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Lakes and alluvial sandflat-playas in the Dartmouth Group, south-west England

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The silty mudstones and sandstones of the Dartmouth Group are conventionally interpreted as distal fluvial sequences, deposited during tectonic quiescence. This paper interprets some exposures to the east of Plymouth Sound to show that this model should be discarded for this part of the sequence. Instead, lacustrine sedimentation is thought to be important with heterolithic intervals, wave ripples, lenticular bedding, phosphorite nodules and fish remains suggesting subaqueous deposition. Pebbly mudstones, thought to have been emplaced as subaqueous debris flows, are also present. These lacustrine intervals are overlain by distal fluvial and playa sediments. The presence of a substantial sequence of lacustrine sediments suggests large-scale differential subsidence and tectonic activity.

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Introduction

The Dartmouth Group is a thick (about 3-4km) sequence of silty mudstones with subordinate siltstones and sandstones which crop out in southern Devon and northern Cornwall (Ussher 1904, 1907). The group is of Lower Devonian age, most probably spanning the Pragian Stage (Evans 1981; House 1988). Relatively little is known of the sedimentology of the Dartmouth Group. Indeed, the only detailed published information is that of Dineley (1966) who studied the Bigbury Bay area (Fig. la) and suggested a distal alluvial setting, possibly on a coastal plain. This interpretation was based on the presence of fish and plant remains and on a general comparison with Devonian sediments in Wales (Dineley 1961, 1966). Recently, Seago (1987) gave a brief account of the sedimentology of the sequence at Heybrook Bay (Fig. 1b). His study also suggested a distal floodbasin setting for this part of the Dartmouth Group. The rarity of studies probably reflects the structural complexities of the region, the difficulties of correlation and, possibly, the rather monotonous field appearance of the silty mudstones.

This paper discusses the sedimentology of coastal exposures of the Dartmouth Group in the Plymouth Sound area, between Andurn Point and Wembury (Fig. 1). The paper describes some preliminary results; these are especially interesting as they suggest that a distal alluvial interpretation cannot be applied throughout the group.

Dineley (1966) recognised four formations in the Bigbury Bay area. His Wembury Siltstones Formation, which crops out in the present study area, was thought to be the youngest (Fig. 1 d). While Hobson (1976) accepted these divisions, he argued on structural grounds that the Wembury Siltstones Formation is the oldest division. Seago (1987) and Seago and Chapman (1988) modified this sequence in the Wembury area by recognising another division, the Renney Rocks Formation. This study divides the sequence between Andurn Point and Wembury into three facies associations, which are based on the proportions of sandstone to silty mudstone and on bedding styles. These outcrop successively from the north to the south and show an overall younging in this direction (Fig. 1b).

Facies association 1

Between the faulted contact with the Meadfoot Formation near Andurn Point (SX 49254985) and Lentney Brake (SX 49104955), the Dartmouth Group consists of silty mudstones and fine-grained sandstones with subordinate siltstone beds (Fig. 2a). The rocks are mainly grey-green with subordinate red and purple colours. Typically, the latter are associated with packages of silty mudstone which contain relatively few discrete sandstones. The grey-green rocks are most abundant and contain more sandstone. The sand occurs as both millimetrescale streaks and laminae, micro-linsen and relatively thin (less than 25cm) discrete beds. Much of the sandstone is intimately interbedded with the mudstone, giving the sediments a heterolithic character. Many of the sandstones appear to be lenticular and pinch-out in 5-10m. Sedimentary structures are obscured both by cleavage and the small scale of interbedding. Some sandstones show faint, low-angle laminae and small ripple cosets (Fig. 3a). Where these display form discordance, opposed cross-laminae and undulatory set bases, they are interpreted as wave ripples (de Raaf et al. 1977). Lenses of fragmented fish scales and striated spines occur on several bedding planes just south of Andurn Point. Scattered phosphorite concretions are also present at some horizons; Xray diffraction analysis shows that they largely consist of francolite (Humphreys and Smith 1989).

The heterolithic character of much of this sequence indicates sedimentation from both suspension (deposition of mud) and traction (deposition of silt-fine sand). In turn, this implies fluctuating but generally rather weak currents (Terwindt 1981). This condition is typical of deposition during gentle wave agitation of shallow bodies of standing water (e.g. Clemmensen 1979; Allen 1981). Subaqueous deposition is also suggested by the presence of wave ripples, fish remains and concretionary phosphorite nodules. A fluvial sheetflood origin for this part of the sequence is precluded by the common lenticularity of the sandstones, lack of erosional contacts and their heterolithic character.

Facies association 1 is therefore interpreted as the deposits of relatively shallow, but substantial lakes with mild wave agitation and sedimentation above wave base. The variability in the amount of sandstone probably reflects varying water depths, proximity to sites of fluvial elastic input and sedimentation in shallow sheltered embayments (van Dijk et al. 1978). An alternative model might involve deposition along a muddy coastal plain on intertidal and supratidal flats. This setting has been described from modern examples (Thompson 1968; Meckel 1975; Glennie and Evans 1976) and recognised in the geological record (e.g. Walker and Harms 1971; Pollard and Steel 1978; Reif and Slatt 1979; Roe and Steel 1985). These sediments show the effects of frequent exposure alternating with subaqueous deposition e.g. desiccation cracks, calcrete nodules, rootlets and plant remains. Also, tidal channel deposits with erosive bases and intraclast conglomerates are common in this setting. Both features are absent from facies

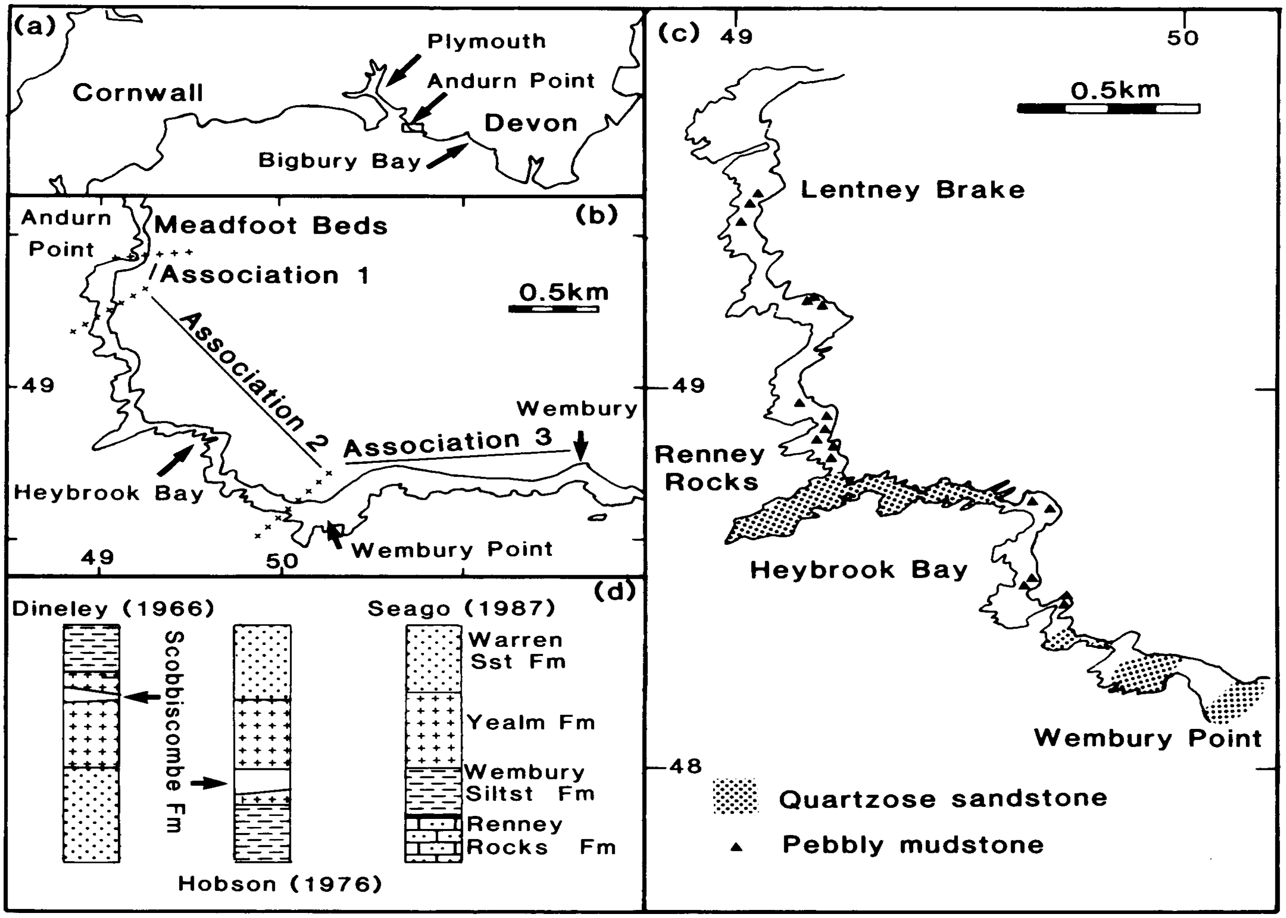

Figure 1. (a) Location of the study area. (b) Subdivisions of the Dartmouth Group between Andurn Point and Wembury. (c) Geological sketch map of the outcrop of facies association 2 (figures refer to the lines of the national grid). (d) Stratigraphic subdivisions of the Dartmouth Group east of Plymouth Sound.

association 1 of the Dartmouth Group. Although this makes a tidal flat setting rather unlikely, one cannot totally preclude some form of marine influence. This is because phosphorite concretions generally form in marine settings, although some lacustrine examples have been described (e.g. Gore 1988). Their presence in this sequence may therefore show that the lakes had a marine connection, at least periodically.

Facies association 2

Between Lentney Brake (SX 49104955) and Wembury Point (SX 50054820) the Dartmouth Group consists of four facies: pebbly mudstone, siltstone or very fine-grained sandstone, silty mudstone, and coarse-grained, quartzose sandstone. These appear to be interbedded, although the proportions change along the coastline with coarse, quartzose sandstones becoming more abundant to the south (Fig. 1). The junction with facies association 1 is marked by a bed of pebbly mudstone about 2m thick which is exposed on the foreshore just north of Lentney Brake. Representative graphic sedimentary logs are shown in Fig. 2b.

Pebbly mudstone facies

The pebbly mudstones are striking and distinctive, consisting of angular to subrounded clasts of red-brown or buff medium-grained sandstone, fine-grained sandstone and subordinate quartzite set in a silty mudstone matrix (Fig. 3b). The clasts are always matrix-supported and are typically widely scattered. Clasts appear to be orientated randomly, although some have been rotated during tectonism. The mean thickness of the pebbly mudstone beds is 3.7m with a range of 1.6 to 6m. The mean maximum clast size (long axis dimension of the 10 largest clasts) ranges from 9.7cm to 32.7cm, with most clasts in the range 12-20cm. Typically, the clasts of each pebbly mudstone bed are graded. Where "way-up" is established, this grading is the normal, coarse-tail type i.e. the base is sharp and is associated with the largest clasts. As a result, the tops of some pebbly mudstones merge with the "background" silty mudstones facies. Some pebbly mudstones are probably amalgamated, with hidden contacts between each depositional unit. This is suggested by the presence of lenticular siltstones and very fine sandstones in pebbly mudstones which otherwise appear to be homogeneous.

Dineley (1966) briefly described these deposits and suggested that they represented exceptionally large fluvial flood deposits. However, it is now known that matrix-supported clasts and lack of stratification are diagnostic of debris flows e.g. Lowe (1979) and Smith (1986). These are water-saturated flows with plastic properties that deposit sediment *en masse* when shear stress decreases below the yield strength of the flow. A debris flow interpretation is also strongly implied when deposits show a

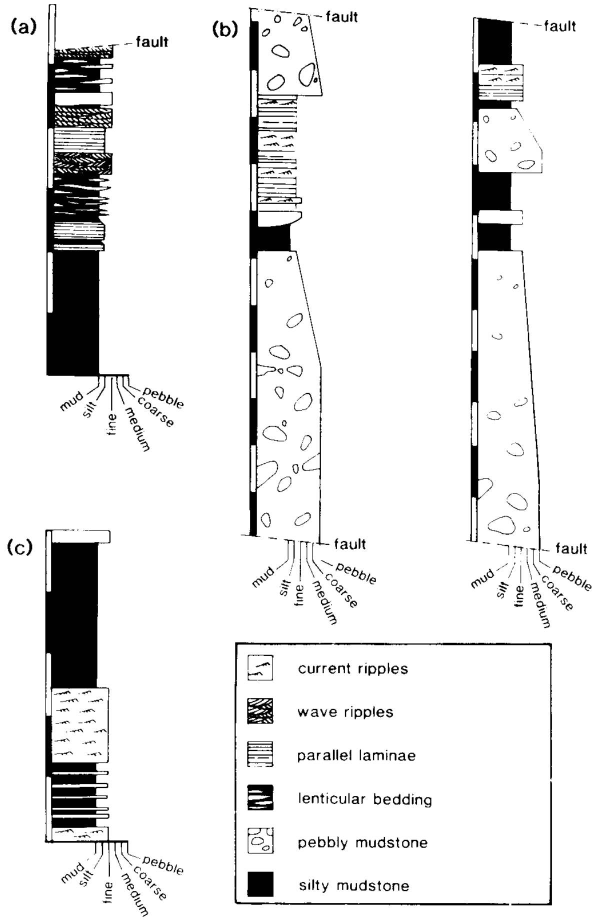

Figure 2. Representative sedimentary logs of the Dartmouth Group, scale divisions are in metres. (a) Facies association 1, (b) facies association 2 and (c) facies association 3.

correlation between bed thickness and maximum clast size, which reflects a positive relationship between competence and size of flow (Bluck 1967; Larsen and Steel 1978). Such a correlation, although weak, does occur in these deposits (Fig. 4).

A debris flow interpretation for these sediments was also suggested by Seago (1987), who thought that they formed between channels by bank collapse. This setting is not viable on two counts. Firstly, most sandstones are only a few tens of centimetres thick and any channel would be on the same scale. However, the debris flows are much thicker than the sandstones (about 4m) and cannot represent collapse of the channel banks. Also, the debris flows are typically associated with silty streaked mudstones, not the sandstones. Secondly, one would expect blocks of overbank siltstones and mudstones showing syn-sedimentary deformation to be formed by bank failure and to be incorporated into the debris flow (e.g. Piint 1986; Rust and Jones 1987). Such blocks are, however, completely absent.

Rather, we believe that the pebbly mudstone beds have characteristics which suggest that they were deposited subaqueously. When debris flows enter bodies of standing water, or are initiated subaqueously, water is incorporated into the flow. Viscosity is therefore reduced, so altering the character of the flow. Nemec and Steel (1984) and Kessler and Moorhouse (1984) suggested that subaqueous debris flows can be distinguished from subaerial flows by their relatively well developed normal grading, an increase in matrix content towards the bed top, and the character of associated sediments.

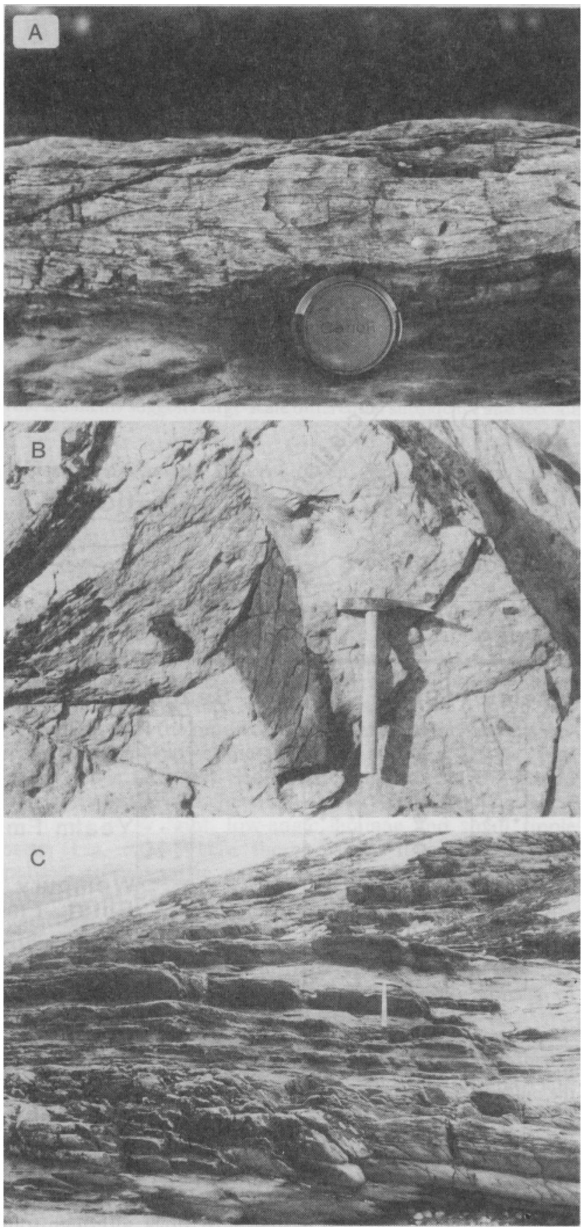

Figure 3. (a) Detail of thin-bedded sandstone of facies association 1 showing low-angle ripple cosets. (b) Pebbly mudstone with angular matrix-supported sandstone clasts. (c) Parallel-laminated and sheetlike sandstones interbedded with silty mudstones; note the upwardsthinning motif.

Also, Gloppen and Steel (1981) suggested that subaqueous debris flows have relatively high matrix contents and a low ratio of maximum pebble size (MPS) to bed thickness (BTh). The pebbly mudstone facies of the Dartmouth Group shows all the suggested characteristics of low-viscosity, subaqueous debris flows. That is, clasts are normally graded, and beds have low clast densities and low MPS/BTh ratios.

Siltstone and fine-grained sandstone facies

Siltstone or very fine-grained sandstones occur at several localities along this part of the coast, although it is not a common facies. Generally they form beds about 0.5m thick, but are up to 2.5m thick. The siltstones and very fine-grained sandstones display both current ripple cross-lamination and parallel lamination (Fig. 2b) and have sharp bases and tops.

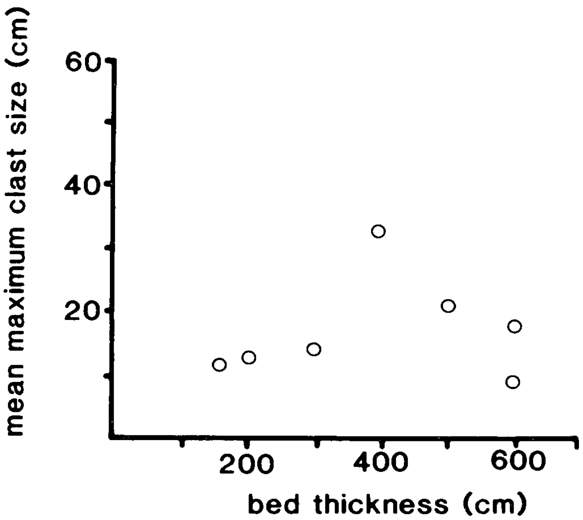

Figure 4. Clast size - bed thickness data from the pebbly mudstones of facies association 2.

Some examples appear to be massive. Typically, the sediments are sheet-like, although some lenticular beds have been observed. Rarely, bases of the sandstones are lined with imbricated mudclast chips and granule-grade grains of white quartz.

The sedimentary structures and pebble imbrication show deposition from unchannellised tractional currents. Generally these were rather slow, as implied by the abundance of ripples in such fine-grained sediment (Allen 1982; Harms *et al.* 1982). Beds of this facies may be associated with the pebbly mudstones and some examples sharply overlie pebbly mudstones. Accepting a subaqueous interpretation for the pebbly mudstones therefore implies subaqueous deposition for the siltstones and very fine-grained sandstones. This might have occurred as fluvial flood waters discharged into the lake or as fine-grained sediment gravity flows moved along the lake floor. Rippled or massive very fine-grained sediments, which are similar to this facies, have been recognised from both settings (e.g. Steel and Aasheim 1978; Clemmensen 1979; Pollard *et al.* 1982).

Silty mudstone facies

Most of facies association 2 consists of variegated silty mudstones. These are generally rather dull grey-brown with some red and purple hues. Some display silt streaks or are faintly laminated or massive. Small (1-2cm), reddish-brown "blebs" are locally seen on bedding surfaces. These are also seen in other parts of the sequence (see below).

The facies is less sandy than that at Andurn Point and heterolithic intervals are very rare. The very fine grain size of this facies implies deposition from suspension in a low-energy setting. This was probably the "background" sedimentation from the lake waters. However, the lack of diagnostic structures means that some silty mudstones may reflect sedimentation in fringing lake mudflats.

Quartzose sandstone facies

This facies consists of pale, quartzitic sandstones. They are more abundant in the southern part of association 2 and are also coarser grained to the south, i.e. in the direction of general stratigraphic younging. At Renney Rocks the sandstones are deformed and riddled with vein quartz. As a result, the sedimentary structures are obscured and parallel laminae and ripple cross-stratification can be seen only rarely. The sandstones are thin to medium-bedded (less than 0.5m) with subordinate siltstones and silty mudstones. Both upwards-thickening and upwards-thinning sequences are present. Seago (1987) mentions that calcretes and intraclast calcrete conglomerates are associated with sandstones along this section, but none were observed during this study.

Further south, around the Gunnery School, the sandstones are less deformed and appear to be coarser grained (medium to coarse) with some poorly-sorted pebbly or granule-grade horizons (white quartz clasts as well as mudstone intraclasts). The sandstones show stacked sets of trough cross-bedding (individual sets up to 0.5m thick) with subordinate parallel lamination. They have sharp and locally scoured contacts with the silty mudstones and individual sandstone beds are up to 2m thick.

The depositional style of this facies is markedly different from that of other sandstones in the sequence. These sediments were deposited by relatively fast-flowing currents which were able to transport coarse sand and granules and mould it into upper plane beds and dunes. Bed thicknesses and the stacked nature of some cross-beds show that flows were also deeper and longerlived than those depositing other sandstone facies. The sharp, erosive bases and sheet-like nature show erosion and subsequent deposition by broad, weakly confined flows. This facies is therefore interpreted as relatively proximal fluvial sheetfloods.

Facies association 3

From Wembury Point (SX 50054820) to Wembury (SX 51604840), which is the eastern limit of the present study, the sequence is dominated by silty mudstones interbedded with subordinate sheet-like, fine-grained sandstones. The contact with the stratigraphically underlying association 2 appears to be a sharp one.

Laminated sandstone facies

These sandstones are fine-grained, thin-bedded and sheet-like. They show parallel laminae and subordinate ripple cross-stratification. Soft sediment deformation structures include ball and pillow structures, loaded bases and convolute laminae. Intraclast conglomerates were not observed. These sandstones do not show the small-scale and intimate interbedding with mudstone that gives parts of facies association 1 a heterolithic character. The facies is concentrated at several sites along the foreshore, giving alternating sandstone-rich and sandstonepoor packages (Figs 2c, 3c). Within these, some sandstones form upwards-thinning sequences over a few metres as succeeding beds of sandstone, separated by thin mudstones, become progressively thinner.

These sandstones were deposited by waning flows, which were only weakly confined. The rarity of intraclast conglomerates with these sandstones shows that there was flow over the substrate rather than channelling through it. Rapid deposition is shown by the presence of soft sediment deformation structures. These sandstones are interpreted as distal fluvial sheetfloods (c.f. Tunbridge 1984). The alternations of sandstonerich and sandstone-poor sequences are interpreted as reflecting tectonic rejuvenation of the fluvial system. The smaller scale upwards-thinning sequences are similar to those described by Hubert and Hyde (1982), which they interpreted as being initiated by channel avulsions on the fan. This creates a new sheetflood and sandflat network. Gradual infilling and plugging of such channels ensures that progressively smaller floods reach the sandflats, resulting in thinner sandstones.

Silty mudstone facies

These are massive or faintly laminated, streaked with siltstone and they are typically red-purple with subordinate grey-green hues. Locally, the mudstones contain dark, reddish-brown "blebs". These appear to be concentrated on bedding surfaces, do not penetrate the bed and have a consistent orientation. They are typically elongate and are 1-2cm long. Dineley (1966) describes them as ferruginous and siliceous concretions and suggests (p. 199) that they were originally calcareous. Bioturbation and irregular sand-filled synaeresis cracks (Plummer and Gostin 1981) are sporadically developed. Bioturbation fills are distinguished from the "blebs" as they are piped downwards from silty layers, may be branched and display a range of orientations. Fish remains are present in one thick, silt-poor sequence, which also contains phosphorite nodules.

This facies was deposited from suspension in a low-energy setting. At least locally, this probably involved standing bodies of water as suggested by the fish remains, bioturbation and phosphorite (Allen and Collinson 1986; Gore 1988). However, the bulk of the mudstones are interpreted as the deposits of generally subaerial mudflats and floodplain flats because they are associated with the laminated sandstones.

Depositional setting

Previous workers have suggested a distal fluvial setting for the Dartmouth Group between Andurn Point and Wembury. This interpretation has always been stated in very general terms, but would presumably involve sedimentation from shallow sheetfloods and broad, low-relief channels which debouched across alluvial sandflats and shallow, ephemeral playas. There are several accounts of modern and ancient examples of this sort of setting (e.g. Hardie *et al.* 1978; Tunbridge 1981, 1984; Hubert and Hyde 1982; Olsen 1987). These accounts suggest that the depositional record will be dominated by thin to mediumbedded, sheet-like sandstones with erosive bases, waning flow sequences, and abundant parallel laminae. These are intercalated with siltstones and mudstones, deposited from suspension. The sandstones typically show some trends of bed thickness, grain size and type of lower flow regime bedforms which are interpreted as representing the advance and retreat of terminal alluvial fan complexes (Hubert and Hyde 1982; Tunbridge 1984). Thicker multistorey sandstones may locally be present, representing stacked, low-relief channels.

This type of sequence can be discerned only in facies association 3; associations 1 and 2 compare very poorly. Not only do they show evidence for subaqueous deposition such as wave ripples, bioturbation, phosphorite nodules, fish remains and heterolithic sequences, but they do not contain sheetlike, erosive-based sandstones. Also, the debris flows cannot be reconciled with a distal fluvial setting, regardless of whether they are subaqueous or subaerial (Rust 1978; Collinson 1986). Indeed, the very presence of the debris flows is enough to preclude a distal fluvial setting for this part of the sequence. Clearly, the depositional setting of this part of the Dartmouth Group needs to be revised. A possible model for the subaqueous part of the succession is now outlined.

Association 1 represents deposition in relatively shallow but perennial lakes. The depositional setting of association 2 is more complex. The presence of subaqueous debris flows suggests a steepening of the lake margin, which encouraged the formation of sediment gravity flows. The absence of wave ripples and heterolithic intervals in association 2 suggests that this was accompanied by lake deepening below wave base. Hentz (1985) has also described pebbly mudstones with these features from a Jurassic lacustrine sequence in Virginia. These examples accumulated on the lowest lake slopes and basin plain and were derived from failure in the shallower parts of the lake. Sediment-rich plumes periodically entered the lake, depositing the rippled fine-grained sandstones of facies association 2. There is an overall upwards-coarsening within facies association 2 as quartzose fluvial sandstones become more common and coarser grained to the south i.e. a shoaling sequence which records the infilling of the lake. The exact nature of these fluvial incursions is problematic. The quartzose sandstones are in direct contact with the silty mudstones only, never with pebbly mudstones. In turn, silty mudstones and pebbly mudstones alternate with quartzose sandstones on a scale of a few metres to tens of metres. There are probably two interpretations of this relationship: (1) the quartzose sandstones represent the fluvial portions of episodes of fan delta progradation *(sensu* Nemec and Steel 1988), or (2) they are distinct fluvial episodes, which are abruptly interbedded with lacustrine sediments. Similar rapid and small-scale alternation of fluvial and lacustrine sediments are known to be common (e.g. Hentz 1985). Lake margins are inherently dynamic because of fluctuating water levels and irregular pulses of fluvial sedimentation (Frostick and Reid 1986, 1987; Gore 1988).

In either case, the contact with facies association 3 shows an abrupt change to distal fluvial sedimentation with only subordinate lacustrine episodes. Preliminary studies suggest that much of the Dartmouth Group to the east of the present study area was also deposited in a similar setting.

Some palaeogeographical inferences

At this stage of the study it is inappropriate to suggest elaborate tectonic models for the sequence. However, it is possible to make some deductions about palaeogeography which may prove to be useful building blocks in constructing such a tectono-sedimentary model. Firstly, one should note the palaeogeography implied by the distal fluvial interpretation of previous workers. This suggests subdued relief and low gradients, and its persistence would imply tectonic quiescence. We believe that there is strong evidence for discarding this model for much of the section between Andurn Point and Wembury and for suggesting deposition in substantial perennial lakes.

Large perennial lakes are typically tectonic in origin (Picard and High 1981; Allen and Collinson 1986; Frostick and Reid 1987); this setting prevents the otherwise rapid process of infilling. The presence of a thick lacustrine sequence therefore implies a regime of large-scale, differential subsidence i.e. tectonic activity. This is supported by the presence of debris flows, which require periods of relatively steep slopes. Such a pattern of differential subsidence would presumably be associated with syn-sedimentary faults, which were intermittently active. The abrupt contact between the coarse, fluvial sediments at the top of association 2 and the distal fluvial sediments of association 3 is interesting. It may represent rapid abandonment of the active basin, or possibly a phase of very rapid subsidence which limited coarse sediment by-pass to the active margin, a mechanism recently suggested by Blair and Bilodeau (1988).

Clearly, this picture is very different from the tectonically quiescent fluvial plain of previous workers. Having shown that the basin was tectonically active, the next step is to document the evolution and setting of the basin(s) in more detail. At the present state of our knowledge of the Dartmouth Group, it is not possible to distinguish between pull-apart, rift or foreland basins with any confidence. On-going studies are tackling this problem.

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