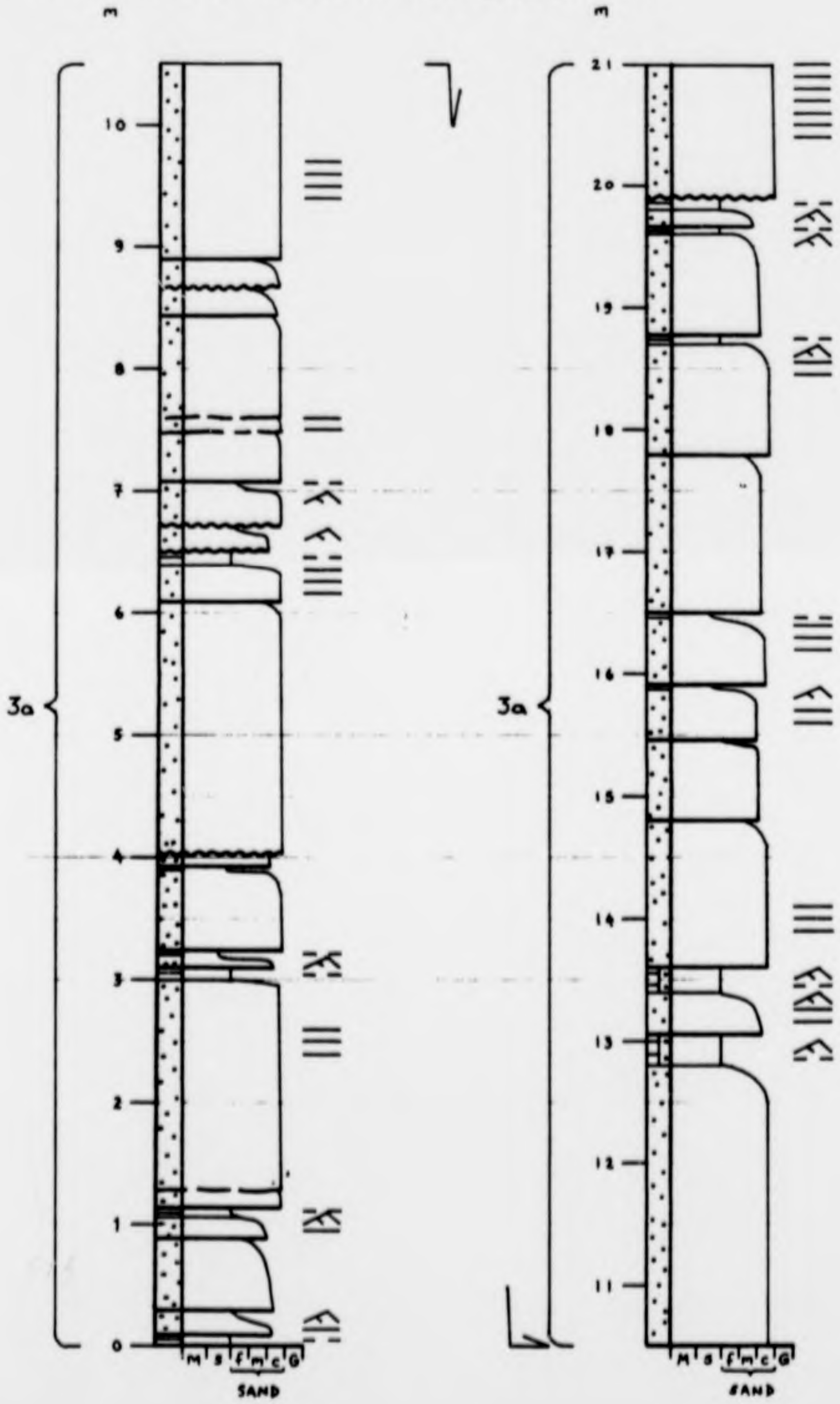
L15 **Locality:** Salt Pans Bay (NX 0708 4604)
Stratigraphical Unit: Stinking Bight Formation
Probable Age: Llandovery (cyphus-gregarius Zone interval)



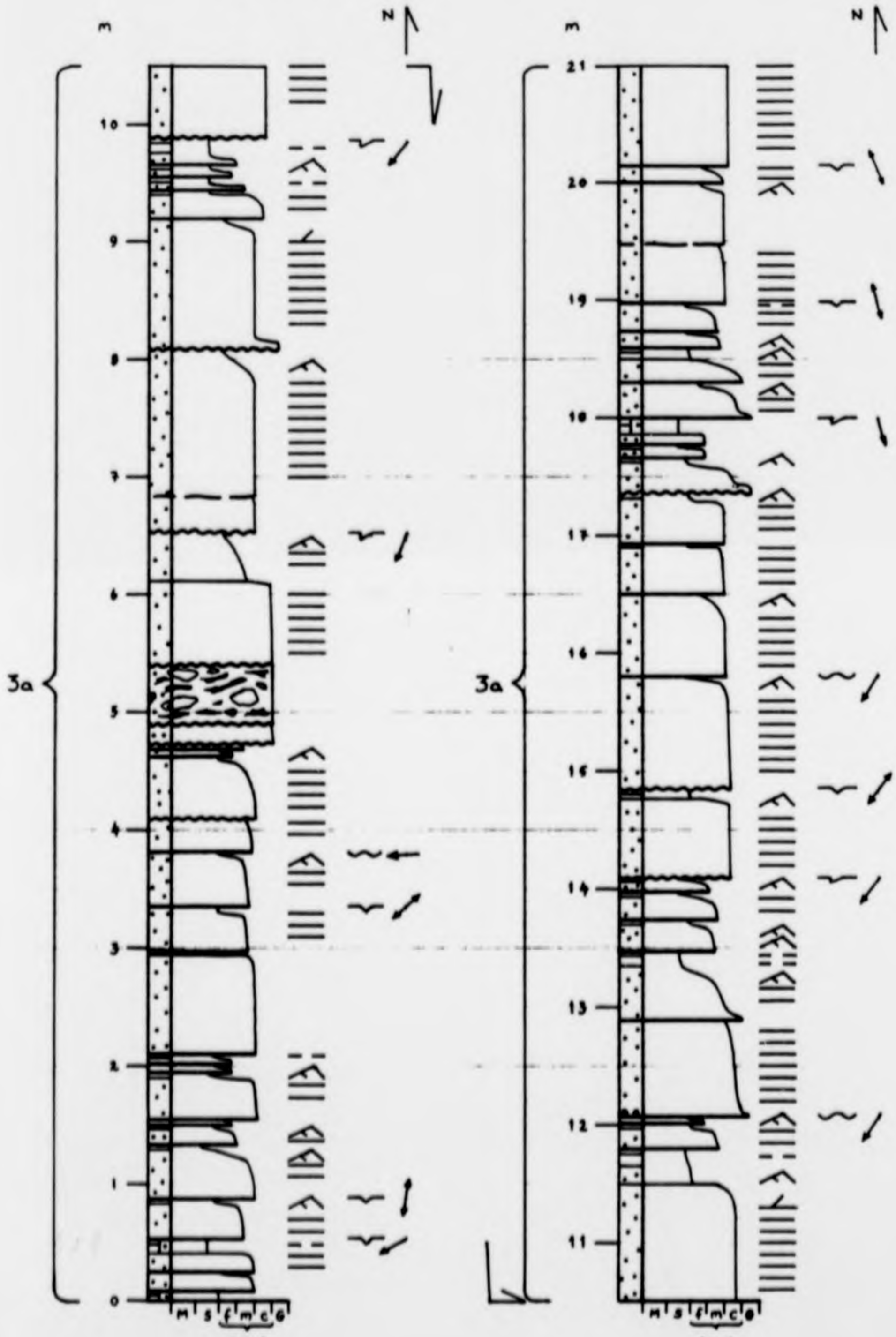
<u>L16</u> **Locality:** Small rocky point immediately north of the outflow of Craignarget Burn into Luce Bay (NX 2589 5114)

Stratigraphical Unit: Garheugh-A Formation

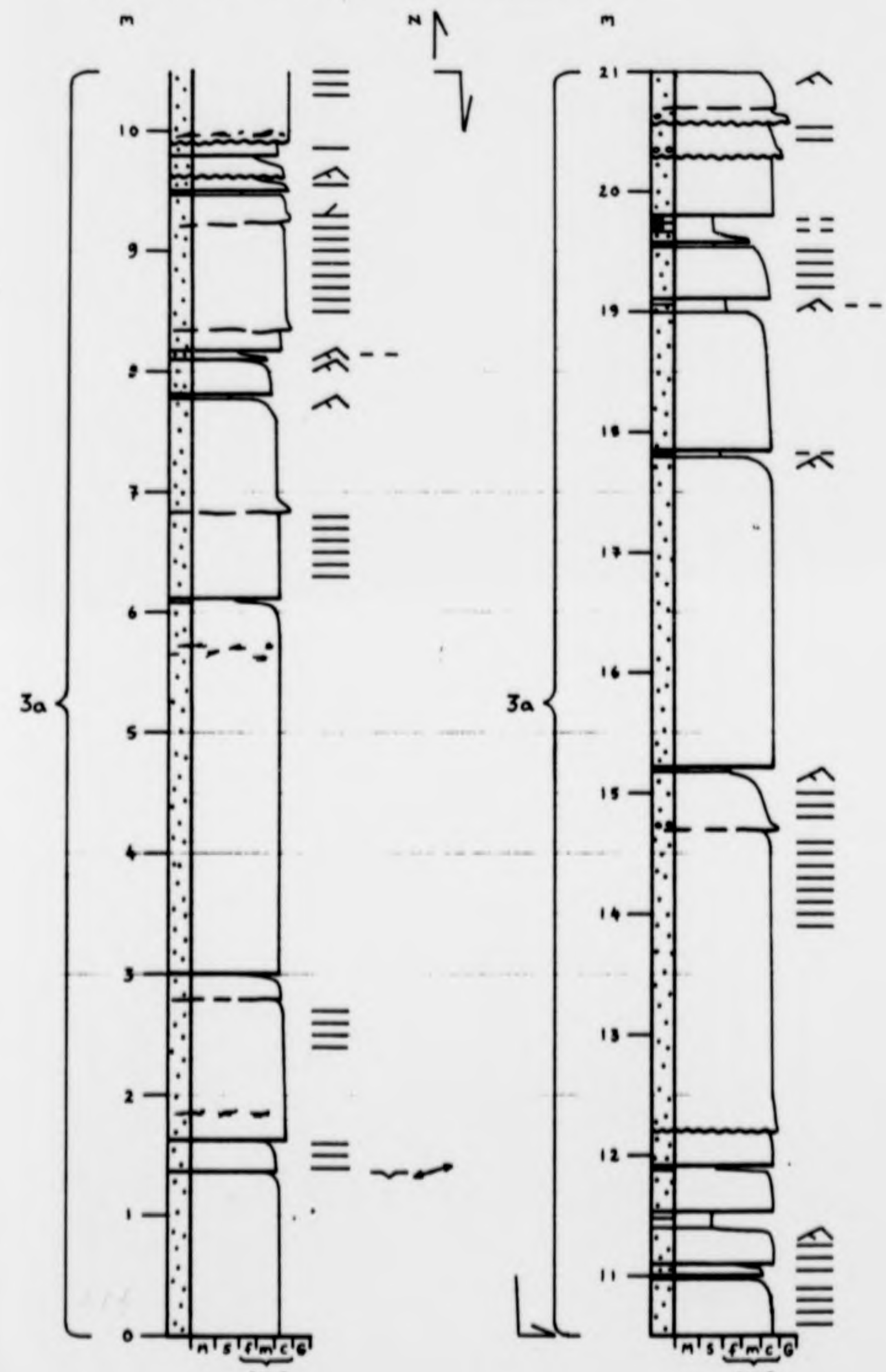
Probable Age: Landovery (<u>gregarius</u> Zone)



<u>L17</u> **Locality:** North shore of Drumbreddan Bay (NX 0763 4367)
Stratigraphical Unit: Grennan Point Formation
Probable Age: Llandovery (<u>convolutus</u>-<u>sedgwickii</u> interval)



<u>L18</u> **Locality:** Rocks of Garheugh (NX 2676 5015)
Stratigraphical Unit: Garheugh-B Formation
Probable Age: Llandovery (<u>gregarius</u> Zone)



<u>L19</u> **Locality:** Rocks of Garheugh (NX 2676 5015)
Stratigraphical Unit: Garheugh-B Formation
Probable Age: Llandovery (<u>gregarius</u> Zone)