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Lithofacies of Lower Palaeozoic deep-marine sediments in the Isle of Man: a new map and stratigraphic model of the Manx Group

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Abstract: A classification scheme for lithofacies in the Lower Palaeozoic Manx Group has been designed based on a simple assessment of the sandstone:mudstone ratio, bed thickness and sedimentary structures. The scheme was used to acquire high-resolution, standardized field data over areas of good exposure on the Isle of Man. These data were then correlated in order to produce a lithostratigraphic framework and a simplified geological map. Overall, the succession appears to young northwestwards from early Arenig, sand-rich sediments on the southeast coast to mud-rich sediments of mid–late Arenig age inland and on the northwest coast. A number of alternative structural reconstructions have been made which fit to a greater or lesser degree with limited biostratigraphic data. The favoured model involves a compromise between inferred duplication of stratigraphic units by reverse faults and repetition of similar depositional cycles or sequences within the succession. This model implies that the Manx Group is between 5400 and 9250 m thick and contains within it both a lateral facies change (from proximal to distal character east–west) and an overall fining-upwards stratigraphic signature. The sediments are interpreted to have been rapidly deposited on the west dipping margin of a basin situated between the Isle of Man and southeast Ireland, which forms an embayment on the northwest edge of Eastern Avalonia. The main depositional processes were turbidity currents and debris flows, with evidence of possible current deflection or reworking of the upper parts of turbidites by northwards flowing contour currents. During the Caledonian orogeny, the basin was inverted with the development of northeast–southwest trending thrusts and east–west dextral faults. Tentative evidence also exists for the presence of an older north-northeast–south-southwest normal fault trend, although whether it was active during the Arenig is uncertain. It is recommended that future stratigraphic work should concentrate on testing possible correlations between and within the mixed sand–mud Lonan, Port Erin, Injebreck and Creggan Mooar Formations.

During recent years it has become clear, mainly from micropalaeontological evidence (e.g. Molyneux 1979), that the stratigraphy of the Isle of Man proposed by Simpson (1963) is flawed. Little explanation is given by Simpson (1963) of the criteria used to identify and classify his units, making it difficult to use his stratigraphic framework in the field and casting doubt on his structural model (cf. Fitches *et al.* 1999). For example, Quirk & Kimbell (1997) and Quirk *et al.* (1999*b*) have shown that the Isle of Man is traversed by major northeast–southwest and east–west faults, unrecognized by Simpson (1963), making the great lateral persistence of some of his stratigraphic units seem untenable (see Ford *et al.* 1999). A solution to these problems was to resurvey the distribution of different rock types in the Manx Group, rather than the more subjective approach of assigning the rocks to formations and mapping their boundaries. However, although it appears that all the sediments are marine (and probably deep marine) in origin (Orr & Howe 1999), it was found that existing classification schemes for these sort of sediments provide insufficient resolution to subdivide the Manx Group into more than a few distinctive rock types. For example, the lithofacies scheme of Pickering *et al.* (1989) is useful for sedimentological analysis but not ideal for mapping (cf. Woodcock & Barnes 1999; Woodcock & Morris 1999). Instead, a new lithofacies scheme was developed specifically for the Manx Group based on simple sedimentological characteristics such as sandstone type, mudstone content, sedimentary structures and bed thicknesses. The

From: Woodcock, N. H., Quirk, D. G., Fitches, W. R. & Barnes, R. P. (eds) 1999. *In Sight of the Suture: the Palaeozoic geology of the Isle of Man in its Iapetus Ocean context.* Geological Society, London, Special Publications, **160**, 69–88. 1-86239-046-0/99/$15.00

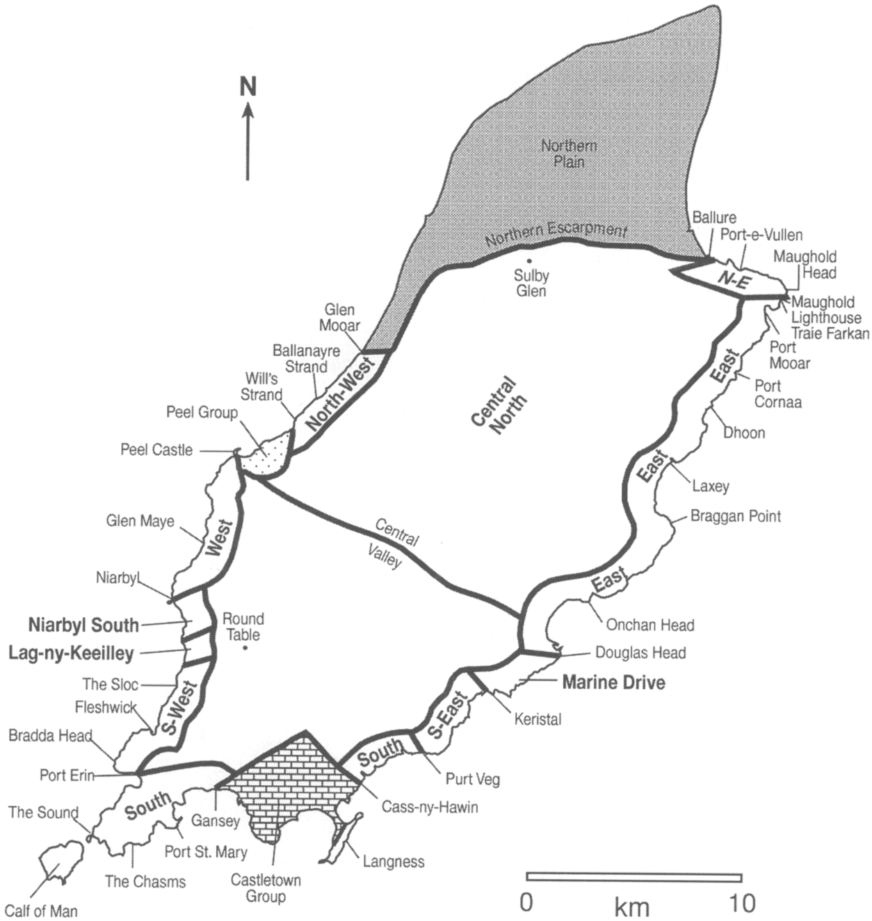


Fig. 1. Map of the Isle of Man showing coastal regions and localities referred to in the text.

scheme is summarized in Table 1, illustrated in Fig. 2 and described in detail in a Supplementary Publication.[1]

The lithofacies nomenclature that has been adopted reflects the sandstone:mudstone ratio of the sediments: e.g. a lower limit of 55% mudstone defines lithofacies class M (mudstone) suffixed by the letters V, H, I and L to indicate very high (95–100%), high (90–95%), intermediate (70–90%) and low (55–70%), respectively. In addition to these standard mudstone lithofacies, lithofacies M_P and M_{IC} are two distinctive types that comprise pebbly mudstone and mudstones with iron–manganese carbonate bands, respectively (Table 1). Sandstone-bearing lithofacies are divided into three field-based classes, and further subdivided in a similar way to the mudstones. Sandstones (S_L, S_I and S_H) comprise quartz arenites containing moderate to low amounts of interbedded mudstone. Quartzites (Q_H and Q_V) are coarser grained, recrystallized quartz arenites with no visible matrix. Wackes (W_H and W_U) are lithofacies containing varying amounts of lithic fragments and feldspar grains.

After a pilot study, the scheme was applied in mapping outcrops in detail along coastal exposures and inland transects. The results were then used to correlate the succession and to determine the gross lithostratigraphic and structural relationships, based on large-scale trends in the dominant lithofacies

[1]Supplementary Publication No SUP 18134 (12 pages) contains detailed descriptions of each lithofacies. It is available from the Society Library or the British Library Document Supply Centre, Boston Spa, Wetherby, West Yorkshire LS23 7BQ, UK.

Table 1. *Main field characteristics of lithofacies in the Manx Group, described in detail in the Supplementary Publication No. SUP 18134*

Lithofacies	Type section	Sand-stone (%)	Sandstone bed thickness (cm)	Distinguishing characteristics	Bouma units	Pickering class*	Lithostratigraphic unit in which commonly found	Field term used by Lamplugh (1903)	Associated lithofacies
$\mathbf{M_V}$	Round Table	< 5	< 0.1	Dark grey, massive	Te	E1.1, E1.2	Barrule Fm, Glen Rushen Fm	Barrule slate	M_H, M_P (, M_I)
$\mathbf{M_H}$	Maughold Head	5–10	< 0.5 (0.1 av)	Laminated	Te	E2.2, D2.3	Barrule Fm	Barrule slate	M_V (, M_P, M_I)
$\mathbf{M_I}$	Sulby Glen	10–30	< 1 (0.2 av)	Laminated, slumping common	Tde	C2.3, D2.3	Injebreck Fm (lower unit)	Unassigned	M_L (, M_P, M_H, Q_H)
$\mathbf{M_{IC}}$	Niarbyl south	5–20	< 2 (0.15 av)	Contains bands of Fe–Mn carbonate	Tde	C2.3, D2.3	Creggan Mooar Fm	Unassigned	M_P, M_V (, M_I)
$\mathbf{M_L}$	Port Erin	30–45	< 3 (1 av)	Planar (-ripple) laminated	Tde	C2.3	Port Erin Fm	Mostly unassigned	M_I, S_L, Q_H, Q_V
$\mathbf{M_P}$	Ballanayre Strand	< 30		Conglomeratic (matrix supported)		A1.3	Fleshwick Unit, Lady Port Fm	Crush conglomerate	M_V (, M_I, W_U, Q_H)
$\mathbf{S_L}$	Traie Farkan (S)	45–60	< 5 (1 av)	Ripple-planar laminated	Tcde?	C2.3	Lonan Fm	Flags	S_I, M_L (, Q_H)
$\mathbf{S_I}$	Port Mooar	60–80	< 0.1–15 (7.5 av)	Quartzose, ripple-planar laminated	Tcde?	C2.3, C2.2	Lonan Fm	Flags	S_H, S_L (, W_H, Q_H)
$\mathbf{S_H}$	Port Cornaa	80–100	1-50 (10 av)	Quartzose, convolute lam. common	Tabcd	B1.1	Ny Garvain Fm (lower unit)	Flags	S_I
$\mathbf{Q_H}$	Traie Farkan (N)	80–90	3–50 (12.5 av)	Quartzite, commonly planar laminated	Tabcde	B1.2	Creg Agneash Fm	Grit	M_L (, M_P, M_I, S_L)
$\mathbf{Q_V}$	The Chasms	80–100	10–100 (40 av)	Quartzite, massive (-planar laminated)	Tabcd	B1.1	Mull Hill Fm, Keristal Mbr	Grit	M_L, S_I (, M_P)
$\mathbf{S_V}$	Purt Veg	95–100	50–300 (125 av)	Arkosic, planar-massive, coarse-gran.	Tab	A2.8	Santon Formation (rare)	Grit	S_H (, M_I ?)
$\mathbf{W_H}$	Marine Drive	80–90	3–50 (12.5 av)	Wacke, commonly planar laminated	Tbcde	B1.2	Santon Fm (Marine Drive)	Flags	S_I (, S_H)
$\mathbf{W_{HP}}$	Lag ny Keeilley	80–90	2–100 (50 av)	Wacke, conglomeratic, planar laminated	Ta	A2.5	Eary Cushlin Unit (very rare)	Unassigned	M_P, S_L, W_U
$\mathbf{W_U}$	Not defined	85–100	1–300	Commonly wacke, undifferentiated	Tabc	B1.1, C2.1	Glion Cam Unit	Grit	M_P, M_I, M_{IC}, M_H

*Pickering *et al.* (1989).

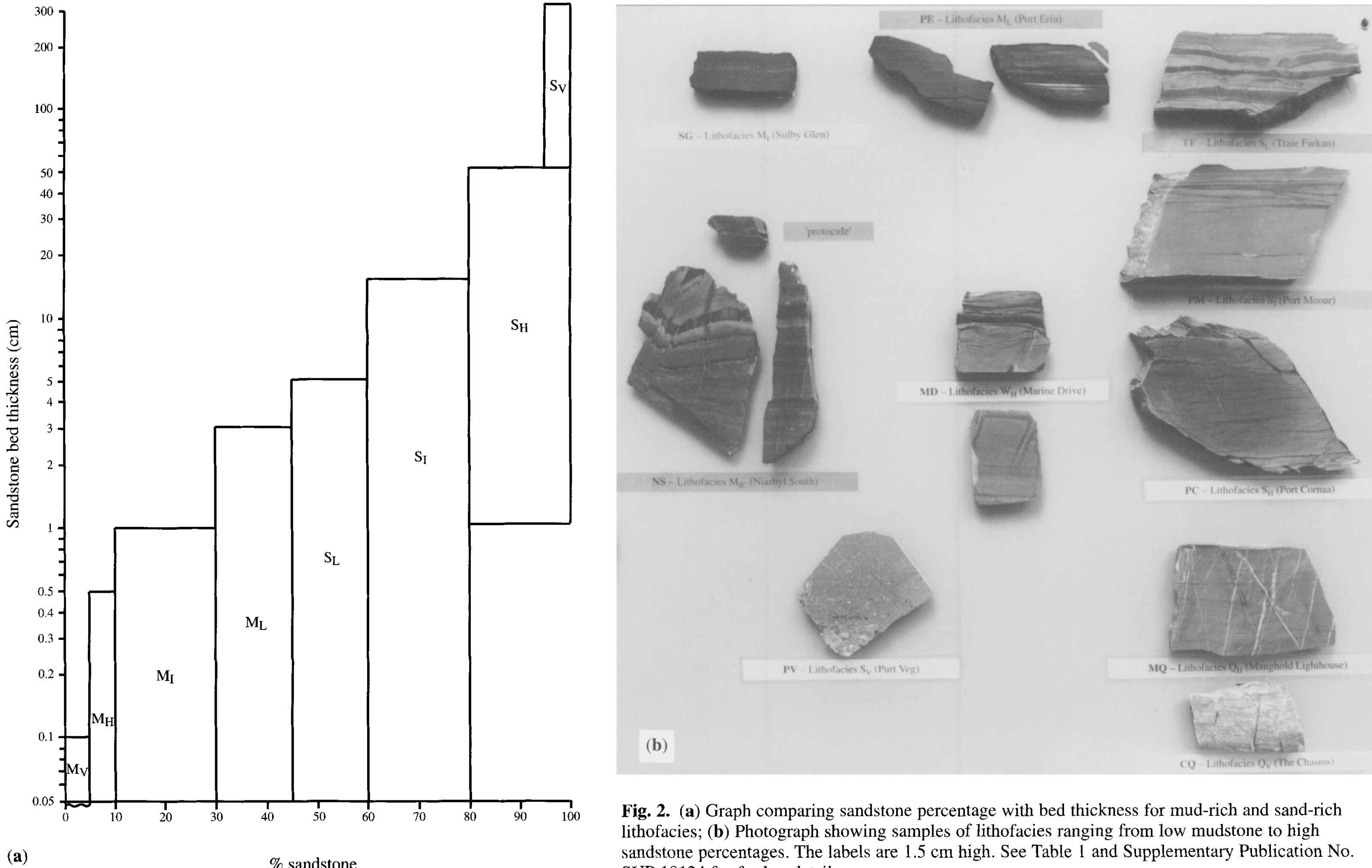


Fig. 2. (**a**) Graph comparing sandstone percentage with bed thickness for mud-rich and sand-rich lithofacies; (**b**) Photograph showing samples of lithofacies ranging from low mudstone to high sandstone percentages. The labels are 1.5 cm high. See Table 1 and Supplementary Publication No. SUP 18134 for further details.

and the observed or inferred positions of boundaries between markedly different groups of lithofacies. The interpretation was also improved by integration with the pioneering geological survey work of Lamplugh (1903) who mapped the entire island in detail (cf. Fig. 3).

The results are shown in Fig. 4 as a set of lithological columns. Each column represents a more or less continuously exposed section separated from adjacent sections by observed or inferred faults, intrusive bodies or gaps in exposure. Each lithofacies has been assigned a colour in logical progression with the next most similar lithofacies. An interval is shown as containing a single lithofacies if at least 75% of the interval conforms with the description of that lithofacies (Table 1). If the interval contains an estimated 25–75% of another lithofacies, then it is given a shared name (shown with horizontal stripes in Fig. 4). Where another lithofacies makes up only 5–25% of the interval, it is regarded as a minor constituent (shown with coloured dots in Fig. 4). Where a lithofacies forms < 5% of an interval it is generally not depicted, except where pebbly mudstone or beds of quartzite help to characterize the interval.

Correlations and vertical succession of the Manx Group

There is a virtual absence of marker beds in the Lower Palaeozoic rocks of the Isle of Man and

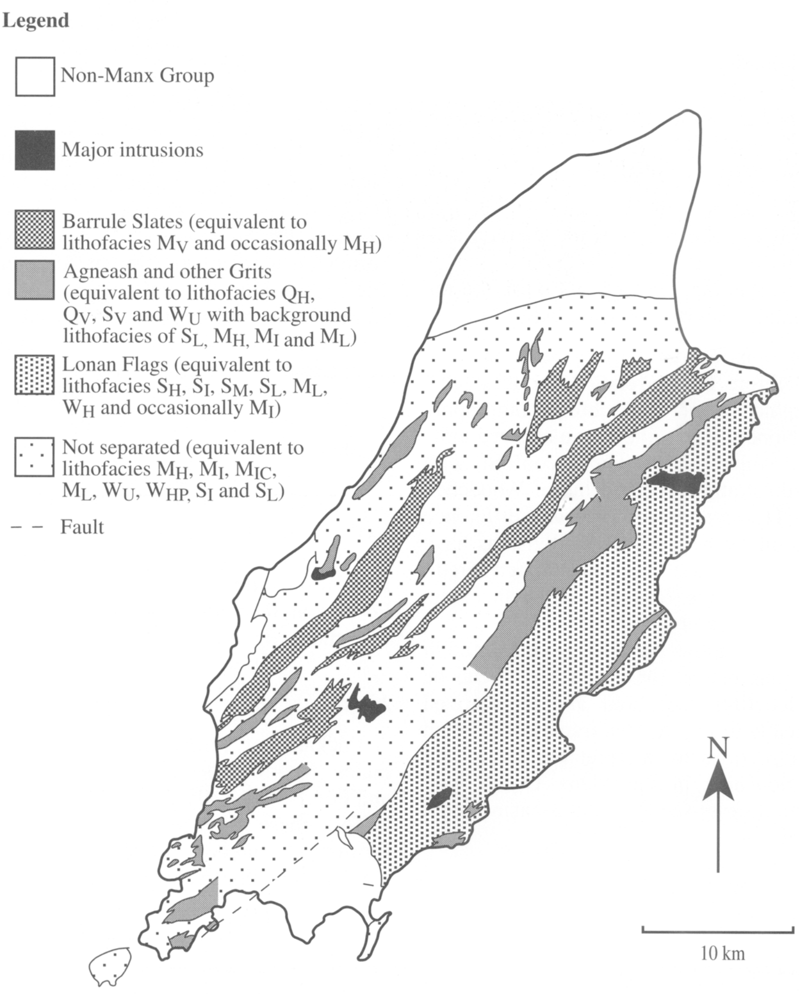


Fig. 3. Simplified map of lithotypes surveyed by Lamplugh (1903).

currently only a poor biostratigraphic framework on which to tie the stratigraphy (cf. Molyneux 1999; Orr & Howe 1999). However, certain lithofacies clearly occur grouped together in areas or tracts with a specific lithofacies signature (Fig. 4). Within each tract, correlations can be made with a fair degree of confidence but correlations between tracts are more difficult to establish. Some flexibility has been used during correlation because of inferred lateral facies variations and some imprecision in classifying certain outcrops, particularly inland where weathering and limited exposure can be a problem. Within tracts, correlations across faulted boundaries have been made using the minimum offset required to produce a good match between columns, unless there is geological evidence to suggest otherwise. Alternatively, the data in each column can be used independently of the lithostratigraphic interpretation shown on Fig. 4. Thus, in the future, the columns can be rearranged and added to as new field and laboratory data are acquired that help improve the correlations.

Probable and possible correlation surfaces are numbered upwards from oldest to youngest (Fig. 4), making the general assumptions that:

- in an overall sense, lithofacies units get younger to the northwest, except where the contrary was observed in the field;
- there are no missing sections and therefore the full stratigraphy can be reconstructed.

These assumptions are unlikely to be completely valid and therefore the correlation surfaces set a lithostratigraphic rather than chronostratigraphic framework. None the less, they have allowed units to be defined which, on the whole, conform with the formal lithostratigraphic scheme of Woodcock *et al.* (1999). However, where there is a difference in interpretation, or where new subdivisions have been made, the term 'unit' has been adopted here to distinguish it from the formations and members defined by Woodcock *et al.* (1999).

The main observations are briefly synthesized in separate sections below, for which Fig. 1 can be used as a location map, and are summarized diagrammatically in Fig. 5. This framework is then used in later sections to interpret the lateral and vertical relationships in the Manx Group with which structural cross-sections and a basin model are developed.

East coast

Access along the coast between Onchan and Maughold is generally good and has allowed confident correlations to be established within the quartzose sand-rich lithofacies (S_L, S_I and S_H) which dominate this part of the succession. Only where a probably sand-rich lithofacies (?S_H) exposed in Dhoon Bay has been strongly recrystallized due to contact metamorphism by the Dhoon Granite is there any uncertainty in the classification. In all, a total stratigraphic thickness of *c.* 1800 m is exposed but this estimate is complicated by the presence of some large folds and strike-slip faults (Fig. 4).

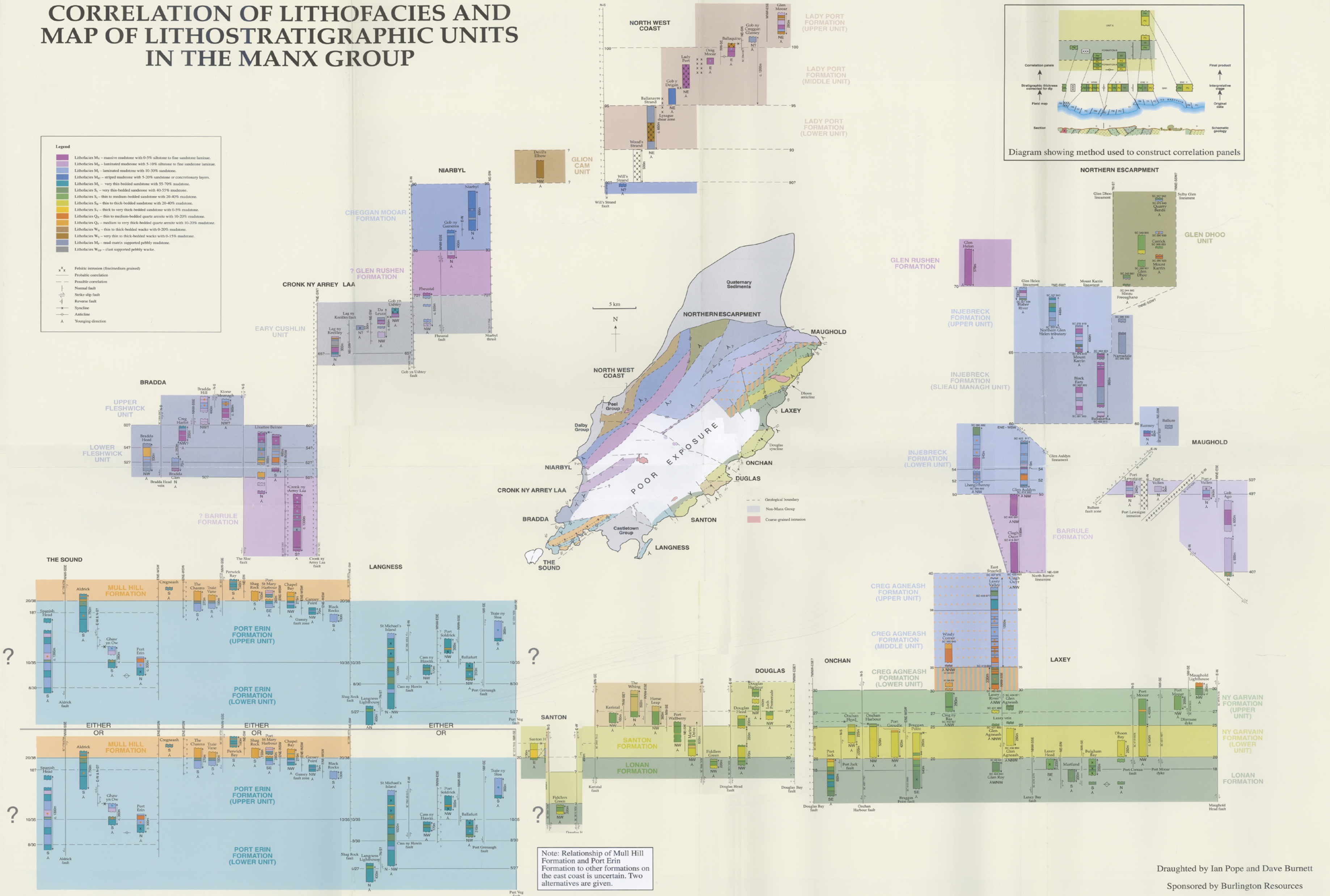
The key to correlating this tract is the recognition of a distinctive 500–550 m thick section (interval 20–25) of highly sand-rich lithofacies (S_H) forming the lower unit of the Ny Garvain Formation. Below and above this section the sediments are more muddy, in the Lonan Formation (interval 10–20, lithofacies M_L–S_I) and the upper unit of the Ny Garvain Formation (interval 25–30, mostly lithofacies S_L–S_I), respectively. Woodcock *et al.* (1999) have assigned the coastal section from Braggan Point to Onchan Head, north of Douglas, to the Santon Formation lying within the axis of the Douglas syncline. However, the lithofacies are identical to the lower unit of the Ny Garvain Formation north of the Dhoon Anticline (Fig. 4). The type Santon Formation (south of Douglas) is more muddy but almost certainly correlates with the lower unit of the Ny Garvain Formation. The axial trace of the Douglas Syncline appears to cut down-section from Douglas to Port Groudle (Fig. 4), suggesting that the fold axis plunges to the southwest. The top of the Lonan Formation (correlation surface 20) is marked in places by a thin package of quartzites (lithofacies Q_V), the Keristal Member of Woodcock *et al.* (1999). A faulted contact between the top of the Ny Garvain Formation and the overlying Creg Agneash Formation (correlation surface 30) is present at Maughold Lighthouse.

Northeast coast

A thickness of 1200 m of highly mud-rich lithofacies (M_V–M_H) occurs between Maughold Head and Port e Vullen. By contrast withWoodcock *et al.* (1999), these rocks are assigned to the Barrule Formation (interval 40–50) due to their close similarity in lithofacies and thickness with rocks

Fig. 4. Compilation of lithofacies mapped by authors between 1995 and 1997 presented in the form of correlation panels and simplified map.

CORRELATION OF LITHOFACIES AND MAP OF LITHOSTRATIGRAPHIC UNITS IN THE MANX GROUP



Note: Relationship of Mull Hill Formation and Port Erin Formation to other formations on the east coast is uncertain. Two alternatives are given.

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exposed around Clagh Ouyr in the central-north area (Fig. 4). However, the possibility remains that the eastern (lower) part of the section represents a lateral variant of the upper part of the Creg Agneash Formation. The base of the Maughold Head–Port e Vullen section is exposed at [SC 497 916], where a significant part of the Creg Agneash Formation (interval 30–40) has been faulted out by a large east–west dextral fault (Quirk *et al.* 1999*b*). The top of the section is interrupted by several thick felsitic intrusions and associated shear zones around Port e Vullen and Port Lewaigue (Fig. 4). A short muddy section (lithofacies M_V, M_{IC} and M_P) at Ballure is thought to be faulted in from higher up in the succession, probably the middle part of the Injebreck Formation (interval 60–65).

Central-north area

Figure 4 shows a composite section made up of the best exposed sections along traverses between Laxey and the northern escarpment. It is estimated that the stratigraphic thickness of this part of the succession is at least 8000 m (assuming no fault repetition), dipping on average 45° to the northwest. An overall change is seen from quartzose sand-rich lithofacies in the lower (eastern) part of the succession to mud-rich lithofacies in the upper (western) part.

Probably the oldest rocks in the area, in Glen Roy, comprise low to moderately sand-rich lithofacies (S_L–S_I) correlating with the Lonan Formation (interval 10–20) on the eastern coast. Above this is the lower unit of the Ny Garvain Formation (interval 20–25), the distinctive highly sand-rich lithofacies (S_H) seen, for example, in Glen Agneash. The more muddy upper part of the Ny Garvain Formation (interval 25–30) is best seen at Creg ny Baa.

The Laxey Valley exposes a 1700 m thick unit above the Ny Garvain Formation known as the Creg Agneash Formation (interval 30–40) consisting predominantly of moderately mud-rich and quartzite-bearing lithofacies (M_I–Q_H). It appears to thin to less than half its original thickness and become slightly less sandy in a northeast direction. However, at least some of the change in thickness is due to faulting at Maughold Head (see preceding section). The Creg Agneash Formation has been divided into a lower, middle and upper unit on the basis of three apparent fining-upwards cycles (Fig. 4). At the base of the lower and middle units, the quartzites are particularly thick and well developed around Creg ny Baa and Windy Corner, reminiscent of the Mull Hill Formation in the south of the island (lithofacies Q_V). The upper unit, which is the thickest, is distinctly less sandy, comprising mostly lithofacies M_I with the occasional quartzite bed. This interval is assigned to the Maughold Formation by Woodcock *et al.* (1999) on the basis of correlations with a highly muddy section on the northeast coast, between Maughold Head and Port e Vullen (equated with the Barrule Formation here), and a pebbly mudstone-bearing interval on the south coast, between Bradda Head and Lhiattee Beinee (the Fleshwick Unit, Fig. 5). On top of the Creg Agneash Formation is the very highly mud-rich lithofacies (M_V) of the Barrule Formation, estimated to be *c.* 1200 m thick in the vicinity of Clagh Ouyr, assuming that there is no structural repetition. The Barrule Formation appears to thin rapidly between Snaefell and Beinn y Pott ([SC 397 879]–[SC 381 860]) and on the west side of North Barrule (e.g. [SC 414 900]). This thinning corresponds with the apparent truncation of units within the underlying Creg Agneash Formation and the overlying lower unit of the Injebreck Formation. This relationship, and the fact that linear aeromagnetic anomalies are observed at these boundaries, suggest that the Barrule Formation is partly fault bounded, e.g. by the North Barrule lineament at the base of the Barrule Formation (Quirk *et al.* 1999*b*). The North Barrule lineament coincides with the position of a trial mine adit at [SC 387 872], which intersected a mineralized fault of unknown orientation.

The interval between the Barrule and the Glen Rushen Formations (interval 50–70) is defined as the Injebreck Formation (Woodcock *et al.* 1999), and is here divided into three units. However, the stratigraphic picture is complicated by the inferred presence of at least one major fault (Quirk *et al.* 1999*b*). The lowest unit (interval 50–60) occurs in Glen Auldyn and Lhergyrhenny and comprises moderately mud-rich and quartzite-bearing lithofacies (M_I–Q_H) with similarities to parts of the Creg Agneash Formation. A pebbly, highly mud-rich lithofacies (M_P–M_V) in Ballakerka forms the middle part of the Injebreck Formation (interval 60–65). This Slieau Managh Unit pinches out southwards (Fig. 4). Its thickness is hard to estimate, due to probable faulting and lateral facies variations. A large east-northeast–west-southwest trending fault is interpreted to separate it from the lower unit of the Injebreck Formation. However, the extreme scarcity of pebbly mudstone (M_P) between the Barrule and Glen Rushen Formations (interval 50–70) further south suggests that some lateral facies variation may also exist, possibly due to syn-sedimentary movement on the same fault (Quirk *et al.* 1999*b*). The Slieau Managh Unit probably correlates to the east with a faulted section exposed on the coast at Ballure (Fig. 4). The base of the upper unit of the Injebreck Formation is marked by a thin package of quartzites (lithofacies Q_H) and the rest of the interval (interval 65–70) consists of a

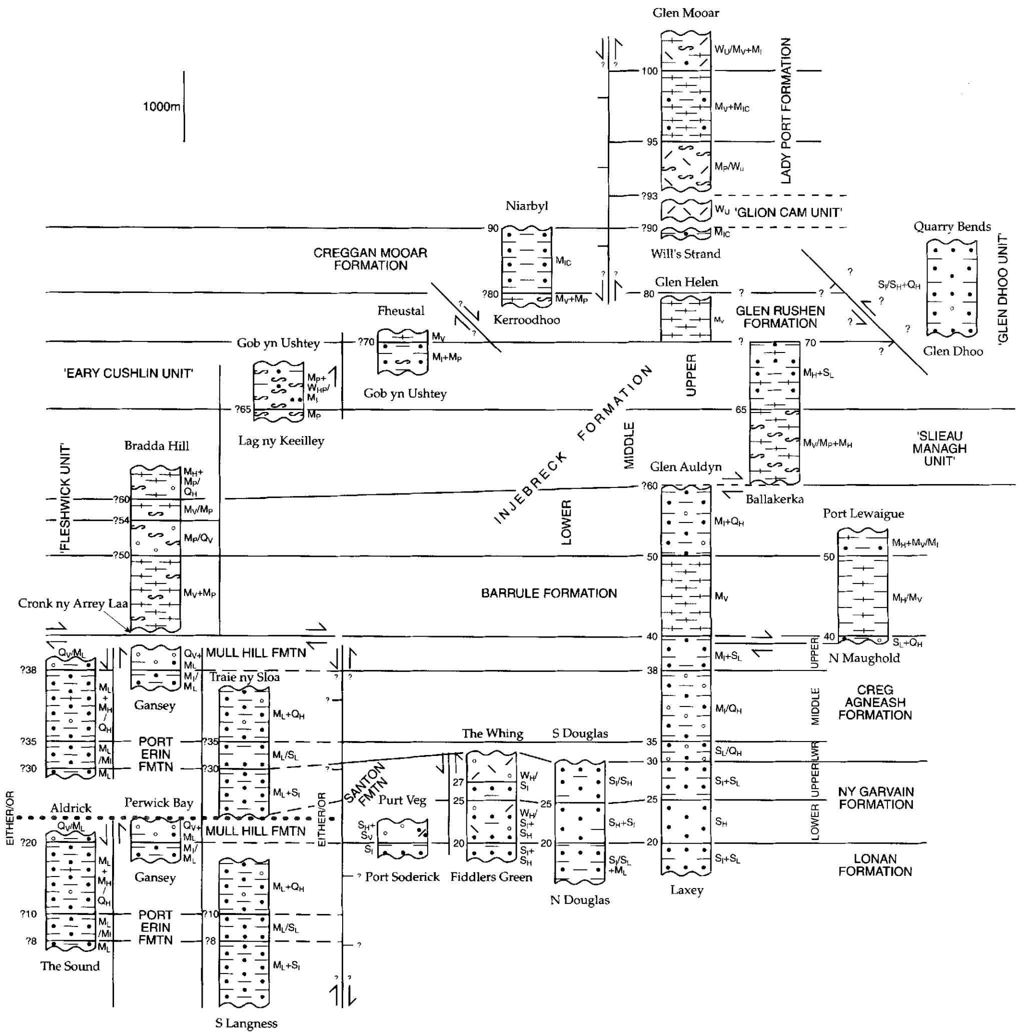

Fig. 5. Schematic lithostratigraphy of the Manx Group based on Fig. 4. The principal lithofacies in each unit are shown on the right-hand side of most columns. Note that the lithostratigraphic position of the Mull Hill and Port Erin Formations (bottom left-hand corner) is uncertain and two alternatives are given. Table 2 gives further information.

broadly mud-rich lithofacies association (M_V, M_H, M_I, M_L and S_L). It shows a higher illite crystallinity grade than the middle and lower parts of the Injebreck Formation, supporting the idea that it is bounded on its southeast side by a reverse fault (Quirk *et al.* 1999*b*). It is difficult to trace the Injebreck Formation towards the Central Valley and further south because of poor exposure. However, the Barrule Formation appears to be offset dextrally by a large east–west fault known as the Greeba Lineament, evidence for which is also seen on aeromagnetic data (Quirk *et al.* 1999*b*).

The Glen Rushen Formation occurs at the top of the succession in the central-north area (interval 70–80). Approximately 600 m of the formation is exposed in Glen Helen, where it is exclusively composed of very highly mud-rich lithofacies (M_V). However, a variable, but generally moderate to highly sand-rich lithofacies (S_I–S_H), similar to the Ny Garvain Formation, is present around Glen Dhoo and Carrick. The stratigraphic relationship of this Glen Dhoo Unit to the Glen Rushen Formation and the underlying mixed lithofacies of the Injebreck Formation is uncertain (Fig. 5). Acritarch data presented by Molyneux (1999) suggest that the Glen Dhoo Unit is early Arenig in age whereas the

Glen Rushen Formation, which occurs along-strike from it, is mid-Arenig in age (Table 2). Field mapping and aeromagnetic data (Quirk *et al.* 1999*b*) indicate that they are in faulted contact (Fig. 4), suggesting a number of possible structural models which are discussed later.

Southeast coast, including Marine Drive

Most of the succession exposed from Santon Head to Loch Promenade in Douglas is thought to correlate with the Ny Garvain Formation (interval 20–30) which is present further north (Fig. 4). However, differences in the lithofacies led Woodcock *et al.* (1999) to instead assign this succession to the Santon Formation, albeit the lateral equivalent of the Ny Garvain Formation. The area has been divided into three separate sections (Santon, Marine Drive and south Douglas) with uncertain mutual relationships.

The south Douglas section comprises *c.* 1200 m of moderate to highly sand-rich lithofacies (S_I–S_H), the base of which, on Douglas Head, may represent the top of the Lonan Formation (correlation surface 20). Marine Drive contains a highly wacke-rich lithofacies (W_H) unique to that section, which may represent an immature lateral equivalent of the highly sand-rich lithofacies (S_H) in south Douglas (Fig. 4). However, the presence of a ?northwest–southeast sinistral fault offsetting the Douglas Syncline by 1500 m at Keristal and an east–west ?dextral fault juxtaposing different lithofacies at Fiddlers Green allows for the possibility that the Marine Drive section has been faulted in from lower in the succession (Quirk *et al.* 1999*b*). Approximately 450 m of section is exposed between Keristal and Santon Head. As well as moderate to highly sand-rich lithofacies (S_I–S_H), it includes an unusually thick-bedded, very highly sand-rich lithofacies (S_V), interpreted as a turbidite channel. It appears to correlate with a moderately mud-rich lithofacies containing thin bedded quartzites ($M_I + Q_H$) (Fig. 4) which may represent a levee deposit.

South coast (Langness–Purt Veg)

A vertical northwest–southeast trending fault at Purt Veg [SC 324 703] marks an important change in lithofacies (Quirk *et al.* 1999*b*). The direction and amount of offset on this fault is uncertain and two possibilities exist, depending on how the low to moderately mud-rich lithofacies (M_L–M_I) between Purt Veg and Langness correlates with the succession to the northeast (Fig. 5). The correlation favoured by Woodcock & Barnes (1999) assigns the section to the Lonan Formation (interval 5–20) implying that it is much muddier here than, for example, around Port Jack (lithofacies S_L–S_I) further north. In this interpretation, the amount of stratigraphic offset across the fault at Purt Veg may be as much as 700 m in a dextral sense, although this estimate depends on assumptions made in reconstructing the rather faulted succession south of Purt Veg (Fig. 4). The alternative correlation is with the Creg Agneash Formation (interval 30–40) which shows a generally similar mud-rich background lithofacies (M_I) but contains significantly greater amounts of quartzite (lithofacies Q_H). Based on a tentative match with the Laxey Valley (Fig. 4), the likely stratigraphic offset in this interpretation is *c.* 3000 m by sinistral movement.

There is a marked similarity in the mud-rich lithofacies between Purt Veg and Langness and the Port Erin Formation, exposed further south (lithofacies M_I–M_L; Fig. 5), to which the section is therefore assigned. Whether the Port Erin Formation is the lateral equivalent of the Lonan Formation or the Creg Agneash Formation is yet to be established. Detailed correlations in this area are difficult to make because of structural complexity and the relationships shown on Fig. 4 remain speculative.

South coast (Port Erin–Gansey)

In the area around Port St Mary, The Sound and Port Erin, the Manx Group is affected by some large faults leading to uncertainties in correlation, particularly between The Sound and Aldrick and between Port Erin and Cregneash. Almost 2000 m of low to moderately mud-rich sediments belonging to the Port Erin Formation are overlain by the Mull Hill Formation comprising *c.* 300 m of quartzites and mudstones (mostly lithofacies Q_V and M_L). The quartzites are concentrated towards the base of the Mull Hill Formation. The contact with the Port Erin Formation (correlation surface 20–38) is best seen at The Chasms, at Port St Mary, where it is overturned, and at Aldrick, truncated by a major fault (Fig. 4). Assuming that the Port Erin Formation is not equivalent to the highly sandy parts of the Santon–Ny Garvain Formations, the Mull Hill Formation may correlate to the northeast in one of two ways; either with the upper part of the Creg Agneash Formation (interval 38–40), which contains few quartzites in the Laxey River, or with the lower parts of the Santon and Ny Garvain Formations (interval 20–25) (Fig. 5), which contain equivalent amounts of quartzose sand but in a different type of lithofacies (S_H). A second thinner package of quartzites occurs within the middle of the underlying Port Erin Formation at the north end of Port Erin. This package could correlate with the base of the middle unit of the Creg Agneash Formation (correlation surface 35) or else marks

Table 2. *Estimated thickness, sequence stratigraphic interpretation and possible correlatives for each of the main lithostratigraphic units shown in Fig. 4, north of Cronk Ny Arrey Laa*

Lithostratigraphic subdivision	Estimated thickness (m)	Sequence stratigraphic interpretation	Biostratigraphic age	Established correlative	Possible correlatives		Potential correlative
Lady Port Fm	*c.* 2100 m	Tectonically complex	Late Arenig			Creggan Mooar (±)	
Glion Cam Unit	?500–1000 m	Late highstand	?Early Arenig?		Glen Dhoo (3,4)	Ny Garvain (4)	Upper Injebreck (2)
Creggan Mooar Fm	≥900 m	Early highstand			Lower Injebreck (2, 3, 4)	Upper Injebreck (3, 4)	Lonan (4)
Glen Rushen Fm	≥600 m	Transgression	Mid-Arenig		Barrule (2, 3, 4)	Slieau Managh (3, 4)	
Glen Dhoo Unit	*c.* 1000 m	Lowstand	Early Arenig			Ny Garvain (2, 4)	Glion Cam (3, 4)
Upper Injebreck Unit	950 m	(?Late) highstand		Eary Cushlin[a] (S)	Lower Injebreck (3, 4)	Creggan Mooar (3, 4)	Lonan (4)
Slieau Managh Unit	≥1000 m	Slope instability	?Trem(-Aren)?	Upper Fleshwick[b] (S)	Barrule/Glen Rushen (3, 4)		
Lower Injebreck Unit	*c.* 1200 m	(?Early) highstand		Lower Fleshwick[c] (S)	Creggan Mooar (2, 3, 4)	Upper Injebreck (3, 4)	Lonan (4)
Barrule Fm	1200 m	Transgression			Glen Rushen (2,3,4)	Slieau Managh (3, 4)	
Creg Agneash Fm	1700 m	Late lowstand–early transgression			Port Erin/Mull Hill (S)		
Ny Garvain Fm	1050 m	Early lowstand	Early Arenig*	Santon[d] (S)	Mull Hill[e] (S)	Glen Dhoo (2, 4)	Glion Cam (4)
Lonan Fm	550 m	Late highstand			Port Erin[f] (S)	Injebreck/Creggan Mooar (4)	

Refer to Fig. 5 for an overview of the principal lithofacies present within each lithostratigraphic unit. Biostratigraphic ages are based on data in Molyneux (1999) and Orr & Howe (1999).

*based on correlation with Santon Formation; (±) and/or Glen Rushen Formation and/or Glion Cam Unit; (2), (3), (4), in structural Models 2, 3 and 4, respectively (see Fig. 7); (S) in south of Isle of Man; [a]*c.* 800 m thick; [b]*c.* 440 m thick; [c]*c.* 800 m thick; [d]*c.* 1100 m thick; [e]*c.* 300 m thick; [f]*c.* 2400 m thick.

the top of the oldest part of the Manx Group (correlation surface 10).

Southwest coast

A marked change in lithofacies occurs at the north end of Port Erin across a major east–west trending fault at [SC 193 697] (Quirk *et al.* 1999*b*). Depending on whether the Port Erin Formation on the south side of this fault is correlated with the Creg Agneash Formation or with the Lonan Formation (Fig. 5), the fault accounts for either *c.* 2800 or 5400 m of stratigraphic offset, respectively, by apparent dextral movement. In contrast to the south and east coasts, pebbly mudstones (lithofacies M_P) make up an important part of the succession north of the fault, in addition to quartzites and very highly mud-rich lithofacies (Q_H–M_V). In total, *c.* 2300 m of succession is interpreted in this southwest area. The succession is here called the Fleshwick Unit rather than the Maughold Formation (cf. Woodcock *et al.* 1999), to avoid structural inconsistencies and problems in equating the lithofacies. Roberts *et al.* (1990) show that the lower part of the Fleshwick Unit has a significantly lower illite crystallinity grade than the Port Erin Formation, supporting the idea that it is from higher in the succession. The lithofacies in the Bradda Head–Lhiattee Beinee section are most similar to those of the lower and middle units of the Injebreck Formation (interval 50–65). However, there are no pebbly mudstones in the lower part of the Injebreck Formation (interval 50–60) around Lhergyrhenny and Glen Auldyn (Fig. 4), implying that moderately mud-rich lithofacies (M_I) may pass laterally into pebbly mudstones (lithofacies M_P). The very highly mud-rich and pebbly mudstone lithofacies (M_V–M_P) on Cronk ny Arrey Laa are correlated with the underlying Barrule Formation (interval 40–50) but, similarly, there are no pebbly mudstones in the Barrule Formation in the northeast, e.g. around Clagh Ouyr (Fig. 4). However, as explained below, the pebbly Slieau Managh Unit may also correlate with the Barrule Formation because of possible fault repetition, in which case debris flows are a common feature at this level (?mid-Arenig). As in the northeast, where the base and top of the Barrule Formation are probably fault-bounded, the Cronk ny Arrey Laa section is separated from the overlying Eary Cushlin Unit and probably also from the Lhiattee Beinee section by approximately northeast–southwest trending faults (Quirk *et al.* 1999*b*).

Lag ny Keeilley

The northwest side of Cronk ny Arrey Laa is marked by a southeast dipping thrust estimated to account for *c.* 3400 m of stratigraphic offset (Quirk *et al.* 1999*b*). The section exposed on the coast north of the thrust, from Lag ny Keeilley to Gob yn Ushtey, forms part of the Eary Cushlin Unit (Fig. 5). It contains a varied lithofacies association, different from that on Cronk ny Arrey Laa, including a unique conglomeratic wacke (W_{HP}). Due to a number of faults and shear zones bounding and cutting this short section, as well as its relatively poor exposure, correlation is problematic (cf. Fitches *et al.* 1999). However, the nearest similar lithofacies association (M_V–S_L) occurs within the upper part of the Injebreck Formation (interval 65–70) around, for example, the Blaber River, which is the correlation tentatively suggested here and supported by Woodcock *et al.* (1999).

Niarbyl south

The section between Gob yn Ushtey and Niarbyl consists of a relatively poorly exposed lower part, south of Fheustal, forming the upper part of the Eary Cushlin Unit, and a well-exposed upper part, north of Fheustal (Fig. 5). On the basis of correlations with the central-north area (Fig. 4), most of the very highly mud-rich Glen Rushen Formation (interval 70–80) appears to have been faulted out at Fheustal (Quirk *et al.* 1999*b*). Consequently, the section south of here, comprising moderately mud-rich and pebbly mudstone lithofacies (M_I–M_P), is correlated with the upper unit of the Injebreck Formation (interval 65–70). The Creggan Mooar Formation (interval 80–90) lies north of Fheustal and consists mostly of moderately mud-rich lithofacies with characteristic red–brown iron–manganese carbonate bands (M_{IC}) (Kennan & Morris 1999). Inland this lithofacies is rarely exposed, but it reappears on the northwest coast within the Lady Port Formation (interval 90–100). It may, however, be indistinguishable from lithofacies M_I inland in the Injebreck Formation, as the suspicion is that the iron–manganese bands only become obvious on wave-washed outcrops. In fact, the only other place where lithofacies M_{IC} has been observed is on the coast near Ramsey at [SC 460 934], probably within the Injebreck Formation (Fig. 4), with which the Creggan Mooar Formation may correlate (see below and Table 2). Approximately 900 m of Creggan Mooar Formation is estimated to be present and it is bound to the north by a shear zone and fault separating it from the graded wackes of the Silurian Dalby Group (Morris *et al.* 1999).

Although the boundary is not well exposed, the Glion Cam Unit is thought to overlie the Creggan Mooar Formation (Woodcock *et al.* 1999). Limited outcrop suggests that it is 500–1000 m thick and consists mostly of lithofacies W_U.

Northwest coast

A highly faulted section containing diverse lithofacies (M_P, W_U, M_V and M_{IC}) is exposed between Will's Strand and Glen Mooar. This represents the Lady Port Formation (interval 90–100) which is tentatively estimated to be *c.* 2200 m thick, excluding several thick felsitic igneous bodies (Fig. 4). It is thought to represent the highest part of the succession, as supported by a late Arenig acritarch age (Molyneux 1999) and low illite crystallinity values (Roberts *et al.* 1990). The presence of lithofacies W_U, M_{IC} and M_V, often in fault-bounded packets, as well as thick intervals of pebbly mudstone (lithofacies M_P), indicate that the unit may contain slivers of Glion Cam Unit, and Creggan Mooar and Glen Rushen Formations. It is also worth noting that lithofacies M_{IC} at Gob y Deigan [SC 283 873] is remarkably similar in appearance to an interval on the coast near Ramsey at [SC 460 934] assigned to the Injebreck Formation (Fig. 4). The Lady Port Formation can only be traced for a limited distance inland where a faulted boundary is inferred with the poorly exposed Glion Cam Unit (Woodcock & Morris 1999) (Fig. 4).

Comparison with the lithostratigraphy of Woodcock *et al.* (1999)

The results of the present study have mostly been incorporated into the formal lithostratigraphy proposed by Woodcock *et al.* (1999), but there are specific differences which are briefly discussed below.

Lithostratigraphy

A number of the formations defined by Woodcock *et al.* (1999) have been subdivided here on the basis of obvious lithofacies trends. However, the present authors are more conservative in extrapolating lithostratigraphic units through areas of poor exposure and across large faults, so that few units are shown to continue uninterrupted across the island. For example the Injebreck Formation is shown confined to the north (Fig. 4) whereas Woodcock *et al.* (1999) continue it to the west coast (the Eary Cushlin Unit in this paper). The Maughold Formation of Woodcock *et al.* (1999) has been dropped due to perceived differences between the lithofacies at the southern and northern ends of the island where it is best exposed. Instead, the Maughold Formation in the south is named informally here the Fleshwick Unit, which is thought to overlie the Barrule Formation. Hence, it is tentatively correlated with the lower part of the Injebreck Formation (Fig. 5). The northern outcrop of the Maughold Formation of Woodcock *et al.* (1999), between Maughold Head and Port e Vullen, comprises lithofacies very similar to the Barrule Formation and appears to connect with it (Fig. 4). The Barrule Formation itself is cut out on the southwest side of Snaefell by the North Barrule Lineament (Fig. 6). A similarity in lithofacies between the lower and upper units of the Injebreck Formation supports the idea of possible fault repetition (see below). The rest of the area around Glen Dhoo, Cronk Sumark and Sulby Glen, a region left uninterpreted by Woodcock *et al.* (1999), has been mapped and the lithostratigraphy informally defined by the current authors (Fig. 4). Instead, however, a large area in the centre of the island, south of the Central Valley, has been left uninterpreted because of poor exposure. Unlike Woodcock *et al.* (1999), the present authors assign the rocks between Langness and Purt Veg [SC 324 703] to the Port Erin Formation rather than the Lonan Formation, again on lithofacies grounds. Likewise, the Ny Garvain Formation is correlated with the Santon Formation rather than with the Port Erin and Lonan Formations, which contain far less sandstone.

Faults

Interpretation of tectonic lineaments on the Isle of Man (Quirk & Kimbell 1997; Quirk *et al.* 1999*b*) has indicated that the Manx Group is compartmentalized into a number of fault-bound slices. The Windy Corner Fault of Woodcock & Barnes (1999) is not recognized. However, several larger faults are identified which, despite affecting the stratigraphy, have not been included in the map of Woodcock *et al.* (1999). These include an east–west mineralized fault traversing Maughold Head (e.g. [SC 497 915]), an east-northeast–west-southwest shear zone which cuts off the northern end of the Douglas Syncline (e.g. [SC 442 808]) and a number of north–south and east-northeast–west-southwest lineaments in the central-north area (Fig. 6).

Structural interpretations

The lithostratigraphic units of the Manx Group appear generally to dip and young to the northwest. Some stratigraphic repetition is likely to occur across large northwest dipping reverse faults (Quirk *et al.* 1999*b*), but its magnitude is uncertain without better biostratigraphic control. Seismic evidence suggests that at least some of the northwest dip in the Manx Group is due to post-Caledonian tilting in the footwall of the Eubonia–Lagman Faults (Quirk *et al.* 1999*b*). These offshore faults lie close to the east coast of the Isle of Man, along pre-existing Caledonian weaknesses (Quirk *et al.* 1999*a*). A

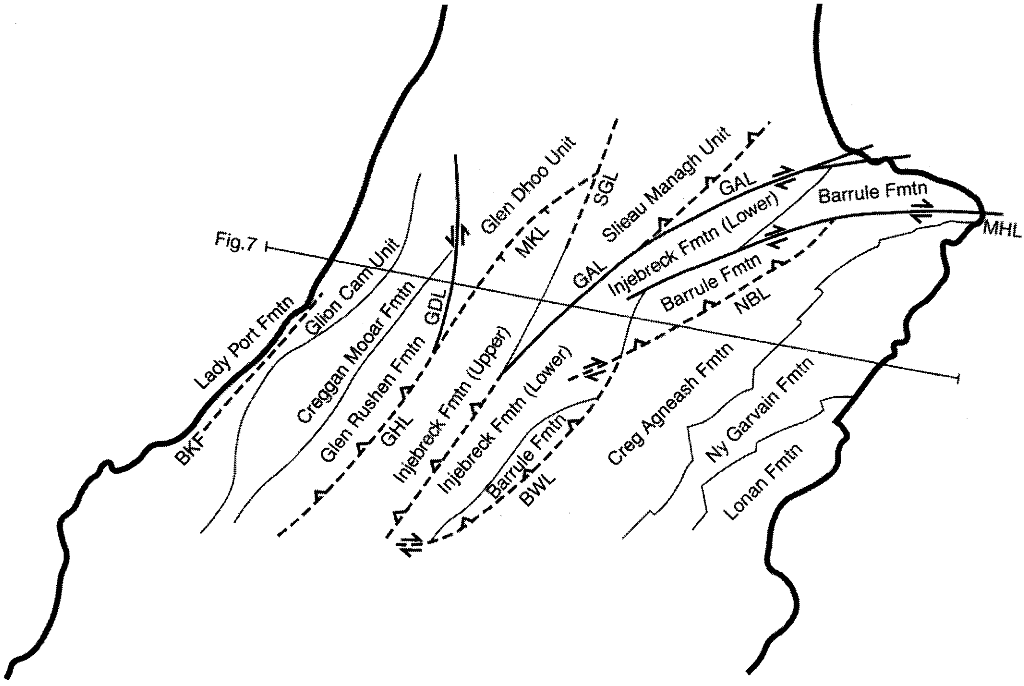

Fig. 6. Simplified lithostratigraphic map of the central-north area showing principal geological boundaries and line of section used in Fig. 7. BKF, Ballakaighin Fault; BWL, Baldwin Lineament; GAL, Glen Auldyn Lineament; GDL, Glen Dhoo Lineament, GHL, Glen Helen Lineament; MHL, Maughold Head Lineament; MKL, Mount Karrin Lineament; NBL, North Barrule Lineament; SGL, Sulby Glen Lineament.

total of 1–4 km of normal movement is recorded following extensional events in the early Carboniferous, early Permian, late Jurassic and early Tertiary (Quirk & Kimbell 1997).

On the basis of the geological boundaries mapped in Fig. 6, four alternative structural cross-sections have been constructed for the north of the island (Fig. 7). These illustrate possible strati-graphic–structural scenarios ranging from a minimum of fault repetition (Fig. 7a) to a maximum of fault repetition (Fig. 7d). The direction of dip of the main faults is generally inferred rather than observed. Lettering is used to order the succession in each model (A being the oldest, N being the youngest) and to indicate proposed correlations, such as the Ny Garvain Formation equating with the Glen Dhoo Unit in Model 2 (C_2 in Fig. 7b). Several assumptions have been made during their construction, in particular:

- different lithostratigraphic units with similar lithofacies associations may correlate (Table 2; Figs 7b–d);
- lateral facies variations are limited except in some cases where lithofacies Q_H, Q_V, M_P, M_V and M_{IC} are present (Fig. 4);
- the overall structure is not complex and is controlled by a number of observed or inferred northeast–southwest reverse or normal faults, east–west dextral faults and north–south sinistral faults (Fig. 6; Quirk *et al.* 1999*b*);
- little of the succession is missing (Fig. 5);
- early Arenig or possible Tremadoc acritarch dates from near the Peel Harbour Fault are not representative of the age of the Glion Cam Unit (cf. Molyneux 1999), except possibly in Model 4 (Fig. 7d).

The total thicknesses quoted below are based on the succession north of Lag ny Keeilley (Figs 1 and 6) and do not take into account the possible lateral equivalence of the Lonan Formation (550 m thick) with the apparently much thicker Port Erin Formation (*c.* 2400 m thick) on the south coast (Table 2). In general, thicknesses may be overestimated due to the difficulty in recognizing contractional structures in certain intervals, particularly those that are predominantly muddy such as the Barrule Formation.

Model 1

Figure 7a assumes that a continuous succession exists from the Lonan Formation to the Lady Port

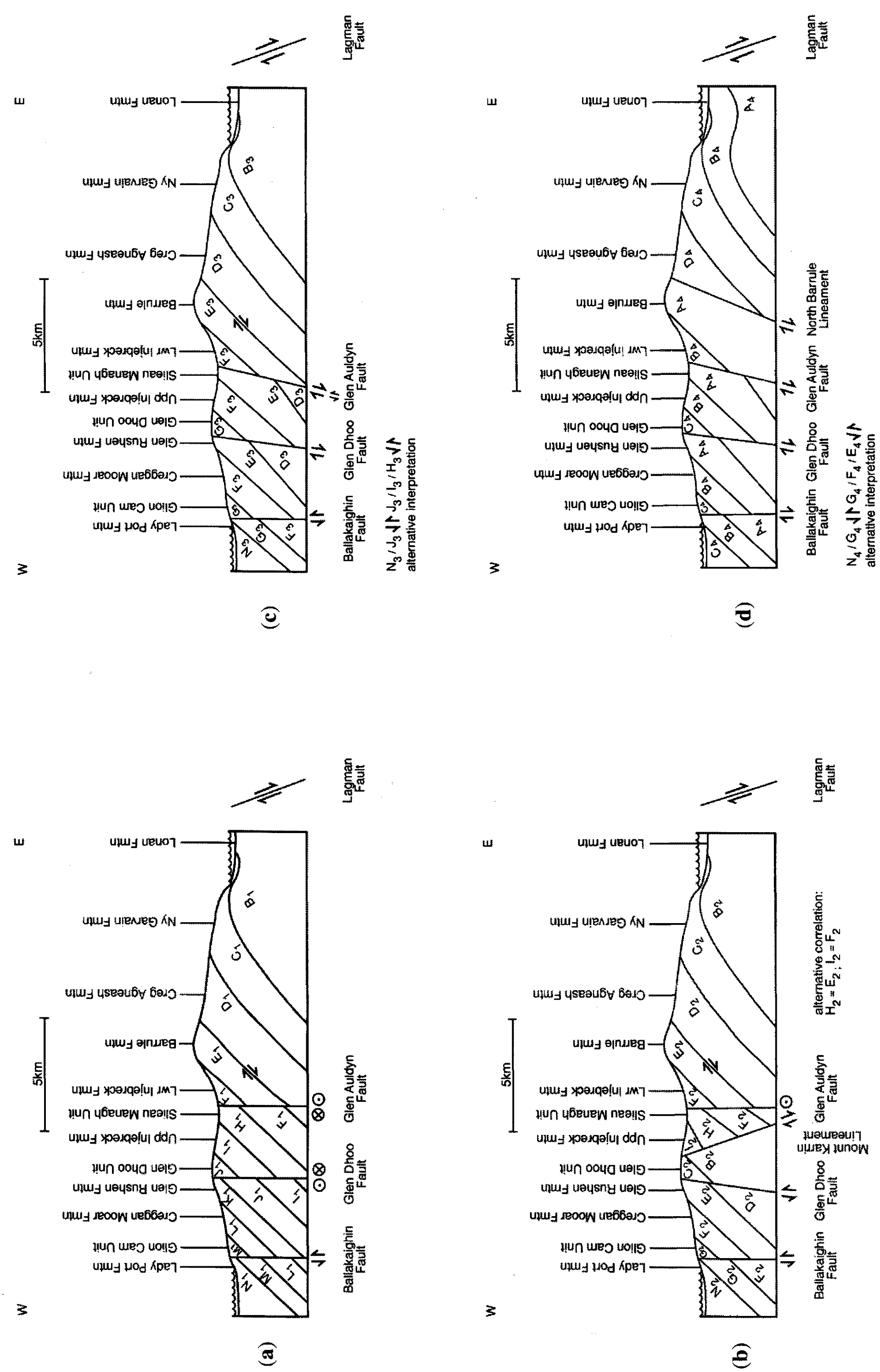

Fig. 7. Schematic cross-sections illustrating alternative structural models across the central-north area (Fig. 6). See text for details. **(a)** Model 1 (interpretation with minimum fault repetition); **(b)** Model 2 (favoured interpretation); **(c)** Model 3; **(d)** Model 4 (interpretation with maximum fault repetition).

Formation with minimal fault repetition. The Glen Auldyn, Glen Dhoo and Ballakaighin Faults throw down to the west. This interpretation implies that the Manx Group is *c.* 12 750 m thick (or 10 650 m if the tectonically complex Lady Port Formation is excluded). Based on two similar acritarch dates from the Glen Dhoo Unit and from the lateral correlative of the Ny Garvain Formation (the Santon Formation) (Table 2; Molyneux 1999), the model suggests that a probably unreasonable 6500 m of sediment was deposited during the early Arenig (*c.* 5 Ma). The youngest acritarch date is late Arenig from the Lady Port Formation at the top of the succession (Table 2).

Model 2

Figure 7b provides the best fit with the biostratigraphy of Molyneux (1999), with the geophysical interpretation of Quirk *et al.* (1999*b*) and with geologically reasonable sedimentation rates. It assumes that a continuous succession exists from the Lonan Formation to the upper unit of the Injebreck Formation, but that the early Arenig Glen Dhoo Unit is equivalent to the Ny Garvain Formation by virtue of a large normal fault (the Mount Karrin Lineament) that throws down to the east. The Slieau Managh Unit may represent a set of debris flows sourced from the fault. This unit may either be confined to the area between the Mount Karrin and Glen Auldyn Faults or it may correlate with the Barrule Formation, implying that the lower and upper units of the Injebreck Formation are lateral equivalents (Fig. 7b). Alternatively, the normal fault may be entirely post-depositional. The mid-Arenig Glen Rushen Formation is a thinner correlative of the Barrule Formation and the Creggan Mooar Formation is a thinner, more distal equivalent of the Injebreck Formation, a correlation supported by the presence of the distinctive lithofacies M_{IC} at a coastal exposure near Ramsey (Fig. 4). The Glen Auldyn, Glen Dhoo and Ballakaighin Faults throw down to the west. South of the section, the Glen Helen Lineament throws down to the east. It either represents a west dipping reverse fault reactivating the Glen Dhoo Fault or, more likely, is an extension of the east dipping Mount Karrin normal fault, implying that the Glen Dhoo Fault is also normal.

In Model 2, the Manx Group reaches a maximum thickness of 9250 m if the Slieau Managh Unit does not correlate with the Barrule Formation (or 7150 m if the Lady Port Formation is excluded). If this does correlate, the Manx Group is *c.* 7500 m thick (or 5400 m if the Lady Port Formation is excluded). Possible syn-sedimentary fault activity during deposition of the Slieau Managh Unit is consistent with a model of Arenig tectonism supported by Woodcock & Barnes (1999) and Woodcock & Morris (1999).

Model 3

Figure 7c shows a continuous succession from the Lonan Formation to the Injebreck Formation. The Glen Rushen Formation and Slieau Managh Unit are equivalent to the Barrule Formation, due to stratigraphic repetition caused by reverse offset on the Glen Dhoo and Glen Auldyn Faults. The Slieau Managh debris flows may have been sourced from a normal syn-sedimentary precursor to the Glen Auldyn Fault. Later reverse offset would be due to Caledonian reactivation. The Creggan Mooar Formation and upper Injebreck Unit are thinner, more distal correlatives of the lower Injebreck Unit, with the Glion Cam and more proximal Glen Dhoo Units interpreted to overlie these. However, biostratigraphic evidence (Molyneux 1999) does not support this interpretation, as the Glen Dhoo Unit is older than the Glen Rushen Formation. The estimated thickness of the Manx Group in this model is 7750 m (or 5650 m excluding the Lady Port Formation). However, to conform with the biostratigraphy, an alternative is also suggested on Fig. 7c where the younger Glen Rushen Formation is juxtaposed against the Glen Dhoo Unit by normal faulting along the Glen Helen Lineament. In this case, the Glen Rushen Formation is not the lateral equivalent of the Barrule Formation. This alternative interpretation adds another 2000 m to the estimated thickness of the Manx Group in Model 3.

Model 4

Figure 7d shows the most stratigraphic repetition due to reverse movement on the Glen Auldyn, Glen Dhoo and Ballakaighin Faults, and an additional fault, known as the North Barrule Lineament, which cuts out part of the Barrule Formation. The complete succession is represented by the Barrule–Slieau Managh–Glen Rushen lateral correlatives at the base, followed by the Lonan–Injebreck–Creggan Mooar correlatives, in turn overlain by the Ny Garvain–Glen Dhoo–Glion Cam correlatives and, finally, by the Creg Agneash Formation. The lateral correlatives tend to thin and fine westwards. The structural configuration shown on Fig. 7d is reminiscent of northwest dipping structures imaged on offshore seismic sections along-strike from the Glen Dhoo, Glen Auldyn and North Barrule Lineaments (Quirk *et al.* 1999*b*). None the less, as in the previous model, this stratigraphic order is not supported by acritarch dates. These indicate that the Glen Dhoo Unit is older than the underlying Glen Rushen Formation. An alternative interpretation, also shown on Fig. 7d, overcomes this problem by making the Glen Helen Lineament a normal fault juxtaposing the younger Glen Rushen Formation against the Glen Dhoo Unit. If, instead, the Glen Rushen data are ignored, then the poorly constrained biostratigraphic data from near Peel may indicate that the base of the Glion Cam Unit is pre-Arenig in age (Molyneux 1999). This interpretation implies that the Manx Group may be as little as 4500 m thick.

Summary

Although Model 2 (Fig. 7b) is favoured here, all four models have aspects to recommend them. Resulting estimates of the thickness of the Manx Group vary from 4500 to 10 650 m, with an average of 7000 m. These estimates do not include the highly faulted Lady Port Formation (*c*. 2100 m thick) at the top of the succession, nor the Port Erin Formation (*c*. 2400 m thick) in the south of the island, with which the upper part of the Lonan Formation (550 m thick) may correlate (Table 2; Fig. 5).

Sequence stratigraphic interpretation and basin model

No matter what structural interpretation is put on the Manx Group, important lithological variations are apparent within the succession (Fig. 5). On the east side of the island, the 550 m thick lower unit of the Ny Garvain Formation comprises > 80% thin–thick-bedded quartz arenites (lithofacies S_I and S_H), whereas the 1200 m thick Barrule Formation consists almost entirely of dark grey mudstone (lithofacies M_V). A similar contrast is seen between other formations, such as the Glen Dhoo Unit and the Glen Rushen Formation. Alternations on this sort of scale in deep-marine sediments are typically caused by second- (10–80 Ma) or third-order (1–10 Ma) variations in the relative height of sea level, the different units within each cycle or sequence being assigned to systems tracts (Vail *et al.* 1977). Sand bypasses the shelf during periods of falling and low relative sea level (lowstands), when it is carried down submarine canyons into the deeper parts of the basin by turbidity currents, depositing thick submarine fans in an otherwise distal environment (Galloway 1998). A subsequent rise in relative sea level causes transgression, when sands are trapped on the shelf and muds are mostly deposited further out in the basin. Thereafter, a subsequent highstand in relative sea level is associated with deltaic progradation on the shelf which may lead to oversteepening and slumping at the front of the delta causing mixed sand–mud turbidites to flow basinwards.

Therefore, a change from low to high relative sea level is likely to be reflected in the deep-marine environment as a change from clean sandstones within a turbidite fan (lowstand systems tract) to mudstones (transgressive systems tract) to mixed sandstone–mudstone turbidites with possible debris flows (highstand systems tract). This corresponds with the change seen from the base of the Santon–Ny Garvain Formations (early Arenig) to the top of the Injebreck Formation (?mid-Arenig) (Table 2). The Creg Agneash Formation, above the Ny Garvain Formation, displays a fining-upwards signature (Fig. 4) typical of the lower part of the transgressive systems tract. The Barrule Formation is thought to represent the upper part of the transgressive systems tract. There are insufficient biostratigraphic data to be sure whether there is another, younger relative sea-level cycle recorded in the Manx Group, from the base of the Glen Dhoo Unit to the top of the Glion Cam Unit (Table 2). Consequently, this part of the succession could be a partial or complete repetition of the early–?mid Arenig cycle (Fig. 7b–d).

Woodcock & Barnes (1999) record a divergence between palaeoflows recorded from flute casts (west directed) at the base of turbidite beds (typically lithofacies Q_H, Q_V, W_H and M_L) and ripple crests (north directed) at the top of other beds (typically lithofacies S_L, S_I and S_H). They propose a model for the deposition of formations exposed on the southern and eastern coast of the Isle of Man involving 2–10 km wide turbidite lobes along an actively faulted margin. The high concentration parts of the turbidity currents are shown running west, subparallel to the continental margin, due to deflection at east-northeast–west-southwest trending fault scarps, whereas the higher, low concentration parts of the currents flow northwards, undeflected by the scarps, towards the deeper basin (Woodcock & Barnes 1999). The present authors regard this model as unlikely for the following reasons:

- evidence for lobe geometries is minimal, with sand-dominated intervals easily correlated over distances of at least 10 km;
- bimodal palaeocurrent data are not usual in faulted areas where, typically, the wide variety of slopes produces a polymodal flow distribution (e.g. Boote & Gustav 1987; Prosser 1993);
- turbidites usually flow down the continental slope, not along it, whether there are faults present or not (e.g. Galloway 1998);
- evidence for thickness variations or other syn-sedimentary features indicative of active faults in the Manx Group is circumstantial.

An alternative model is developed here building on geophysical interpretations by Kimbell & Quirk

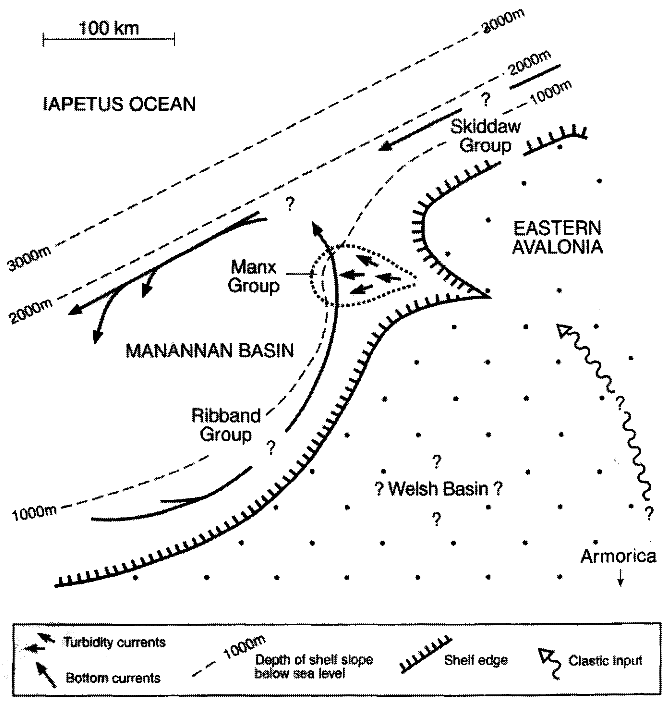

Fig. 8. Tentative palaeogeographic reconstruction of the northwest margin of Eastern Avalonia during the early Arenig showing conceptual current patterns. The relative positions of areas indicated, particularly the Welsh Basin, are speculative and differing amounts of anticlockwise rotation during the late Caledonian have not been taken into account (see Piper & Crowley 1999; Piper *et al.* 1999). See text for discussion.

(1999) and Quirk *et al.* (1999*b*). This work suggests that the Manx Group was deposited on the west dipping margin of an embayment on the northwest edge of Eastern Avalonia, termed the Manannan Basin. The thick sands of the lower part of the Santon Formation and the lower unit of the Ny Garvain Formation, its lateral equivalent, are therefore thought to represent part of an early Arenig lowstand fan, with the basal, high energy parts of turbidity currents flowing westwards down the slope of the margin (Fig. 8). However, ripples were produced by low-energy tractional currents flowing to the north, apparently perpendicular to the dip of the slope, i.e. by contour currents. These contour currents either reworked sands initially deposited as turbidites or deflected the flow of turbidity currents as they slowed down. Reworking may help to explain why the lower unit of the Ny Garvain Formation consists of a thick package of unusually clean sandstones (lithofacies S_H; Fig. 4) and also why flute casts and grading are rarely observed in lithofacies S_L and S_I in the Lonan Formation and the upper unit of the Ny Garvain Formation (Table 1). However, the northwards directed ripples are usually preserved in sandstone beds which are interbedded with thin mudstones, indicating that currents strong enough to move sand were only intermittently active. The favoured explanation is one of episodic flow due to deflection along-slope of the low-energy part of turbidity currents by north moving bottom waters (Fig. 8). What is not recorded in palaeocurrent data is the swing from downslope, westwards flow to along-slope, northwards flow as energy decreased, presumably because this was when massive and planar laminated sands were deposited (Bouma units Tab, e.g. in lithofacies S_H, Q_H and Q_V; Table 1).

A speculative lowstand flow pattern for contour currents along the northwest margin of Eastern Avalonia (Fig. 8) is one of the anticlockwise circulation system constrained only by the ripple cross-lamination palaeocurrent data from the Manx Group (Woodcock & Barnes 1999). As Eastern Avalonia lay in the southern hemisphere at this time (e.g. Noblet & Lefort 1990), this direction of circulation may have been driven directly by the Coriolis force. However, the circulation probably formed part of a larger, more complex flow pattern as is typical in present-day oceans (Stow *et al.* 1996).

A modern analogue for the Manannan Basin, albeit in the northern hemisphere, might be the Faeroe–Shetland channel where bottom waters between 500 and 1700 m below sea level flow southwest from the Norwegian Basin towards the Atlantic Ocean at rates of up to 0.5 m s^{-1} (Stoker *et al.* 1998; Masson *et al.* 1997). The Faeroe–Shetland Channel, unlike the Manannan Basin, is starved of coarse-grained turbiditic input. Nevertheless, a thin sandy contourite sheet is developed here at a water depth of 700–850 m over an area of 60 × 10 km^2, elongate-parallel to the shelf edge.

There are lithological similarities between the Ribband Group and mud-prone (distal) lithofacies in the Manx Group (McConnell *et al.* 1999; Morris, pers. comm.; Brück, pers. comm.), although this is the subject of ongoing research. In contrast to the Manx and Ribband Groups, a good biostratigraphic framework is available for the Skiddaw Group, although lithostratigraphic comparisons are not straightforward. Based on acritarch data (Molyneux 1999), the quartzose Santon and Ny Garvain Formations in the Manx Group seem to correlate with the mud-dominated Hope Beck Formation in the Skiddaw Group. The sandstones in the Watch Hill Formation and Loweswater Formation below and above the Hope Beck Formation are wackes rather than quartz arenites (Cooper *et al.* 1995). Even the slumps and debris flows in the upper Arenig Kirk Stile Formation are different to the pebbly mudstones of the Slieau Managh Unit and Lady Port Formation in that they represent larger scale events (olistostromes) and contain extra-formational clasts (Webb & Cooper 1988; Cooper, pers. comm.). Cooper *et al.* (1995) suggest a passive margin setting for the Skiddaw Group. Similar to most of southeast Ireland (Max *et al.* 1990), subduction-related accretionary prisms and island arcs are not evident until the Llanvirn in the Lake District, probably when Eastern Avalonia broke from Gondwana.

Kimbell & Quirk (1999) propose that the Manannan Basin was initiated by rifting, probably during the late Tremadoc. Felsitic igneous sheets occur throughout the Manx Group (Lamplugh 1903). Many of these appear to have been intruded when the sediment was still soft, perhaps indicating that a limited amount of extension was still occurring during deposition (Quirk & Kimbell 1997). However, evidence for syn-sedimentary normal faults is highly tentative (see Fig. 8 and previous discussion of Model 2, Fig. 7b). At present, the authors regard the eastern margin of the Manannan Basin as essentially passive and undergoing post-rift thermal subsidence during most of the Arenig. This is contrary to the ideas of Quirk & Kimbell (1997).

Cooper *et al.* (1995) propose that some of the more quartzose arenites in the Skiddaw Group were derived from a Gondwanan shelf where widespread shallow water and continental sandstones, known collectively as the Grès Armoricain, were deposited (Noblet & Lefort 1990). A similar link has been suggested by Woodcock & Barnes (1999) for the Manx Group, implying that a connection existed between the northwest margin of Eastern Avalonia and the coastal plain deposits of Arenig age on the Armorican Massif (Fig. 8).

The relationship of the Ribband, Manx and Skiddaw Groups with the Welsh Basin (Fig. 8) is uncertain (Kokelaar 1988). It is, however, noteworthy that Wales was the site of intracratonic rifting in the late Tremadoc, then uplift followed by transgression in the early–mid-Arenig (Kokelaar 1988; Woodcock 1990), consistent with the structural and stratigraphic evidence at the edge of the craton in the deeper-water setting of the Isle of Man.

Conclusions

The Manx Group dips generally northwest with the oldest sediments (quartzose sandstones) in the southeast and the youngest sediments (mud dominated) in the central and northwest parts of the island. The gross structure is controlled by northeast–southwest reverse faults and east–west dextral faults. With only limited biostratigraphic control, several alternative lithostratigraphic correlations are possible, depending on the amount of assumed fault repetition. The Manx Group is > 4500 m thick, with distal units in the west juxtaposed by reverse faults against more proximal units in the east. A large normal fault may define the east-southeast edge of a sand-prone interval (the Glen Dhoo Unit) in the central-north area. Whether this fault was active during deposition is as yet unproven.

The lithofacies observed in the Manx Group are typical of a passive continental margin. A tentative model proposes that the succession represents the inverted, eastern side of a basin stretching at least as far as Leinster, named the Manannan Basin, which formed an embayment on the northwest edge of Eastern Avalonia. In the early Arenig, a large-scale turbidite fan developed in the Isle of Man area during a lowstand in relative sea level, when the Santon and Ny Garvain Formations were deposited, and probably also the correlative Glen Dhoo Unit. Quartzose sand bypassed the shelf and was carried by turbidity currents downslope to the west. The fan may also have been affected by north flowing bottom currents. The onset of a rise in relative sea level, probably towards the end of the early Arenig, was associated with deposition of the fining-upwards Creg Agneash Formation as the fan became inactive. A blanket of fine-grained mud was deposited during the mid-Arenig (the Glen Rushen Formation and its probable lateral equivalent, the Barrule Formation) overlain by thin-bedded turbidites and debris flows corresponding to a relative sea-level highstand (the Creggan Mooar and Injebreck Formations).

Further biostratigraphic work is now required to constrain the lithostratigraphic interpretations, particularly to test whether the Glen Rushen–Creggan Mooar Formations are distal equivalents of the Barrule–Injebreck Formations, and to assess whether the Port Erin Formation is the correlative of the Lonan or Creg Agneash Formations.

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References

BOOTE, D. R. D. & GUSTAV, S. H. 1987. Evolving depositional systems within an active rift: Witch Ground Graben, North Sea. *In*: BROOKS, J. & GLENNIE, K. W. (eds) *Petroleum Geology of NW Europe*. Graham Trotman, 819–833.

COOPER, A. H., RUSHTON, A. W. A., MOLYNEUX, S. G., HUGHES, R. A., MOORE, R. M. & WEBB, B. C. 1995. The stratigraphy, correlation, provenance and palaeogeography of the Skiddaw Group (Ordovician) in the English Lake District. *Geological Magazine*, **132**, 185–211.

FITCHES, W. R., BARNES, R. P & MORRIS, J. H. 1999. Geological structure and tectonic evolution of the Lower Palaeozoic rocks of the Isle of Man. *This volume*.

FORD, T .D., WILSON, E. & BURNETT, D. J. 1999. Previous ideas and models of the stratigraphy, structure and mineral deposits of the Manx Group, Isle of Man. *This volume*.

GALLOWAY, W. E. 1998. Siliciclastic slope and base-of-slope depositional systems: component facies, stratigraphic architecture and classification. *AAPG Bulletin*, **82**, 569–595.

KENNAN, P. S. & MORRIS, J. H. 1999. Manganiferous ironstones in the early Ordovician Manx Group, Isle of Man: a protolith of coticule? *This volume*.

KIMBELL, G. S. & QUIRK, D. G. 1999. Crustal magnetic signature of the Irish Sea region: evidence for a major basement boundary beneath the Isle of Man. *This volume*.

KOKELAAR, P. 1988. Tectonic controls of Ordovician arc and marginal basin volcanism in Wales. *Journal of the Geological Society, London*, **145**, 759–775.

LAMPLUGH, G. W. 1903. *The Geology of the Isle of Man*. Memoir of the Geological Survey, United Kindom. HMSO.

MCCONNELL, B. J., MORRIS, J. H. & KENNAN, P. S. 1999. A comparison of the Ribband Group (southeastern Ireland) to the Manx Group (Isle of Man) and Skiddaw Group (northwestern England). *This volume*.

MASSON, D. G., BETT, B. J. & BIRCH, K. G. 1997. Atlantic margin environmental survey. *Sea Technology*, **10/97**, 52–59.

MAX, M. D., BARBER, A. J. & MARTINEZ, J. 1990. Terrane assemblage of the Leinster Massif, SE Ireland, during the Lower Palaeozoic. *Journal of the Geological Society, London*, **147**, 1035–1050.

MOLYNEUX, S. 1979. New evidence for the age of the Manx Group, Isle of Man. *In*: HARRIS, A. L., HOLLAND, C. H. & LEAKE, B. E. (eds) *The Caledonides of the British Isles – Reviewed*. Geological Society, London, Special Publications, 415–421.

—— 1999. A reassessment of Manx Group acritarchs, Isle of Man. *This volume*.

MORRIS, J. H., WOODCOCK, N. H. & HOWE, M. P. A. 1999. The Silurian succession of the Isle of Man: the late Wenlock Niarbyl Formation, Dalby Group. *This volume*.

NOBLET, C. & LEFORT, J. P. 1990. Sedimentological evidence for a limited separation between Armorica and Gondwana during the Early Ordovician. *Geology*, **18**, 303–306.

ORR, P. J. & HOWE, M. P. A. 1999. Macrofauna and ichnofauna of the Manx Group (early Ordovician), Isle of Man. *This volume*.

PICKERING, K. T., HISCOTT, R. N. & HEIN, F. J. 1989. *Deep Marine Environments. Clastic Sedimentation and Tectonics*. Unwin Hyman.

PIPER, J. D. A. & CROWLEY, S. F. 1999. Palaeomagnetism of (Palaeozoic) Peel Sandstone and the Langness Conglomerate Formation, Isle of Man: implications for the age and regional diagenesis of Manx red beds. *This volume*.

——, BIGGIN, A. J. & CROWLEY, S. F. 1999. Magnetic survey of the Poortown dolerite, Isle of Man. *This volume*.

PROSSER, S. D. 1993. Rift related depositional sequences and their seismic expression. *In*: WILLIAMS, G. D. & DOBB, A. (eds) *Tectonics and Seismic Stratigraphy*. Geological Society, London, Special Publications, **56**, 35–56.

QUIRK, D. G. & KIMBELL, G. S. 1997. Structural evolution of the Isle of Man and central part of the Irish Sea.

In: MEADOWS, N. S., TRUEBLOOD, S. P., HARDMAN, M. & COWAN, G. (eds) *Petroleum Geology of the Irish Sea and Adjacent Areas*. Geological Society, London, Special Publications, **124**, 135–159.

——, ROY, S., KNOTT, I. & REDFERN, J. 1999*a*. Petroleum geology and future hydrocarbon potential of the Irish Sea. *Journal of Petroleum Geology*, in press.

——, BURNETT, D. J., KIMBELL, G. S., MURPHY, C. A. & VARLEY, J. S. 1999*b*. Shallow geophysical and geological evidence for a regional-scale fault duplex in the Lower Palaeozoic of the Isle of Man. *This volume*.

ROBERTS, B., MORRISON, C. & HIRONS, S. 1990. Low grade metamorphism of the Manx Group, Isle of Man: a comparative study of white mica 'crystallinity' techniques. *Journal of the Geological Society, London*, **147**, 271–277.

SIMPSON, A. 1963. The stratigraphy and tectonics of the Manx Slate Series, Isle of Man. *Quarterly Journal of the Geological Society, London*, **119**, 367–400.

STOKER, M. S., AKHURST, M. C., HOWE, J. A. & STOW, D. A. V. 1998. Sediment drifts and contourites on the continental margin off northwest Britain. *Sedimentary Geology*, **115**, 33–51.

STOW, D. A. V., READING, H. G. & COLLINSON, J. D. 1996. Deep seas. *In*: READING, H. G. (ed.) *Sedimentary Environments: Processes, Facies and Stratigraphy*. Blackwell, 395-453.

VAIL, P. R., MITCHUM, R. M. JR, & THOMPSON, S. III 1977. Seismic stratigraphy and global changes of sea level, Part 4: global cycles of relative changes of sea level. *In*: PAYTON, C. E. (ed.) *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*. American AAPG Memoir, **26**, 83–97.

WEBB, B. C. & COOPER, A. H. 1988. Slump folds and gravity slide structures in a Lower Palaeozoic marginal basin sequence (the Skiddaw Group), NW England. *Journal of Structural Geology*, **10**, 463–472.

WOODCOCK, N. H. 1990. Sequence stratigraphy of the Palaeozoic Welsh Basin. *Journal of the Geological Society, London*, **147**, 537–547.

—— & BARNES, R. P. 1999. An early Ordovician turbidite system on the Gondwana margin: the southeastern Manx Group, Isle of Man. *This volume*.

—— & MORRIS, J. H. 1999. Debris flows on the Ordovician margin of Avalonia: the Lady Port Formation, Manx Group, Isle of Man. *This volume*.

——, ——, QUIRK, D. G. ET AL. 1999. Revised lithostratigraphy of the Manx Group, Isle of Man. *This volume*.