Geol. Mag. **144** (*2*), *2007, pp. 319–331.* © *2007 Cambridge University Press*
doi:10.1017/S0016756806003013 First published online 9 February 2007 *Printed in the United Kingdom*

Fan-delta sedimentation in the Silurian Coralliferous Formation of SW Wales: implications for the structure of the southern margin of the Welsh Basin

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(*Received* 19 December 2005; *accepted* 15 May 2006)

Abstract – The uppermost Llandovery to lower Wenlock Coralliferous 'Group' in SW Pembrokeshire is here redefined as a single formation with two members. The Coralliferous Formation is approximately 150 m thick and comprises a basal unit of granule- to pebble-grade rudite beds, the Renney Slip Member, overlain by interbedded mudstones and fine sandstones of the Deadman's Bay Member. The Renney Slip Member lies unconformably above the Skomer Volcanic Group and includes 12.4 m of coarse grained, granule- and pebble-rich rudites, with beds up to 0.94 m thick. Three lithofacies are recognized within this unit: coarse, granule-rich rudite beds are interpreted as a variety of mass flow deposits, some of which have been reworked in a marine environment; thick sandstones with planar and ripple lamination are shoreface to offshore transition zone deposits; silty mudstones interbedded with very fine grained sandstones represent marine offshore deposits, formed largely below mean storm wave base. These facies associations, and abundant bioturbation, indicate an environment with a strong marine influence, and a proximal source of coarse grained sediment. The Renney Slip Member is reinterpreted in the context of a fan delta depositional model. At least seven cycles of deposition are recognized, each showing an upwards-fining pattern, representing deposition from fan delta, shoreface–transition zone to open marine environments. These patterns of deposition are attributed to localized tectonic movements causing variations in relative sea level. At the time the Renney Slip Member was deposited, the southern Welsh Basin margin is interpreted as a fault-block extensional margin, with the landmass of Pretannia to the south. Though fan-delta deposition took place southwards against the uplifted footwall of the Wenall Fault, the basin margin lay to the south of the Ritec Fault.

Keywords: fan delta, sedimentology, Silurian, Wales.

1. Introduction

Research in Wales and the immediately adjacent parts of England, the Welsh Basin and its hinterland, provided the basis on which the Silurian System was originally founded (Murchison, 1839). In SW Pembrokeshire, on the southern (Pretannian) margin of the basin, the Silurian crops out in a series of fault-bounded structural blocks (Fig. 1). The most complete sequence is preserved in the Marloes Block, where there are spectacular, continuously exposed coastal sections, ranging in age from Llandovery to Early Devonian. The Silurian sequence of this area contrasts in important respects with the classic Silurian successions of the Welsh Borderland, which were deposited on the Midland Platform. Notably, the Llandovery succession is much thicker, more complete, and is dominated by volcanic rocks, while the Wenlock and Ludlow parts of the sequence are clastic and lack the prominent limestone formations seen in the type areas of those series. Though the Silurian rocks of the Marloes Block have been the subject of scientific enquiry since they were first described by Murchison (1839), they have been less intensively studied than their equivalents in the Welsh Borderland and their sedimentology and stratigraphy are less fully understood.

The principal Silurian to Lower Devonian lithostratigraphical units currently recognized in the area are the Skomer Volcanic (Ziegler *et al.* 1969), Coralliferous (De la Beche, 1846; Ziegler *et al.* 1969; Walmsley & Bassett, 1976), Gray Sandstone (De la Beche, 1846) and Milford Haven groups (Allen & Williams, 1978). The Skomer Volcanic Group (upper Llandovery, C_{1-2}) is unconformably overlain by the Coralliferous 'Group' of late Llandovery (C_6) to early Wenlock age. It is here accorded formation status, and its two constituent members are formally described for the first time (Fig. 2). The immediately underlying Skomer sediments, separated by a brief time gap, have been interpreted as a coastal barrier island sequence by Bridges (1976). The lower, Renney Slip Member of the Coralliferous Formation is dominantly rudaceous, and was previously

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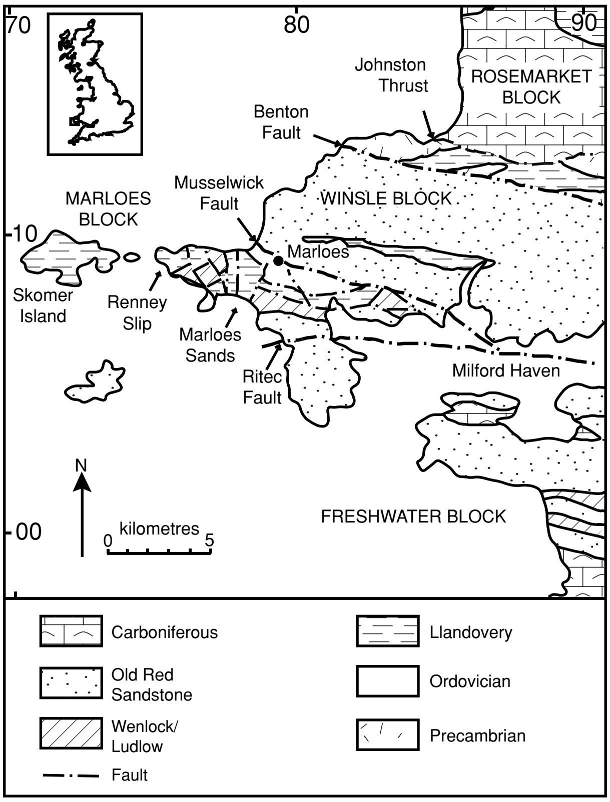

Figure 1. Map summarizing the geology of SW Pembrokeshire (modified from Aldridge *et al.* 2000, fig. 3.18, p. 95). Gridlines indicated are from the Ordnance Survey National Grid, 100 km square SM.

Figure 2. Unconformity between the Renney Slip Member and the Skomer Volcanic Group in Renney Slip (SM 7605 0866, photograph taken facing north). The angular discordance is slight, but older beds can be seen to be truncated, particularly to the right of the white arrow (scale bar 1 m).

considered to be of fluvial/shoreface origin (Hillier, 2002). The overlying Deadman's Bay Member comprises alternating mudstones and rhythmically bedded sandstones and shelly sandstones. The sedimentology of the upper member, and the likely causes of the sedimentary rhythms it displays, will be discussed separately.

2. Stratigraphy

2.a. History of research

The first scientific description of the rocks of the Coralliferous Formation of SW Pembrokeshire was made by Murchison (1839). He described the section at Marloes Sands and, from his plate 35, figure 10, it is possible to recognize the main Silurian lithostratigraphical units. Building on this early work, De la Beche (1846) first described the formation as the fossil-rich 'Coralliferous Series'. The Officers of the Geological Survey (Cantrill *et al.* 1916) continued the use of De la Beche's terminology. Those workers considered that the base of this unit at Renney Slip 'may mark a slight local transgression' (p. 55; Fig. 2), but in the Marloes section they identified a small fault at the base of the sequence, which 'probably cuts out no considerable thickness of strata' (p. 62).

Ziegler *et al.* (1969) restudied the Skomer Volcanic and Conglomerate 'series' of Cantrill *et al.* (1916), and combined them into the Skomer Volcanic Group, noting that the basal beds of the Coralliferous 'Series' had been included by Cantrill *et al*. (1916, p. 61) in their Conglomerate 'Series'. Ziegler *et al*. (1969) also recognized that the base of these coarse beds in the Coralliferous Series is an unconformity, which can also be seen in the upper part of the cliffs at Marloes Sands. They informally separated the Coralliferous 'Series' into two: the coarse basal facies, and the overlying finer grained facies, with the boundary lying above the top conglomerate bed. The Coralliferous 'Series' was renamed by Walmsley & Bassett (1976) as the Coralliferous Group. They did not revise the lithostratigraphy in detail, since their main aim was to improve the biostratigraphy and correlate the full succession. Most recently, Hillier (2002) discussed the sedimentology and sequence architecture of the Coralliferous Group. He identified three facies associations: low sinuosity fluvial (only recorded at Renney Slip), shoreface and distal shelf. These changes in depositional environment were linked to changes in relative sea level associated with tectonism. These interpretations are discussed further in Section 2.d, following the facies descriptions.

2.b. Revised lithostratigraphy

2.b.1. Coralliferous Formation

Given its relationships with older and younger units, the appropriate level in the lithostratigraphical hierarchy for the Coralliferous Group is to recognize a single formation with two members. Although not related to a geographical locality, 'Coralliferous' is retained as part of the name, in harmony with well-established usage and following recommended practice (Whittaker *et al.* 1991, p. 815).

Sanzen-Baker (1972) gave the full thickness of the Coralliferous Group as 133 m; Walmsley & Bassett (1976) stated that it was 130 m. As part of the present study, the sequence between Renney Slip and Deadman's Bay was logged to the highest accessible point on Pitting Gales Point [SM 7601 0841], a thickness of 143.3 m. Higher parts of the cliff there are in the Gray Sandstone Group. It is estimated that the transition between the units lies no more than 10 m above the top of the measured section, indicating a total thickness for the Coralliferous Formation in its type area of ∼ 153 m.

2. b.2. Renney Slip Member

The type section of the Renney Slip Member is seen at low tide in the shore of Renney Slip (SM 7602 0867; Fig. 3, section C). This unit unconformably overlies the Skomer Volcanic Group, with an angular discordance of around 5°, and the beds immediately below the unconformity reddened to a depth of around 0.55 m. In the type section, the Renney Slip Member is 12.4 m thick and comprises dominantly coarse grained, granule- and pebble-rich rudites, some reddened, with beds up to 0.94 m thick. The top of the member is defined by the base of the Deadman's Bay Member (see below).

Two further exposures of the Renney Slip Member occur in Renney Slip. A good reference section is seen in the eastern cliffs (SM 7605 0866; Fig. 3, section B), where the basal contact of the member is best exposed, but only the lower 6.9 m are accessible. A further 4.65 m thick, fault-bounded sequence is exposed in the southeastern cliffs of Renney Slip (SM 7604 0865; Fig. 3, section A). The member crops out also at Marloes Sands (SM 7876 0724; Fig. 3, section D), but the unconformity is not clearly visible in the cliffs there due to minor faulting at the boundary. No great thickness of strata is thought to be cut out (Cantrill *et al.* 1916) and a total thickness of 6.3 m is exposed. The Renney Slip Member is currently exposed nowhere else.

2. b.3. Deadman's Bay Member

The type section of the Deadman's Bay Member is seen in the coastal cliffs between Renney Slip (SM 7604 0864) and Deadman's Bay (SM 7602 0841), where it reaches a maximum of 140.9 m in thickness. The base of this member is clearly recognized where the fine grained, interbedded sandstones and silty mudstones abruptly overlie the characteristic rudite beds of the Renney Slip Member (Fig. 4). The top of the Deadman's Bay Member is defined by the base of the Gray Sandstone Group, which crops out high in the cliffs of Pitting Gales Point (SM 7601 0841). The reference section of the Deadman's Bay Member is exposed in the cliffs at Marloes Sands (SM 7872 0724 to 7878 0711), where it reaches a thickness of at least 97.34 m, and the upper boundary is obscured by fallen blocks. A further section within the Marloes Block is seen near St Ishmael's, between Watch House Point and Longberry Point (SM 8373 0648); 11 m of the uppermost Deadman's Bay Member are exposed, but access is difficult. The upper beds of the Deadman's Bay Member are also recognized in part in the Winsle Inlier (SM 804097 to SM 862087) where the thickness is uncertain due to poor exposure and repetition of strata by folding (Allen *et al.* 1976). These strata occur in the Winsle Block (Sanzen-Baker, 1972) where the upper part of the Coralliferous Formation is stained red, and the exposed sequence is unconformably overlain by the Milford Haven Group (Siveter, Owens & Thomas, 1989). Exposure there is now very limited.

2. c. Biostratigraphy

Walmsley & Bassett (1976) biostratigraphically dated the topmost part of the Skomer Volcanic Group at Renney Slip and Marloes Sands as C_{1-2} (Fronian), lower Aeronian in current terminology. Between 10 and 20 m above the unconformable base of the Coralliferous Formation they found an upper Llandovery (C_6, Telychian) fauna, giving the unconformity a duration from C_3 to C_5. The highest parts of the Coralliferous Formation were found to be of immediately post-*riccartonensis* Biozone age, probably mid–late Sheinwoodian, indicating that the Deadman's Bay Member of the Coralliferous Formation spans the Llandovery–Wenlock boundary.

3. Lithofacies of the Renney Slip Member

Three lithofacies have been identified within the Renney Slip Member: Lithofacies 1, 2 and 3. This distinction was made using grain size, stratal surfaces (bed bases and tops), sedimentary structures, textures and the presence or absence of trace and body fossils.

3. a. Lithofacies 1 (rudite-dominated lithofacies)

3. a.1. Description

This rudite-dominated facies includes the coarsest-grained sediments and thickest beds within the Renney Slip Member. Units of Lithofacies 1 vary from 0.12–3.07 m thick; individual beds range up to 0.94 m in thickness and, at the scale of the exposures, appear tabular.

The total of 38 rudite beds seen in this lithofacies have been classified according to their internal structures and support textures (Table 1 and Fig. 5). In many beds an inversely graded lower level is succeeded by a normally graded upper part. Matrix support

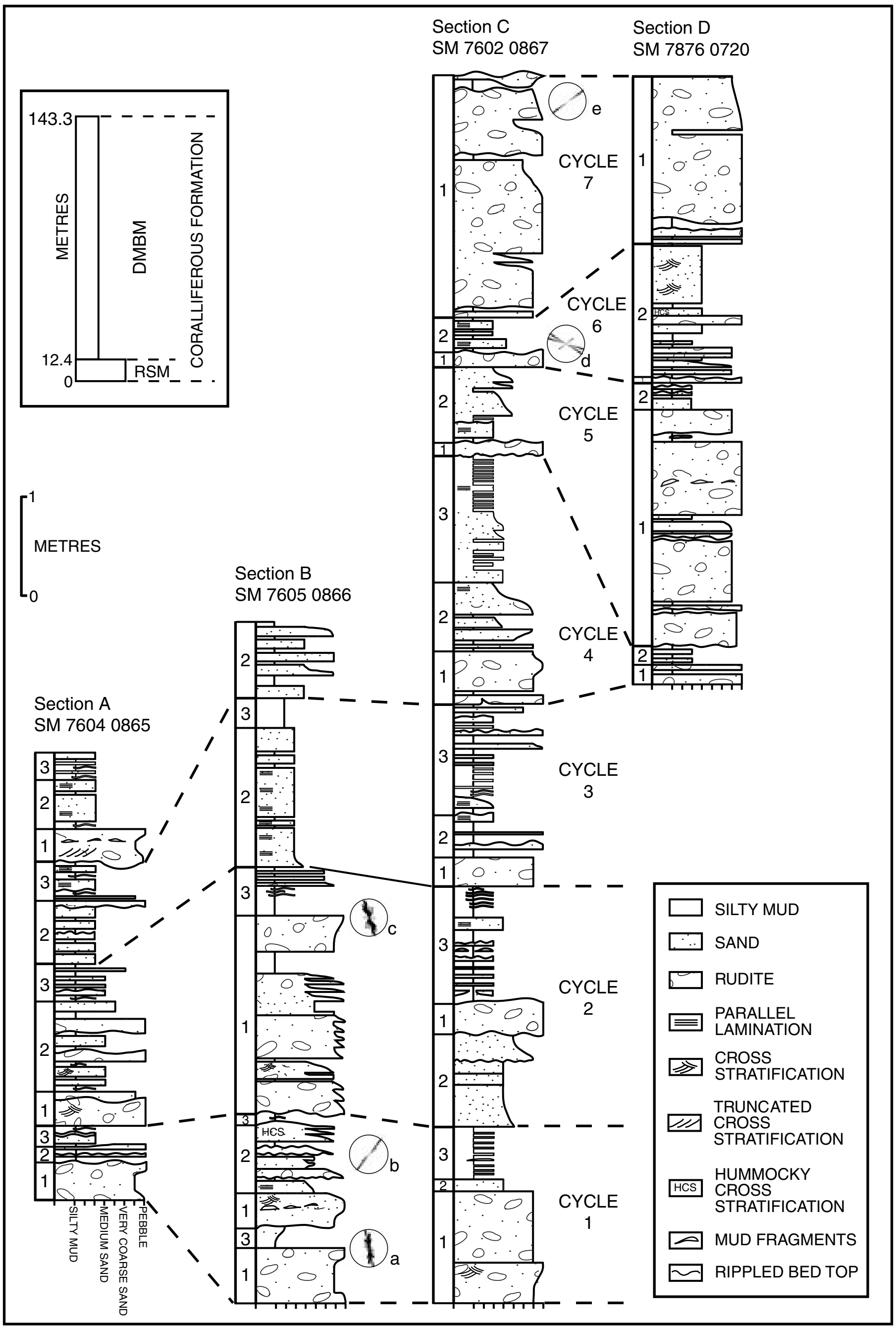

Figure 3. Summary logs and correlations of sections in the Renney Slip Member; C is the type section. Inset to top left shows the situation of the Member in the Coralliferous Formation. Rose diagrams to the right of sections B and C show palaeocurrent data: a, long axes of aligned pebbles in bed top (n = 95); b, ripple crest orientation (n = 3); c, long axes of aligned pebbles in bed top (n = 100); d, ripple crest orientation (n = 5); e, ripple crest orientation (n = 1).

textures are also prevalent. However, over a third of the beds show no grading, are clast-supported, have no internal sedimentary structures and display sharp or erosive bases. Of these beds, 38 % have asymmetrical or symmetrically rippled tops; the rest have flat tops. Ripple crests are orientated approximately E–W (Fig. 3). Two beds have aligned pebbles in their top surfaces, the long axes of these clasts being aligned dominantly N–S (Fig. 3). Two rudite beds appear to be composite, showing uneven internal contacts, marked by large, irregular patches of silty mudstone. Several beds are red in colour, while the rest are grey to grey–green. Evidence of bioturbation is shown in 26 % of all the rudite beds. Two types of burrow are recognized: sand- or mud-filled vertical and horizontal burrows 1–4 mm in diameter, and sand-lined, mud-filled burrows 2 mm across. Five beds contain shell fragments, including lingulid brachiopods.

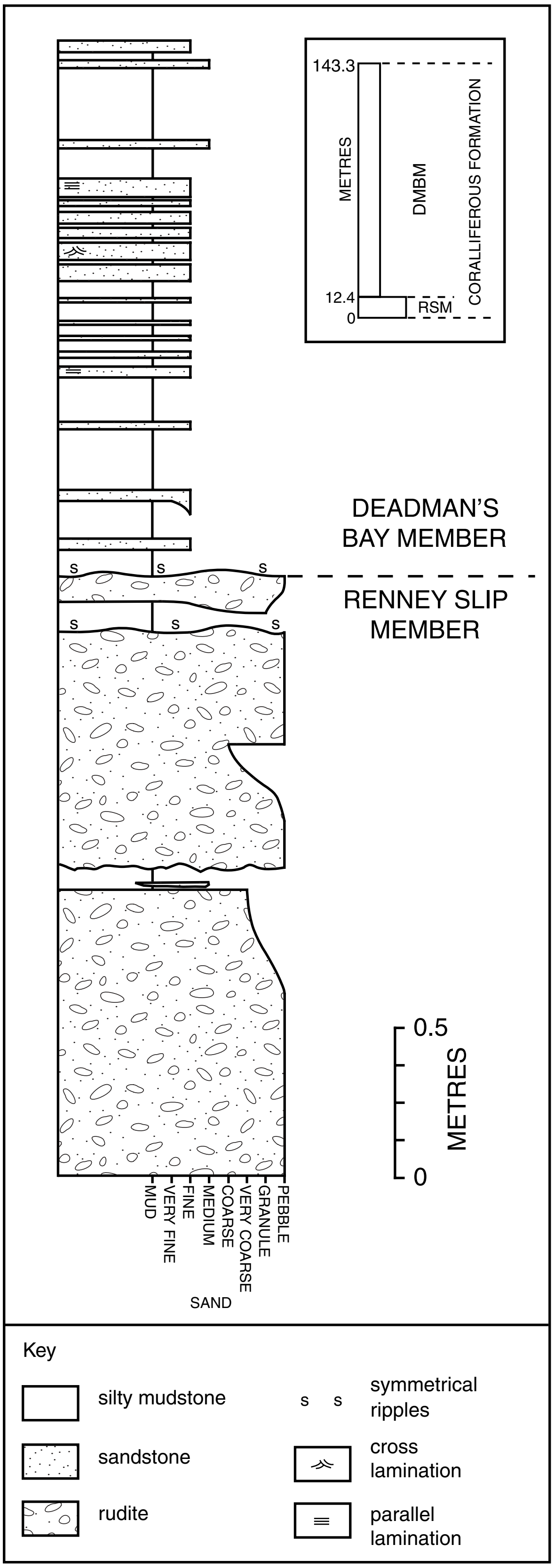

Figure 4. Sedimentary log showing the lithological detail of the boundary between the Renney Slip Member and the overlying Deadman's Bay Member of the Coralliferous Formation. Section is the type section at Renney Slip (see Fig. 3). Inset at top right shows thicknesses of the two members to scale.

Petrologically the rudites are poorly sorted and clasts range from angular to rounded. They are polymictic and especially rich in reddened acid volcanic fragments and large granodiorite clasts. They also contain poly- and monocrystalline quartz, plagioclase and K-feldspar, spherulitic plagioclase, devitrified and other volcanic clasts, detrital zircon, and siltstone clasts.

3.a.2. Interpretation

The coarse grained, poorly sorted rudites of Lithofacies 1 have undergone little transport and were probably deposited close to their source (Wescott & Ethridge, 1990). The presence of sheet-like bed geometry, ungraded to well graded beds, clast- to matrix-supported textures and the presence of large, 'out-sized' clasts indicates deposition from cohesive debris flows (Nemec & Steel, 1984; Ethridge & Wescott, 1984). Over a third of the rudite beds display these characteristics. Under certain conditions of mass flow, large particles may be pushed upwards (Bagnold, 1954; Walton, 1983), resulting in upwards coarsening/inverse grading (Nemec, 1990). Flows with increased volumes of water can convert from debris flows into fully turbulent suspensions which deposit normally graded beds above a basal scour surface (Nemec & Steel, 1984). The presence of shell fragments, bioturbation, wave-generated ripples and aligned pebbles on bed tops indicates that many rudite beds were emplaced subaqueously, in a nearshore environment, and influenced or reworked by marine processes (Hoy & Ridgeway, 2003). Although there are older records of possible terrestrial traces, the existence of abundant bioturbation in a Llandovery sediment is good evidence of marine conditions (Miller *et al.* 2002; Buatois *et al.* 1998). Composite or amalgamated beds with irregular patches of muddy matrix are interpreted as subaqueous debris flows which were largely cohesive and weakly to moderately sheared and so emplaced as closely successive surges (Colmenero *et al.* 1988; Nemec & Steel, 1984). Palaeocurrent data from ripple crests suggest a shoreline orientated approximately E–W. N–S aligned pebbles on the top surfaces of beds are thought to record reworking by waves or currents, removing finer grained material and orientating clast long axes (Nemec, 1990) perpendicular to the envisaged shoreline.

The polymictic and poorly sorted nature of these coarse grained sediments indicates that there was a variety of sources for the clasts. As well as sources in the Skomer Volcanic Group, fragments of igneous rocks could have been derived from contemporary Precambrian or Ordovician outcrops. Rocks of these ages are today mostly seen north of the Marloes Block, but are likely to have been more extensively exposed in Silurian times. Red beds are so coloured due to abundant reddened volcanic clasts: individual grains do not posses haematite rims.

Table 1. Rudite beds of Lithofacies 1

Grading	Support texture	Bed base	Sedimentary structures	Thickness (m)	Other	Number of beds
None	Clast	Erosive & sharp	None	0.01–0.74	–	8
			Asymmetrical and symmetrical rippled tops	0.12–0.30	–	5
Normal	Clast	Erosive & sharp	One bed contains rip-up clasts	0.11–0.94	–	3
			Repeated normal grading, cross-bedding. Two beds show symmetrical rippled tops	0.17–0.62	–	4
None	Matrix	Sharp	–	0.04–0.13	–	3
None	Clast	Sharp	Rippled or uneven bed tops	0.08–0.12	Shelly	2
Inverse to normal	Matrix to clast	Erosive	Cross-bedding at top	0.34–0.40	Composite bed	2
Normal	Varies: clast & matrix	Erosive & sharp	Repeated normal grading	0.40–0.56	–	2
Normal to inverse	Matrix to clast	Sharp	Rippled tops, cross-bedding	0.25–0.32	–	2
Inverse	Clast	Erosive & sharp	Symmetrical rippled top, cross-bedding	0.07–0.40	–	2
Inverse & normal to inverse	Matrix	Sharp	Aligned pebbles in top surface	0.36–0.55	–	2
Normal to inverse	Clast matrix clast	Erosive	–	0.34	Composite bed	1
None	–	Sharp	–	0.64	–	1
None	–	Sharp	Uneven bed top	0.63	–	1

Lithofacies 1 contains a total of 38 rudite beds. They are classified in this table according to their support textures and internal structures, starting with the most common bed types.

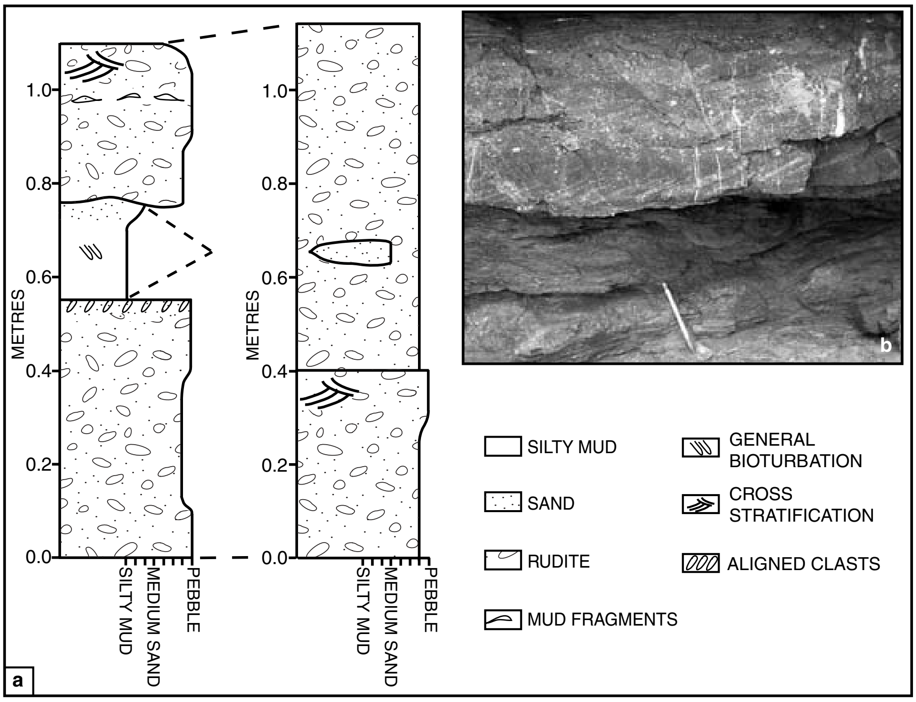

Figure 5. Detailed logs (a) and photograph (b) showing sediments of Lithofacies 1. The logs show Cycle 1 in the reference section (Fig. 3, Section B) and type section (Fig. 3, Section C) respectively. The photograph shows Lithofacies 1 in Cycle 4 in Section A (Fig. 3), demonstrating truncated cross-stratification at the base of the bed and mud flakes higher up (pencil 150 mm long).

3.b. Lithofacies 2 (sandstone-dominated lithofacies)

3.b.1. Description

This facies is characterized by thick sandstone beds (up to 0.67 m), interbedded with thinner silty mudstones and some thin rudite beds. This lithofacies occurs as units 0.12 to 1.41 m thick (Fig. 6).

Within this facies 55 % of beds ($n = 145$) are sandstone; of these, 87 % are 5–200 mm thick. The mudstones in this facies are significantly thinner than the sandstones, with 93 % between 5 and 50 mm thick. The sandstone beds are generally continuous, with sharp to erosive bed bases. Grain size of the sandstones varies from very fine to medium, with occasional beds of sandy matrix-supported pebbly granulestone (18 % of total beds). These coarser grained beds show erosive bases and are up to 200 mm thick, showing both normal and inverse grading. Sedimentary structures

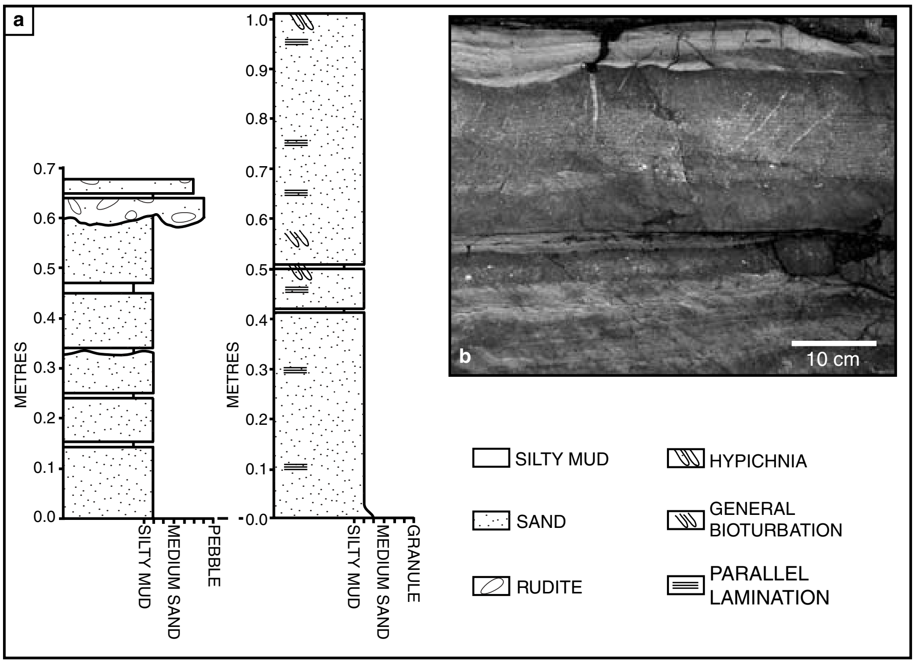

Figure 6. Detailed logs (a) and photograph (b) showing sediments of Lithofacies 2. Logs are from part of Cycle 3 in sections A and B respectively. The photograph shows hummocky cross-stratification in Cycle 1 in Section B.

present in the sandstones include planar lamination (15 % of beds), cross-stratification (3.75 % of beds), hummocky cross-stratification (2.5 % of beds), and symmetrically or asymmetrically rippled (13.75 % of beds) and flat-topped beds; 45 % of the sandstones are structureless. Bioturbation is common in both mudstones and sandstones, including vertical and horizontal sand-filled burrows, and bioturbation is evident in some granulestones. Fragments of calcareous-shelled brachiopods are present in two beds, as well as fragments of lingulids.

Most of the sandstones in this facies are feldspathic arenites, although some are more quartzose. They are poorly to well sorted, have a muddy matrix, and often display very clear parallel laminations. Compositionally they are very similar to the rudites of Lithofacies 1, with fine grained volcanic, granodiorite and large K-feldspar clasts, along with mono- and polycrystalline quartz, plagioclase feldspar, and siltsone clasts. These sediments also contain glauconite, which occurs as isolated and agglutinated pellets up to 1 mm across. The glauconite is often seen in close association with crystals of sedimentary pyrite.

3.b.2. Interpretation

Hummocky cross-stratification, brachiopod fragments and bioturbation (in a Llandovery sediment) are strong indicators of marine deposition. Features such as erosional sole surfaces, planar lamination, wave ripple lamination/hummocky cross-stratification and sharp bed tops are typical of storm beds (Seilacher & Aigner, 1991). Hummocky cross-stratification is particularly diagnostic of the lower shoreface (Walker & Plint, 1992) as are laminated sands and mega-ripples (e.g. Bardaji *et al.* 1990). The presence of these features in Lithofacies 2 indicates that it was deposited in the shoreface to offshore transition zone, from just above mean fair-weather wave base to mean storm wave base (Bardaji *et al.* 1990). The presence of coarser grained granulestones may be due to reworking and resedimentation of material from Lithofacies 1, as evidenced by the tabular nature of the beds (Clifton, Hunter & Phillips, 1971; Hoy & Ridgeway, 2003). Alternatively, they may represent the product of debris flows which passed into water, split, and deposited thin, scourless gravel lenses (Nemec & Steel, 1984).

3.c. Lithofacies 3 (silty-mudstone-dominated lithofacies)

3.c.1. Description

This facies comprises the finest-grained, and most thinly bedded sediments in the Renney Slip Member. Silty mudstones interbedded with very fine- to fine-grained sandstones dominate, but coarser medium sand and granule-grade beds are present. This lithofacies occurs in units 0.71–1.26 m thick.

Over 60 % of the beds ($n = 171$) in this facies are 5–20 mm thick (Fig. 7), but beds up to 0.25 m thick occur. Bed bases are always sharp, but not often erosive. Sedimentary structures in the sandstone beds include planar lamination, cross-stratification, and symmetrically to asymmetrically rippled bed tops.

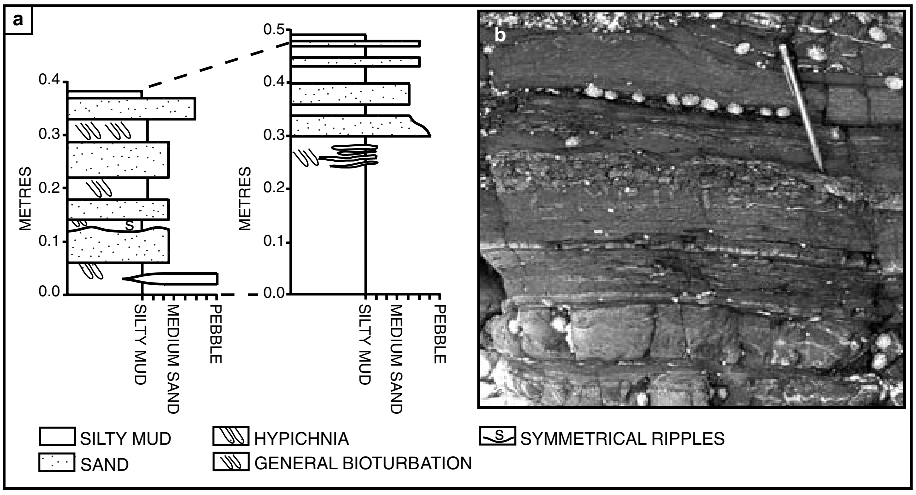

Figure 7. Detailed logs (a) and photograph (b) showing sediments of Lithofacies 3. The logs are from Cycle 2 in sections A and B respectively. The photograph shows heavily bioturbated sediments in Cycle 4 of Section C (pencil is 150 mm).

Sedimentary structures in the sandstone beds are related to the bed geometry. Almost one third of the sandstone beds are discontinuous and, of these, over a third comprise isolated sand ripples. Of the continuous sandstone beds, rippled tops (symmetrical and asymmetrical) occur in 18 % of beds and planar lamination is seen in an additional 12 %. Crinoid fragments are present in some of the sandy beds. Rare, erosively-based, thin, sandy granulestones occur, some of which are clast-supported and clearly reworked from a more proximal environment. Bioturbation is common, but occurs almost exclusively in the interbedded mudstones: 23 % of mudstone beds contain bioturbation, compared with 1.6 % of the sandstones. Both vertical and horizontal sand-filled burrows occur, and range from 2 to 10 mm across, and there are also sand-lined vertical burrows up to 10 mm in diameter. Glauconite is present in silty mudstone near the base of the member as agglutinated pellets up to 2 mm across.

The sandstones in this lithofacies are significantly more mineralogically mature than those of Lithofacies 2. They are moderately well to well sorted, have a muddy matrix, and are often bioturbated.

3.c.2. *Interpretation*

The predominantly fine grain size of this lithofacies suggests it records deposition in much lower energy conditions than other parts of the Renney Slip Member. The presence of crinoid fragments indicates an unequivocal marine origin for these sediments, and this is strongly supported by the presence of bioturbation and glauconite. The thinly interbedded nature of the fine grained sandstones and silty mudstones suggests that they accumulated in an environment largely below mean storm wave base. The silty mudstones represent background sedimentation from suspension during fair-weather deposition, and thus represent relatively long periods of deposition. The sharp-based sandstones with traction-generated internal sedimentary structures represent storm event-beds emplaced by episodic storm-generated currents. Overall this lithofacies records alternating storm and fair-weather sedimentation.

4. Facies analysis and interpretation

The Renney Slip Member comprises a complex interfingering of the three lithofacies, showing a 1–2–3 motif (Fig. 3). Each cycle shows a fining-upwards sequence from the coarse grained rudites of Lithofacies 1, through the sand-dominated sediments of Lithofacies 2 into the mud-dominated sediments of Lithofacies 3. These cycles vary in thickness from 0.39 to 3.07 m and are not always laterally continuous. In the type section, the complete Renney Slip Member comprises seven such cycles. Cycle correlation with other sections is aided either by the presence of the basal unconformity (Fig. 3, section B) or by presence of the upper bounding flooding surface as at Marloes (Fig. 3, section D). Due to its incomplete nature, correlation of the cycles in section A (Fig. 3) is less certain, and that proposed in Figure 3 is made on the basis of the simplest available match. Occasional sub-cycles can be identified within the main cycles (e.g. Cycle 1 in section B, and Cycle 2 in section C).

The association, within a cyclic sequence, of rudite sequences deposited by debris flows or high-concentration turbulent suspensions, with shoreface and offshore deposits, is consistent with a marine fan-delta depositional model. A fan delta is defined as 'a prism of sediments delivered by an alluvial fan and deposited, mainly or entirely subaqueously, at the interface between an active fan and a standing body of water' (Nemec & Steel, 1988, p. 3). Characteristic fan-delta slope deposits are clast-supported, pebble- to cobble-grade conglomerates, with a random fabric, beds up to 1.5 m thick, locally common bioclasts, inverse, normal and inverse-to-normal grading and a sandy matrix, with beds often capped by thin sandstones with parallel and wave ripple lamination (Colmenero *et al.* 1988). Those authors interpreted beds of this type as subaqueously emplaced debris flow deposits, whose tops are to some degree reworked by waves. Over a third of the beds in Lithofacies 1 fall into this category, and most display evidence of reworked tops. Wave-reworked bed tops indicate deposition above storm wave base. The intercalated muddy interbeds between successive fan-delta deposits suggests deposition in deeper and quieter environments, below storm wave base. Mass flows can be variable and the characteristics of their deposits can be varied also (Nemec, 1990). Beds can be ungraded to well graded, depending on the clast-support mode of the flow (Nemec & Steel, 1984). The presence of a variety of facies occurring closely within the same succession suggests that a range of water depths was present and therefore a steep delta slope (Colmenero *et al.* 1988).

Each of the separate cycles recognized in the Renney Slip Member represents an episode of fan-delta lobe advance and deposition (Lithofacies 1), followed by a rise in relative sea level which flooded the fan-delta deposits and laid down shoreface/offshore transition zone sediments (Lithofacies 2). Continuing rise in relative sea level deposited the deeper water sediments which cap many of the cycles (Lithofacies 3). The cycle then began again with the advance of a fan-delta lobe. At the top of the Renney Slip Member a large transgression completely flooded this facies association and the open marine sediments of the overlying Deadman's Bay Member were deposited. The occurrence of at least seven cycles of relative sea level rise could have a number of causes. Localized tectonic movements could cause a change in the available accommodation space and/or sediment flux, e.g. along basin-bounding normal faults, but sediment supply could also be affected by uplift in the source area or equally by sea floor subsidence. Local, basin-wide or eustatic variations in relative sea level might also be the forcing mechanisms behind these cycles. Due to the limited amount of time represented by this thin unit, and the asymmetry of the cycles, the most likely controls on sedimentation are localized tectonic movements, causing small, local variations in relative sea level.

The spatial distribution of the fan delta was relatively small, with a minimum lateral extent of 3 km (the distance between exposure localities). The thin nature of the Renney Slip Member suggests that deposition from the fan delta was relatively short in duration, subsidence and sediment input were relatively low and the source drainage basin was relatively small (Postma, 1990b). Lithofacies 3 is not represented in the Marloes Sands section, suggesting that this area may have been more proximal to source than the sections at Renney Slip. Correlation of the sections shows that not all lithofacies were deposited in each cycle at each location. Variations in deposition from individual fan-delta lobes, variations in sediment supply and relative sea level will all have affected the extent of deposition of sediments from each lithofacies at different times. The sediment was eroded from a hinterland of tectonically exposed older rocks: the presence of a variety of intrusive and volcanic clasts suggests erosion of the underlying Skomer Volcanic Group and also of older Ordovician and Precambrian rocks. Limited palaeocurrent data do not identify the source of the fan delta, only the orientation of an approximately E–W-trending shoreline.

Fan deltas have been classified into three principal systems: shelf-type, slope-type and Gilbert-type (Wescott & Ethridge, 1990). Due to the limited outcrop of the Renney Slip Member, it is not possible to assign it confidently to one of these types. However, certain characteristics of this fan delta have already been defined, such as its limited areal extent and duration. The high rates of change displayed by the cycles in the Renney Slip Member are typical of smaller fan deltas (Postma, 1990a,b). Further interpretation of the fan-delta physiography is difficult, although limited geographical extent may indicate a point-sourced fan geometry, or may simply reflect limited preservation. Uličný (2001) interpreted small bed thickness of fan-delta deposits as being due to local depositional conditions such as a steep local topographic gradient, i.e. a fault scarp. However, the lack of evidence for mass failure or slumping in the Renney Slip Member provides evidence for a more gentle delta slope (Nemec, 1990). There is no preserved evidence of the alluvial fan feeder system, although this may be due to reworking by waves (Nava-Sanchez *et al.* 1999). Hoy & Ridgeway (2003) identified similar fining-upward packages of conglomerate to shale in proximal fan-delta lithofacies of the Minton Formation in Colorado. However, those cycles are 50–100 m in thickness, representing significantly higher rates of net sedimentation/creation of accommodation space.

Previous sedimentological work on the Renney Slip Member (Hillier, 2002) interpreted the basal 4.25 m as of coarse grained low-sinuosity fluvial origin. Upward-thinning and -fining cycles were recognized, but the interbedded marine strata were not. He also identified *Skolithos* burrows within this basal section. Although the environmental range of *Skolithos* is wider than previously thought, it is still regarded as a marine indicator in the Lower Palaeozoic (Uchman *et al.* 2004). The dark red conglomerates Hillier described do not all fine upwards and the red colour is largely due to the presence of reddened volcanic clasts. He also recorded desiccation cracks on bedding surfaces within the basal 2–3 m. These were not observed in this study and are likely to have been syneresis cracks,

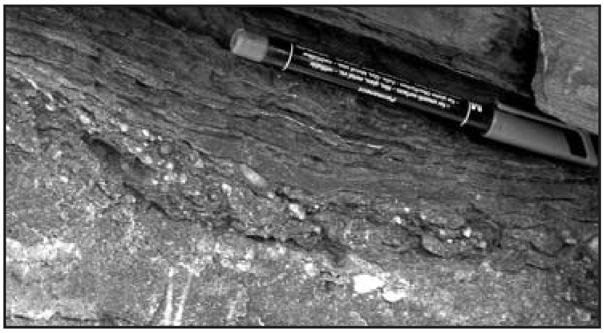

Figure 8. Photograph showing the transgressive lag at the top of Lithofacies 1 in Cycle 4 in Section A, Renney Slip. Pen is 150 mm long.

although desiccation could occur in the subaerial portion of a fan delta. Cross-stratification is quite rare in these beds (it occurs in only 10% of rudite beds). The pattern of upward-fining cycles is similar to that of a braided river, but the internal texture of the gravels shows that debris flow processes were dominant during deposition. Reworking of debris flow deposits by marine currents produced the rippled bed tops. Conditions of climate and vegetation cover on land were significantly different from modern conditions and so comparison with modern low-sinuosity fluvial systems is non-actualistic. No evidence of channels was seen in the field: McPherson, Shanmugam & Moiola (1988) defined braided river deposits as highly channelized, with abundant cross-stratified facies, an absence of debris flow deposits, and a high lateral continuity of facies. Fan-delta facies, by contrast, are interdigitating. Hillier also identified a 10 mm thick, distinctive conglomerate at the top of his fluvial facies association, comprising vein quartz and phosphate nodules. He interpreted this as a transgressive surface representing the landward migration of coastal facies. This horizon was observed at the top of Lithofacies 1 in Cycle 4 (Fig. 3, Section A and Fig. 8). It is interpreted as a reworked, transgressive lag at the top of Lithofacies 1, representing flooding of the fan delta during transgression, reinforcing the marine interpretation for this environment.

5. Discussion and implications for the evolution of the Welsh Basin

The Welsh Basin was formed on thinned continental crust of Eastern Avalonia (Woodcock *et al.* 1996). The eastern margin of the basin is well defined in terms of its structure and tectonic history (e.g. Woodcock & Strachan, 2000; Woodcock *et al.* 1996) comprising a series of normal faults dipping into the basin. Movement on these faults is widely recognized to have affected sedimentation in the Welsh Borderland and in the deeper basin throughout the Lower Palaeozoic. It is likely that the southern basin margin, in the Pembrokeshire area, had similar structural control, but this was probably more complex than the Welsh Borderland Fault System, at least in detail.

Cope & Bassett (1987) reviewed the evidence for a persistent Lower Palaeozoic land area in what is now the Bristol Channel area, the southern Welsh Basin margin, which they named Pretannia. They showed that Pretannia was a substantial positive area from at least Precambrian times until the close of the Silurian. Cope & Bassett (1987, p. 326) noted also that the exact extent of Pretannia was uncertain, and that the position of its shorelines varied in response to successive transgressions and regressions. Sanzen-Baker (1972) suggested that SW Pembrokeshire comprises distinct structural blocks that have been affected by thrusting from the south. These blocks remain in their original orthogonal positions relative to one another, but shortening during the Variscan was suggested to be as much as one seventh. She also noted that the Rosemarket Block formed a positive horst structure on the southern Welsh Basin margin until mid-Llandovery times. Powell (1987) identified the Benton Fault as a long-lived, basin-margin controlling structure with a downthrow to the south from Llandovery times. The Ritec Fault was also identified as a control on sedimentation during the Lower Palaeozoic. Powell additionally inferred the presence of a large fault to the south of Pembrokeshire, which she identified as the major structure controlling the northern margin of Pretannia. Powell (1989) suggested that this large fault was related to the Ritec and Benton faults, as part of the southward dipping extensional fault system of the southern Welsh Basin margin. The northern Pretannia margin was dominated by movement on these faults. Powell concluded that, during early Palaeozoic basin evolution, switching of activity between the Ritec and Benton faults controlled sedimentation rates and facies changes across the basin margin. Soper & Woodcock (1990) suggested that Pretannia was not a sufficiently large landmass to have provided an adequate source for the thick sedimentary sequences of the Welsh Basin. They used data from basinal turbidites to infer a sediment dispersal pattern associated with Avalonia to the SW: the newly uplifted area created by the impact between Eastern Avalonia and Laurentia.

Bassett *et al.* (1992) suggested that, during the Aeronian, the margin of Pretannia was steep or was tectonically positive. However, they made no mention of the nature of this margin during the Telychian, except to note evidence supporting southerly-derived sediments being deposited in the Welsh Basin, and that during *crenulata* Biozone times there was a transgression southwards onto the northern margin of Pretannia. Their Telychian palaeogeographical map (p. 41) indicates only the 'suspected' position of the northern Pretannian shoreline. Woodcock *et al.* (1996) gave evidence for sediment supply from the south and argued that mid Telychian and late Telychian

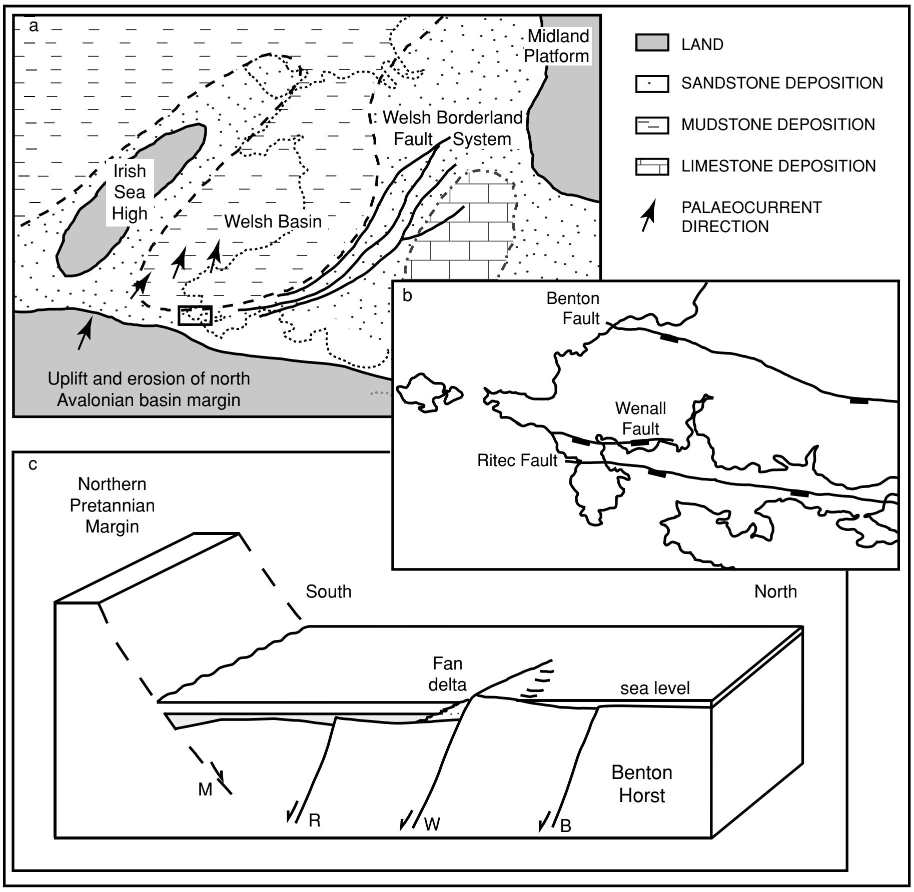

Figure 9. (a) Generalized palaeogeography for the late Llandovery. Arrows indicate overall direction of sediment transport; see discussion in text for further details (modified from Woodcock & Strachan, 2000). (b) position of extensional faults that were active at this time (after Hillier, 2002). (c) model of the southern Welsh Basin margin showing fan-delta deposition of the Renney Slip Member (M: major basin-bounding fault, R: Ritec Fault, W: expression of Wenall Fault, B: Benton Fault).

to early Wenlock eustatic sea level changes did not influence deposition in the Welsh Basin; instead regional subsidence/tectonic effects were the dominant controls on deposition. Through the application of subsidence analysis, they showed that, beginning in the early Telychian, there was a marked increase in subsidence rate, supporting a strong tectonic control on the basin. Siveter, Owens & Thomas (1989) and Woodcock & Strachan (2000) suggested that the sediment source for the late Llandovery turbidites in the Welsh Basin may have been a strongly uplifted Pretannia (Fig. 9a), and that the tectonic driving force for this uplift may have been initial impingement of the western end of Avalonia with the Laurentian margin. A similar view of the southern Welsh Basin margin was given by Aldridge *et al.* (2000). Hillier (2002) showed the Wenall Fault cropping out within the Marloes Block, as synthetic to the Ritec and Benton Faults (Fig. 9b). He suggested that it was active during the deposition of the Skomer Volcanic Group.

Gawthorpe, Hurst & Sladen (1990) identified fan-delta deposits in areas of lithospheric extension where normal faults form fault blocks on basin margins. In the Gulf of Suez they identified two types of fans: aggradational and progradational. Their progradational deposits showed progradational stacking patterns, sheet-like deposits of very low sequence thickness and small areal extent, of sand to rudite grain size. They identified the basin margin as a series of fault-bounded blocks (antithetic and synthetic) tilted towards a main border fault. Surface faulting events may only rupture part of the fault zone, and as a result the surface ruptures are separated by areas called transfer zones (e.g. Gawthorpe & Hurst, 1993). These transfer zones were identified by Gawthorpe, Hurst & Sladen (1990) as conduits for footwall-derived sediments to enter the hangingwall basin. Gawthorpe & Hurst (1993) suggested that transfer zones form important structural elements of extensional basins ‘allowing the accommodation of extension between individual fault and basin segments along the length of the zone of deformation’ (p. 1137). The geomorphology of transfer zones is an important feature controlling basin stratigraphy and can provide the focus for major drainage networks entering extensional basins (Gawthorpe & Hurst, 1993; Leeder & Gawthorpe, 1987). Gawthorpe & Hurst (1993) suggested that the footwall drainage basin is small, limiting sediment flux; in contrast, the transfer zone can have a drainage basin an order of magnitude larger. Jackson *et al.* (2005) suggested that evolution of block-faulted basin margins with transfer zones can result in spatial and temporal variations in uplift and subsidence, resulting in significant variation in spatial distribution of strata and their stacking patterns, which can occur over relatively small distances (< 1 km).

The major basin-bounding faults identified by Powell (1989) may have been part of a fault-block extensional basin margin, with the main fault located to the south of Pembrokeshire on the northern margin of Pretannia, as suggested by Powell (1987). The relationship between these faults could be either antithetic or synthetic, but fan delta(s) probably developed against an expression of the Wenall Fault during the Telychian (Fig. 9c), similar to those described by Gawthorpe, Hurst & Sladen (1990) in the Gulf of Suez. Given the evidence for an uplifted area close by to the south (Pretannia), and the close proximity of the major basin-bounding fault, it is most likely that this fault had an antithetic relationship with the other basin margin faults (Fig. 9c). In such a setting fan deltas on varying scales are likely to have been common: the example described here is the only one currently preserved. Petrography of the fan-delta sediments shows that both Precambrian igneous rocks and the underlying Skomer Volcanic Group provided local sources of sediment, i.e. a small footwall drainage area. The Welsh Basin margin at this time was therefore south of the Ritec Fault. A transfer zone to the west could have provided the large volumes of sediment supplied to the Welsh Basin from late Llandovery to Wenlock time as uplift was caused in this area by the collision of Avalonia with Laurentia (Soper & Woodcock, 1990).

Acknowledgements. SJV acknowledges a School Studentship from the Department of Geography, Earth and Environmental Sciences, University of Birmingham. Many thanks to M. P. Smith, K. T. Ratcliffe, K. Thomson, R. D. Hillier and two anonymous reviewers for useful discussion of the manuscript.

References

ALDRIDGE, R. J., SIVETER, DAVID, J., SIVETER, DEREK, J., LANE, P. D., PALMER, D. & WOODCOCK, N. H. 2000. *British Silurian Stratigraphy*, Geological Conservation Review Series. Peterborough: Joint Nature Conservation Committee, 542p.

ALLEN, J. R. L, BASSETT, M. G., HANCOCK, P. L., WALMSLEY, V. G. & WILLIAMS, B. J. P. 1976. Stratigraphy and structure of the Winsle Inlier, south-west Dyfed, Wales. *Proceedings of the Geologists' Association* **87**, 221–9.

ALLEN, J. R. L. & WILLIAMS, B. J. P. 1978. The sequence of the earlier Lower Old Red Sandstone (Siluro-Devonian), north of Milford Haven, south west Dyfed (Wales). *Geological Journal* **13**, 113–36.

BAGNOLD, R. A. 1954. Experiments on gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proceedings of the Royal Society, London*, **A265** 315–19.

BARDAJI, T., DABRIO, C. J., GOY, J. L., SOMOZA, L. & ZAZO, C. 1990. Pleistocene fan deltas in southeastern Iberian peninsula: sedimentary controls and sea level changes. In *Coarse-grained deltas* (eds A. Colella and D. B. Prior), pp. 129–51. Special Publication No. 10 of the International Association of Sedimentologists. Oxford: Blackwell Scientific Publications.

BASSETT, M. G., BLUCK, B. J., CAVE, R., HOLLAND, C. H. & LAWSON, J. D. 1992. Silurian. In *Atlas of Palaeogeography and Lithofacies* (eds J. C. W. Cope, J. K. Ingham and P. F. Rawson), pp. 37–56. Geological Society of London Memoir no. 13.

BRIDGES, P. H. 1976. Lower Silurian transgressive barrier islands, southwest Wales. *Sedimentology* **23**, 347–62.

BUATOIS, L. A., MNGANO, M. G., GENISE, J. F. & TAYLOR, T. N. 1998. The ichnologic records of the continental invertebrate invasion: evolutionary trends in environmental expansion, ecospace utilization, and behavioral complexity. *Palaios* **13**, 217–40.

CANTRILL, T. C., DIXON, E. E. L., THOMAS, H. H. & JONES, O. T. 1916. *The geology of the South Wales Coalfield, Part XII. The country around Milford*. Memoir of the Geological Survey, UK, 185p.

CLIFTON, H. E., HUNTER, R. E. & PHILLIPS, R. L. 1971. Depositional structures and processes in the non-barred high-energy nearshore. *Journal of Sedimentary Petrology* **41**, 651–70.

COLMENERO, J. R., AGUEDA, J. A., FERNANDEZ, L. P., SALVADOR, C. I., BAHAMONDE, J. R. & BARBA, P. 1988. Fan-delta systems related to the Carboniferous evolution of the Cantabrian Zone, northwestern Spain. In *Fan Deltas: Sedimentology and Tectonic Settings* (eds W. Nemec and R. J. Steel), pp. 267–85. London: Blackie & Son Ltd.

COPE, J. C. W. & BASSETT, M. G. 1987. Sediment sources and Palaeozoic history of the Bristol Channel area. *Proceedings of the Geologists' Association* **98**, 315–30.

DE LA BECHE, H. T. 1846. On the formation of the rocks of South Wales and South Western England. *Memoir of the Geological Survey of the United Kingdom* **1**, 1–196.

ETHRIDGE, F. G. & WESCOTT, W. A. 1984. Tectonic setting, recognition and hydrocarbon reservoir potential of fan-delta deposits. In *Sedimentology of Gravels and Conglomerates* (eds E. H. Koster and R. J. Steel), pp. 217–35. Canadian Society of Petroleum Geologists Memoir no. 10.

GAWTHORPE, R. L. & HURST, J. M. 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. *Journal of the Geological Society, London* **150**, 1137–52.

GAWTHORPE, R. L., HURST, J. M. & SLADEN, C. P. 1990. Evolution of Miocene footwall-derived coarse-grained deltas, Gulf of Suez, Egypt: implications for exploration. *American Association of Petroleum Geologists Bulletin* **74**, 1077–86.

HILLIER, R. D. 2002. Depositional environment and sequence architecture of the Silurian Coralliferous Group, Southern Pembrokeshire, UK. *Geological Journal* **37**, 247–68.

HOY, R. G. & RIDGEWAY, K. D. 2003. Sedimentology and sequence stratigraphy of fan-delta and river-delta deposystems, Pennsylvanian Minturn Formation, Colorado. *American Association of Petroleum Geologists Bulletin* **87**, 1169–91.

JACKSON, C. A. L., GAWTHORPE, R. L., CARR, I. D. & SHARP, I. R. 2005. Normal faulting as a control on the stratigraphic development of shallow marine syn-rift sequences:the Nukhul and Lower Rudeis Formations, Hammam Faraun fault block, Suez Rift, Egypt. *Sedimentology* **52**, 313–38.

LEEDER, M. R. & GAWTHORPE, R. L. 1987. Sedimentary models for extensional tilt-block/half-graben basins. In *Continental Extensional Tectonics* (eds M. P. Coward, J. F. Dewey and P. L. Hancock), pp. 139–52. Geological Society of London Special Publication no. 28.

MCPHERSON, J. G., SHANMUGAM, G. & MOIOLA, R. J. 1988. Fan deltas and braid deltas: conceptual problems. In *Fan Deltas: Sedimentology and Tectonic Settings* (eds W. Nemec and R. J. Steel), pp. 14–22. London: Blackie & Son Ltd.

MILLER, M. F., MCDOWELL, T., SMAIL, S. E., SHYR, Y. & KEMP, N. R. 2002. Hardly used habitats: dearth and distribution of burrowing in Paleozoic and Mesozoic stream and lake deposits. *Geology* **30**, 527–30.

MURCHISON, R. I. 1839. *The Silurian System, Part 1. Founded on geological researches in the counties of Salop, Hereford, Radnor, Montgomery, Caermarthen, Brecon, Pembroke, Monmouth, Gloucester, Worcester, and Stafford; with descriptions of the coal-fields and overlying formations*. London, John Murray, 578 pp.; *Part II. Organic remains*, pp. 579–768, pls 1–37 (crinoids by J. Phillips, Chapter 48, pp. 670–5, pls 17, 18).

NAVA-SANCHEZ, E. H., GORSLINE, D. S., CRUZ-OROZCO, R. & GODINEZ-ORTA, L. 1999. The El Coyote fan delta: A wave-dominated example from the Gulf of California, Mexico. *Quaternary International* **56**, 129–40.

NEMEC, W. 1990. Aspects of sediment movement on steep delta slopes. In *Coarse-grained deltas* (eds A. Colella and D. B. Prior), pp. 3–12. Special Publication No. 10 of the International Association of Sedimentologists. Oxford: Blackwell Scientific Publications.

NEMEC, W. & STEEL, R. J. 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravely mass-flow deposits. In *Sedimentology of Gravels and Conglomerates* (eds E. H. Koster and R. J. Steel), pp. 1–31. Canadian Society of Petroleum Geologists Memoir no. 10.

NEMEC, W. & STEEL, R.J. 1988. What is a fan delta and how do we recognize it? In *Fan Deltas: Sedimentology and Tectonic Settings* (eds W. Nemec and R. J. Steel), pp. 3–13. London: Blackie & Son Ltd.

POSTMA, G. 1990a. An analysis of the variation in delta architecture. *Terra Nova* **2**, 124–30.

POSTMA, G. 1990b. Depositional architecture and facies of river and fan deltas: a synthesis. In *Coarse-grained deltas* (eds A. Colella and D. B. Prior), pp. 13–27. Special Publication No. 10 of the International Association of Sedimentologists. Oxford: Blackwell Scientific Publications.

POWELL, C. M. 1987. Inversion tectonics in SW Dyfed. *Proceedings of the Geologists' Association* **98**, 198–203.

POWELL, C. M. 1989. Structural controls on Palaeozoic basin evolution and inversion in southwest Wales. *Journal of the Geological Society, London* **146**, 439–46.

SANZEN-BAKER, I. 1972. Stratigraphical relationships and sedimentary environments of the Silurian–early Old Red Sandstone of Pembrokeshire. *Proceedings of the Geologists' Association* **83**, 139–64.

SEILACHER, A. & AIGNER, T. 1991. Storm deposition at the bed, facies, and basin scale: the geologic perspective. In *Cycles and Events in Stratigraphy*. (eds G. Einsele, W. Ricken and A. Seilacher), pp. 249–69. Berlin: Springer-Verlag.

SIVETER, D. J., OWENS, R. M. & THOMAS, A. T. 1989. *Silurian field excursions: a geotraverse across Wales and the Welsh Borderland*. Cardiff: National Musuem of Wales, Geological Series No. 10, 133p.

SOPER, N. J. & WOODCOCK, N. H. 1990. Silurian collision and sediment dispersal patterns in southern Britain. *Geological Magazine* **127**, 527–42.

UCHMAN, A., DRYGANT, D., PASZKOWSKI, M., PORĘBSKI, S. J. & TURNAU, E. 2004. Early Devonian trace fossils in marine to non-marine redbeds in Podolia, Ukraine: palaeoenvironmental implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* **214**, 67–83.

ULIČNÝ, D. 2001. Depositional systems and sequence stratigraphy of coarse-grained deltas in a shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic. *Sedimentology* **48**, 599–628.

WALKER, R. G. & PLINT, A. G. 1992. Wave- and storm-dominated shallow marine systems. In *Facies Models: Response to Sea Level Change* (eds R. G. Walker and N. P. James), pp. 219–38. Ottawa: Geological Association of Canada.

WALMSLEY, V. G. & BASSETT, M. G. 1976. Biostratigraphy and correlation of the Coralliferous Group and Gray Sandstone Group (Silurian) of Pembrokeshire, Wales. *Proceedings of the Geologists' Association* **87**, 191–220.

WALTON, O. R. 1983. Particle-dynamics calculations of shear flow. In *Mechanics of Granular Materials: New Models and Constitutive Relations* (eds J. T. Jenkins and M. Satake), pp. 327–38. Amsterdam: Elsevier.

WESCOTT, W. A. & ETHRIDGE, F. G. 1990. Fan deltas – alluvial fans in coastal settings. In *Alluvial Fans: a Field Approach* (eds A. H. Rachocki and M. Church), pp. 195–211. Chichester: John Wiley & Sons.

WHITTAKER, A., COPE, J. C. W., COWIE, J. W., GIBBONS, W., HAILWOOD, E. A., HOUSE, M. R., JENKINS, D. G., RAWSON, P. F., RUSHTON, A. W. A., SMITH, D. G., THOMAS, A. T. & WIMBLEDON, W. A. 1991. A guide to stratigraphical procedure. *Journal of the Geological Society, London* **148**, 813–24.

Woodcock N. H. & Strachan R. A. (eds) 2000. *Geological History of Britain and Ireland*. Oxford: Blackwell Science Ltd, 423p.

WOODCOCK, N. H., BUTLER, A. J., DAVIES, J. R. & WATERS, R. A. 1996. Sequence stratigraphical analysis of late Ordovician and early Silurian depositional systems in the Welsh Basin: a critical assessment. In *Sequence Stratigraphy in British Geology* (eds S. P. Hesselbo and D. N. Parkin.), pp. 197–208. Special Publication of the Geological Society, London, no. 103.

ZIEGLER, A. M., MCKERROW, W. S., BURNE, R. V. & BAKER, P. E. 1969. Correlation and environmental setting of the Skomer Volcanic Group, Pembrokeshire. *Proceedings of the Geologists' Association* **80**, 409–39.