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**DISCUSSION**

# Return of 'The Fan That Never Was': Westphalian turbidite systems in the Variscan Culm Basin: Bude Formation (south-west England)

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## INTRODUCTION

Thirty-five years ago, Harold Reading stated (1963; p. 69): 'The precise depositional environment of the Bude Sandstones is not easy to establish'. Appropriately, two of his former students are still arguing whether the environment was a storm-affected shelf (Higgs, 1986a, 1987, 1991) or a deep-water fan (Burne, 1969, 1995). The paper by Burne (1995) questions my shelf interpretation, prompting this Discussion.

Burne and I agree that deposition took place offshore, in a large Westphalian lake with occasional marine connections, based on faunal aspects and on the lack of evidence for emergence (Goldring & Seilacher, 1971; 'Lake Bude' of Higgs 1986b, 1994). We also agree that the majority of the sandstone beds are turbidites, but whereas I argued for river-fed turbidites on a shelf, with storms accounting for both catastrophic rainfall (hence sandy underflows) and accompanying waves, Burne (1995) invokes slump-generated(?) turbidites on a deep-water fan below storm wavebase. The tectonic setting was the northern, passive margin of a foreland basin (Higgs, 1991; Burne, 1995).

Burne (1995) argues that all of the sedimentary structures interpreted by Higgs (1991) as indicating shallow-water deposition (above storm wavebase) can also occur in deep-water turbidite settings. These structures are: quasi-symmetrical ripples; irregular cross-lamination; hummocky cross-stratification; multidirectional tool marks; and mud-draped scours. Rare symmetrical 'wave' ripples occur in the Bude Formation, although Burne (1995; p. 130) points out that: '*no convincing illustration of them has been published to date*' (his italics).

In the following Discussion, I shall sequentially address these and other contentious issues raised by Burne (1995). My intentions are threefold: (1) to question the basis of Burne's fan model; (2) to reiterate evidence for my lake-shelf model; and (3) to explain that the shelf origin has been 'masked' for decades by certain unusual facies characteristics, including 'slurried' and 'slumped' beds formed *in situ* as seismites, but widely misinterpreted as debris flows and slumps.

The shelf-vs.-fan debate is not only interesting academically, but also important economically, because the easily accessible cliffs of Bude are a magnificent natural laboratory in which to gather data for petroleum-reservoir models.

### Cyclicity in the Bude Formation

The Bude Formation consists of about 1300 m of decimetre- to metre-scale alternations of: (1) amalgamated tabular sandstone bodies up to 10 m thick; and (2) mudstones containing thin (< 40 cm), nonamalgamated sandstone and siltstone beds (Higgs, 1991; figs 7, 9; Burne, 1995; figs 20, 36). These alternations were interpreted by Higgs (1991) as cycles. A symmetrical 'ideal' or 'composite' cycle, comprising a central sand body flanked above and below by muds, was proposed by both Higgs (1991; fig. 16) and by Burne (1995; fig. 5, after Burne, 1969). However, our interpretations of the cyclicity differ radically. Higgs (1991) proposed an *allocyclic* origin, reflecting fluctuations in water depth and salinity on a lake shelf, controlled by glacio-eustatic sea-level oscillations. In this interpretation, the presence of a thinning- and fining-up (transgressive) portion in the cycle suggests that, unlike *marine* shelves, which are 'starved' during transgressions (sediment trapped in estuaries), the lake shelf continued to receive sediment; this may reflect the efficiency of lake underflows or the absence of (tidal) estuaries in lakes. Burne (1995), in contrast, infers an *autocyclic* control, reflecting advance and abandonment of deep-water fan channels. Resolution of this disagreement is related to the overall question of palaeodepth, and presence or absence of wave-influenced sedimentary structures, to be addressed in the remainder of this Discussion.

## Presence of symmetrical ripples

Symmetrical ripples appear (unintentionally) in a photograph published by Higgs (1991; fig. 11c), capping a sandstone at the base of the photograph, and also as a string of connected symmetrical ripples 6 cm above, encased in mudstone. In addition, Melvin (1987; p. 381) stated that 'The presence of wave ripples in the Bude Formation is not in dispute: I have recently revisited the area and observed them in a number of places'.

The scarcity of symmetrical ripples does not refute my shelf interpretation, as some shelf successions lack them (Brenchley, 1985; Brenchley *et al.*, 1993).

## Quasi-symmetrical ripples: are they wave-formed?

Straight or slightly sinuous-crested ripples with only slight asymmetry are the typical ripple forms of the Bude Formation, capping decimetric turbidite-like beds of largely massive, very fine sand. I interpreted these as combined-flow ripples, formed under the joint action of a unidirectional sediment-supplying current (river-fed underflow) and a wave-induced oscillatory current (Higgs, 1984, 1991). In contrast, Burne (1995) suggests that they are nonequilibrium bedforms formed by a unidirectional current, by analogy with experiments by Baas (1994), who showed that 'current ripples' formed in very fine sand are initially straight-crested to sinuous, evolving to linguoid given sufficient time. However, Baas' ripples are unlike those of the Bude Formation in two fundamental respects: (1) they are more asymmetrical, with a symmetry index exceeding 3 (Baas, 1994; fig. 5a, b) , compared to only 2 to 3 in the Bude Formation (Higgs, 1984, 1991); (2) they average only 1–10 mm in height (Baas, 1994, p. 193), compared to heights of 5–20 mm in the Bude Formation *after compaction* (Higgs, 1991). Thus, the ripples produced by Baas (1994) are not comparable to those of the Bude Formation. Furthermore, the question arises, if the quasi-symmetrical ripples *are* nonequilibrium current ripples, why are equilibrium linguoid forms virtually *absent* in the Bude Formation, considering that: (A) equilibrium in some cases is reached quickly (minutes; Baas, 1994); and (B) linguoid ripples and corresponding 'rib-and-furrow' internal structure are very common in deep-water turbidites (Seilacher, 1982; p. 337).

Therefore, I reject Burne's (1995; p.128) contention that the quasi-symmetrical ripples 'are more logically interpreted as the product of reworking by the tail of a turbidity current'. I stand by my original interpretation, that the ripples are combined-flow forms, based on three lines of evidence:

**1** their similarity to the 'wave-dominated combined-flow ripples' produced experimentally by Harms (1969), albeit in coarser material (medium sand);
**2** their association with other sedimentary structures, many of which are discussed below, which, although individually are equivocal as indicators of wave action, in combination suggest that the Bude Formation was deposited above storm wavebase; and
**3** the unimodality of ripple crestlines, in contrast to the polymodality of sole marks (Higgs, 1991; Burne, 1995; fig. 6a,b). Ripples almost invariably run subhorizontally across exposed bedding surfaces (e.g. Burne, 1995; multiple bedding planes in figs 16, 17), indicating an east–west palaeotrend. This preferential clustering of ripple trends suggests that the ripples were wave-influenced, and that the direction of storm-wave approach was constant (Higgs, 1991). The steeper flank of the ripples faces south, as does the internal cross-lamination (also strongly unimodal; see Burne, 1995; fig. 6c), suggesting that the unidirectional component (which I infer to have been a river-fed underflow) of the combined flow always approached the ripples from their northern side.

The near-absence of truly symmetrical ripples in the Bude Formation suggests that storm waves were *invariably* accompanied by unidirectional currents, consistent with the susceptibility of lakes to underflows and wind-driven circulation (Allen & Collinson, 1986).

## Combined-flow model

I envisage deposition of rippled sand beds to have involved two currents: (1) a river-fed underflow generated by storm-flooding; and (2) oscillatory flow due to waves induced by the same storm. The underflow was not necessarily *always* accompanied by waves: one can imagine storms in distant areas of the lake's drainage basins producing underflows in the lake, but too remote to produce waves. Such 'wave-free' events could account for the abundant simple massive, graded beds in the Bude Formation ('fine-grained graded beds' of Burne, 1995; p. 112). The lack of lamination or ripples in these beds suggests that underflows operating alone (without storm waves) were too weak to induce tractional transport. Supporting this inference, river-fed underflows recorded in modern lakes are slow (< 0·5 m $s^{-1}$ (Higgs, 1991)). Such low velocities, in contrast to much higher speeds of slump-generated turbidity currents (e.g. Grand Banks turbidity current, up to 19 m $s^{-1}$ (Piper *et al.*, 1988)), can also explain why the Bude Formation is so fine-grained (max. fine sand; Burne, 1995; fig. 7c), and why deeply incised channels are absent (see below).

When a river-fed underflow was augmented by storm waves, deposition is envisaged to have begun with rapid fallout from the sediment-laden combined flow, producing the massive lower division characteristic of Bude sand beds; then, as the underflow waned, the bed top was sculpted into quasi-symmetrical ripples (and/or parallel lamination and/or hummocky cross-stratification, given larger waves or shallower water).

## 'Slurried' beds: are they debrites or *in situ* seismites?

This particular controversy has important palaeogeographic implications, because a debris-flow interpretation implies a significant palaeoslope, whereas *in situ* 'seismites' (Seilacher, 1984) imply a negligible gradient.

As described by Burne (1970, 1995), 'slurried' beds are sharp-based beds mainly 2–20 cm thick, which commonly grade upward from a massive or laminated sandstone into a 'slurried' silty layer in which large (cm-dm) tabular intraclasts of dark mudstone are common, as are water-escape tubes. The 'slurried' layer can be capped by an irregular sandy layer comprising small (cm) sand volcanoes in various stages of foundering (Burne, 1970). Burne (1995) interprets these beds as allochthonous debris-flow deposits, as have many other observers. In contrast, I interpreted them ('mixed beds' of Higgs, 1991) as seismites formed *in situ* by earthquake-induced liquefaction of lake-bottom silt containing one or more bands of darker, cohesive clayey mud prone to brecciation (Figs 1, 2). Silt and mud are common throughout the Bude Formation as 'background' sediment (Facies 2 and 1 of Higgs (1991); 'muddy siltstone' and 'black shale' facies of Burne (1995)), and also as silt turbidites (Burne, 1995).

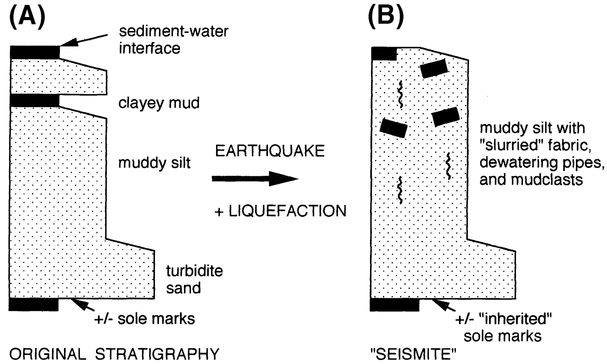


**Fig. 1.** Model for *in situ* development of a Bude Formation 'slurried' bed. (A) Hypothetical stratigraphy of the topmost 10–100 cm at the lake floor (precompaction; pre-earthquake). Two 'muddy silt' intervals are shown, which could be either turbidites (two or more) or 'background' sediment, alternating with cohesive mud. Also shown arbitrarily is a basal sand interval. (B) The same interval after earthquake-induced liquefaction of the muddy silt intervals, and sinking of the brecciated clayey mud layers, forming a 'slurried' bed, a type of 'seismite'. The basal sand is a 'passive' component of the seismite (see text).

An inferred prerequisite for forming 'slurried' beds containing mudclasts were silts at the lake bottom, with at least a one centimetre-scale mud layer above or within (Fig. 1). During an earthquake, the surficial silt layer(s) underwent liquefaction, while the cohesive mud layer(s) broke up and sank, until encountering the base of the liquefied layer. While sinking, mudclasts underwent partial to total 'digestion' (Burne, 1970). Examples of imbricated and folded mudclasts suggest that limited downslope shearing occurred in some cases.

In the seismite interpretation, the basal sand interval, where present, is not necessarily involved in the liquefaction, and may therefore 'block' the sinking mudclasts (Fig. 3). This could explain why mudclasts are usually confined to the upper part of slurried beds (Burne, 1995); alternatively, postearthquake ascent of the liquefaction front could be responsible. The basal sand may bear tool or scour marks, which I interpreted to have been 'inherited' from a precursor event-bed (Higgs, 1991).

Support for the *in situ* seismite interpretation is diverse and persuasive:

**1** identical structures have been produced experimentally by liquefaction *in situ* (Anketell *et al.*, 1970; fig. 16);
**2** very similar beds in Precambrian to Lower Cambrian shelf deposits of Newfoundland were

 

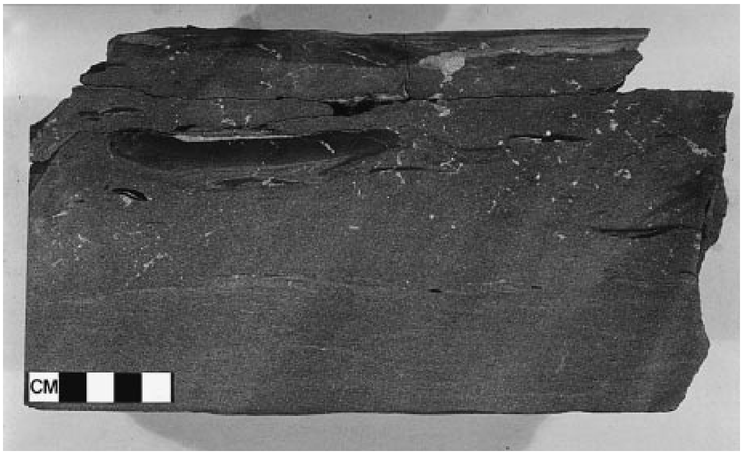


**Fig. 2.** Sawn section of a Bude Formation 'slurried' bed (cf. field photograph of same bed in Higgs, 1991; fig. 11a). There is no basal sand layer (cf. Fig. 1). The bed consists of muddy silt containing subhorizontal mudclasts, and grading abruptly at the top into mud. The mudclasts are inferred to be remnants of a formerly continuous mud layer which suffered brecciation and foundering, caused by earthquake-induced liquefaction of the underlying silt. The mudclasts have diffuse boundaries, suggesting partial 'digestion'. This 'slurried' bed probably originated as two or more amalgamated silt turbidites; a possible plane of amalgamation is preserved as a pale 'wispy' lamina about 5 cm above the base. The pale lamina resting on the large mudclast is possibly a sandy microturbidite, or the (sandy) base of a thicker, silt turbidite. The small black mud chip (centre-left), darker than the rest, may be genuinely detrital.

attributed to *in situ* liquefaction by Myrow & Hiscott (1991; their 'disturbed beds');

**3** examples of *incipient* 'slurried' beds occur, with the original stratification largely conserved (Fig. 3); and

**4** examples occur in which the mudclasts can easily be 'correlated', one to another, as in an example photographed by Burne (1995; fig. 24), in which the clasts are closely spaced, of equal

**Fig. 3.** Two incipient 'slurried' beds in the Bude Formation, with their original stratigraphy largely preserved. Coin 2·8 cm across. Two turbidites show 'step-wise' grading from pale sand into grey silt. The 'background' sediment is black mud, visible at the base of the photograph, and also near the top, immediately below a third sand turbidite. A further black mud layer in the centre, originally overlying the first turbidite, has fragmented and sunk through the underlying silt, to the top of the basal sand. In contrast, the upper mud layer broke into smaller fragments, which have only partially foundered into the silt beneath. Fragmentation of the two mud layers is attributed to earthquake-induced liquefaction of the underlying silt. Two separate liquefaction events can be inferred, each forming a 'slurried' bed at the sediment–water interface, based on: (1) non-deformation of the base of the overlying turbidite; and (2) presence of a thin (1–5 mm) lamina of undisturbed black mud (barely visible) above each 'slurried' bed, representing background deposition *after* the earthquake and *before* the next turbidite. Intrusion of sand dykes and sills (centre) could have occurred during the first or second event.

thickness, all subhorizontal, and all containing a central silt stripe.

Also consistent with the seismite interpretation are dewatering pipes and sand volcanoes. Both phenomena reflect liquefaction, whereas the sand volcanoes confirm that the 'slurried' beds formed at the sediment–water interface. Examples of sand volcanoes which are asymmetrical suggested to Burne (1970) eruption into a 'residual' current. Instead, I would invoke a permanent or semipermanent (wind-driven?) current. However, most sand volcanoes on 'slurried' beds and 'slumped' beds (see below) are symmetrical (Burne, 1970 and my own observations), suggesting no 'residual' current, which in itself supports an *in situ* origin of the host bed.

Burne notes that 'In places, beds have 'frozen' in the act of peeling up fragments of mudstone from the substratum' (Burne, 1995; p. 115). However, a photograph (his fig. 25) shows two problems with this interpretation: (1) in the photograph, a 'slurried' interval grades down into a basal set of fading ripple cross-laminae, but the ripples indicate a palaeocurrent direction (right-to-left) approximately opposite to the sense of 'peeling-up' of a tilted intraclast; and (2) the delicate basal cross-lamination would probably have been deformed by the impact of the 'dense current' (Burne, 1995; p. 125) which deposited the 'slurried' interval. Instead, I suggest that the mass of sediment which Burne interprets as having been 'peeled up' has actually sunk from above and now lies tilted, in partial contact with the basal rippled layer.

Similar mudclast-bearing beds in Korea were also attributed to earthquake-triggered liquefaction by Chough & Chun (1988). However, these authors interpreted the clasts as being plucked from above ('rip-down clasts') by limited downslope flow of a liquefied layer *beneath an overburden* .

The Bude 'slurried' beds have been cited (Burne, 1970), along with similar deposits, in reviews of sediment-gravity-flow products (Pickering *et al.*, 1986; Facies C1·1; Ghibaudo, 1992; Facies MyS). However, I suggest that citation of the Bude examples, and perhaps some of the others, is inappropriate as they are *not* products of sediment gravity flow. Other candidates for reinterpretation are the 'fragmented' and 'slurried' beds of the Aberystwyth Grits (Wood & Smith, 1959), from whom Burne (1970; p. 221) borrowed the name. A bed strongly resembling a Bude 'slurried' bed was interpreted by Lowe (1976; fig. 4) as a liquefied flow deposit, but an *in situ* origin should also be considered.

## 'Slumped' beds: not slumped

The 'slumped' beds of Burne (1995), for which Higgs (1991) preferred the nongenetic name 'contorted beds', are similar to 'slurried' beds except that they are thicker (up to 20 m) and contain folded sandstone layers. These beds can pass both laterally and downward into undeformed sediments (Melvin, 1986; p. 25; Higgs, 1991; pp. 456–457; Burne, 1995; p. 116), proving that the deformation occurred *in situ*, and prompting Higgs (1991) to interpret them as (bigger) seismites. Slight preferential southward vergence of internal folds (Enfield *et al.*, 1985) may indicate minor downslope shearing during liquefaction.

Despite this evidence for *in situ* development, Burne (1995) maintains that the 'slumped' beds are (high-) density-flow deposits, as does Hartley (1991). The 'slumped' beds can be considered as more advanced manifestations of the local 'intrastratal folding and small-scale synsedimentary faults' seen by Burne (1995; p. 111).

## Low depositional gradient

The lack of evidence for significant lateral flow of the slurried/slumped beds may reflect a very low palaeo-gradient, because subaqueous sliding and slumping can occur on slopes of as little as 0·5° (Coleman, 1981). This gentle gradient immediately excludes slope- and base-of-slope fans, which have gradients of 1–10° (Stow, 1986; table 12·3), whereas the average gradient of modern shelves is only 0·1° (Shepard, 1963). Therefore, *in situ* seismites are consistent with a shelf interpretation, as are the polymodal palaeocurrents mentioned earlier, which I attributed to deflection of (gravity-driven) underflows *across* the gentle shelf gradient by wind-driven currents (Higgs, 1991).

## Hummocky cross-stratification

Hummocky cross-stratification was tentatively identified in the Bude Formation by Higgs (1983, 1984), and later confirmed (Higgs, 1991). Burne (1995) agrees that 'irregular lamination comparable to hummocky cross-stratification' is present, and includes a photograph (his fig. 22). Hummocky cross-stratification appears to be uncommon in the Bude Formation, but could be masked in some cases by 'lack of grain size contrast' (Burne, 1995; p. 117), or erased by liquefaction. Widespread liquefaction in the Bude sandstones is indicated by abundant evidence for dewatering (Higgs, 1991), including intervals with 'faint traces of lamination, often disrupted into dish structures' (Burne, 1995; p. 114). Moreover, the Bude sandstones are very fine to fine grained (Melvin, 1986; fig. 3; Burne, 1995; fig. 7c), and therefore particularly susceptible to liquefaction (Myrow & Hiscott, 1991). Erasure by liquefaction is also suggested by the presence, in many amalgamated-sandstone bodies, of undulatory partings resembling hummocky cross-stratification set boundaries (Higgs, 1991; Burne, 1995; figs 20, 21). Strikingly similar tabular sandstone bodies with internal undulatory partings occur in the Ordovician of Newfoundland (Brenchley *et al.*, 1993; fig. 14; compare Higgs, 1991; fig. 7), differing only in the presence (preservation?) of hummocky cross-stratification. These sandstones were attributed to storm-wave reworking on a shelf by Brenchley *et al.* (1993), an interpretation which I would also apply to the Bude Formation.

Burne's (1995; p. 129) interpretation of the hummocky cross-stratification differs from the conventional storm-wave interpretation (Dott & Bourgeois, 1982). Citing reports of structures resembling hummocky cross-stratification in deep-water deposits, he concludes: 'In the absence of associated unequivocal evidence for shelf sedimentation … the rare hummocky cross-stratification recorded from the Bude Formation is interpreted to represent the result of either upper flow-regime structures or traction across a quick bed during deposition from a turbidity current' (Burne, 1995; p. 129). However, Einsele & Seilacher stated (1991, table 1) that hummocky cross-stratification is absent in turbidites.

## Absence of channels

The thick (3–10 m) sandstones typical of the Bude Formation do *not* occupy channels, apart from flat-bottomed scours only 5–20 cm deep, which can also occur *within* sand bodies, truncating interfingering mudstone layers (Higgs, 1991; fig. 8). The absence of deep channels results in tabular external geometry (Higgs, 1991; fig. 9; Burne, 1995; figs 33, 36).

Other channels in the Bude Formation are mud-draped scours up to 1 m deep, occurring as both undulating and pan forms (Higgs, 1991). The mud drape can be only millimetres thick, followed by a sandy event-bed fill (e.g. Burne, 1995; fig. 32). Reading (1963; p. 69) was probably referring to these when he stated that 'Channelling is common, but the bases of the channels are gently curved and not sharply erosive'.

One thick sandstone contains inclined partings, interpreted by Burne (1995; fig. 33) as the laterally accreting margin of a channel more than 4 m deep, *cut in sand*. However (p. 119), the same feature was previously interpreted as tectonic (Mapeo & Andrews, 1991; Tanner, 1992), and significantly, his sketch of the sandstone unit includes an area labelled 'duplex' (Burne, 1995; fig. 34a). On the basis of this possible channel, Burne (1995; p. 129) compared the Bude Formation to Italian turbidite-fan formations (Ricci-Lucchi, 1975), which *differ strongly* in containing abundant channels, cut in interbedded sandstone and mudstone, and filled by medium to very coarse-grained sandstone.

## Other problems with the fan interpretation

Three additional features of the Bude Formation are more characteristic of storm beds than of turbidites, according to summaries by Seilacher (1982) and Einsele & Seilacher (1991): (1) many sandstone beds have sharp, rippled tops; (2) individual (nonamalgamated) sandstone beds commonly pinch out laterally within a few metres, truncated by mud-draped scours (Higgs, 1991; fig. 7; Burne, 1995; fig. 10); this is typical of storm beds (Goldring & Bridges, 1973; Brenchley, 1985); and (3) rib-and-furrow and (Bouma C) convolute lamination are absent.

Turning to the fauna, Burne (1995; p. 129) states that 'the absence of a shallow-water benthic fauna … (supports) … a turbidite-basin interpretation rather than that of a storm-affected shelf'. However, as the water body was a 'lake or inland-sea basin' (p. 130) containing 'generally … fresh or brackish water' (p. 103), one wonders what fauna would be *expected*, given the relative scarcity of macrofauna in Palaeozoic lakes (Gray, 1988), and the dearth of studies on bathymetric zonation of Palaeozoic lake fauna.

## Bude Formation too thick to be a shelf deposit?

Burne considers (1995; p. 131) that the thickness of the Bude Formation, calculated as about 1300 m (Freshney & Taylor, 1972), is excessive for shelf deposits. However, other examples of thick shelf deposits are the Jura Quartzite

(> 5 km; Anderton, 1976) and the Lower Sandfjord Formation (1·5 km; Levell, 1980). Furthermore, recent recognition of thrusts in the strongly folded Bude Formation suggests that repetitions of the stratigraphy are likely (Enfield *et al.*, 1985; p. 170; Whalley & Lloyd, 1986), such that the total thickness may have been overestimated.

## CONCLUSION

I believe that the weight of evidence supports my contention that the Bude Formation was deposited on a storm-influenced lake shelf, supporting Goldring & Seilacher's (1971; p. 434) interpretation that the lake was 'large, though probably not very deep'. Four factors can be identified which have masked the shelf origin of the Bude Formation: (1) presence of disturbed beds resembling debrites and slumps, implying a substantial palaeogradient, but actually formed *in situ* by earthquakes; (2) scarcity of fauna, reflecting the lacustrine origin; (3) widespread erasure of hummocky cross-stratification by liquefaction; and (4) near-absence of symmetrical ripples.

Finally, and on a lighter note, I am happy to observe that Burne's (1995) paper fulfils his promise, made 25 years previously (Burne, 1970; p. 213), that 'A detailed account of the sedimentology … is deferred for a later paper'!

## ACKNOWLEDGMENTS

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## DISCUSSION

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That the Bude Formation could provoke so much controversy after more than 30 years' study shows that there are some formations, beautifully exposed though they are, whose interpretation still defies a consensus. There is clearly uncertainty when we try to interpret processes and environments from the observed facies, even distinguishing 'deep' from 'shallow' water. As with so many controversial formations, simplistic models do not work; comparisons with modern environments and published interpretations of other ancient formations can be misleading. All these problems are compounded when we are dealing with lakes. Non-actualistic interpretations are essential.

The Bude basin was the youngest and the most southerly of many Namurian to early Westphalian basins that lay along the northern, passive margin of the Variscan foreland. The palaeogeographic and tectonic setting for the Bude Formation has been ably described by both Higgs (1991) and Burne (1995). However, three features stand out.

Firstly, the Bude basin, like most Upper Carboniferous basins, was fed by rivers that carried sediment derived from predominantly 'Old Red Sandstone' sedimentary rocks and recycled earlier Upper Carboniferous sediments. Thus it was filled by predominantly fine-grained sediments and was essentially a mud-rich system (Reading & Orton, 1991). Hence gradients were very low and distinction between 'shelf', 'slope' and 'basin' may often have been difficult to determine. Secondly, latitudes were equatorial and the very heavy rainfall led to an enormous input of fresh water, as in many of these Upper Carboniferous basins (Martinsen *et al.*, 1995). The Bude basin was therefore filled with fresh water for most of the time, and this affected not only the nature of the lake bottom but predisposed incoming currents to be underflows. Thirdly, as the Bude basin was connected, for most of the time, directly or indirectly, to a distant sea, it was affected by glacio-eustatic rises and falls of sea level, of varying magnitude. Thus salt water entered the basin at times of high sea level. At times of low sea level, not only was salt water flushed out of the basin, but sea level may have dropped below the lake threshold and lake levels would have become dependent more on the hydrological budget of the lake than on sea-level fluctuations. Sedimentary sequences were thus a consequence of eustasy, variations in rainfall and delta switching.

The controversy between Burne and Higgs falls under two headings, interpretation of sedimentary processes and of environment.

### Sedimentary processes

**1** Storms, as indicated by 'hummocky' cross-stratification and 'wave' ripples are the principal evidence for Higgs (1991) interpreting the Bude Formation as a shelf. The supposed hummocky cross-stratification is, however, very rare and the exposures are equivocal as to whether they were formed by storms or by some 'turbiditic' process, as argued by Burne (1995; pp. 125–126), such as migrating dunes or antidunes. The ripples, interpreted by Higgs (1991, 1998) as wave ripples, do occasionally occur as straight crested symmetrical ripples on the surfaces of some Bude sandstones. Yet wave ripple cross-lamination is very difficult to see and symmetrical ripples are generally confined to the top surfaces of beds.

It is impossible to rule out completely the possibility that these structures were formed during very rare periods of lowered lake level when the lake bottom was within the reach of storm and wave activity, and a possible alternative is that the lake bottom could have been reached by oscillatory water movements produced by seiches, the effects of which on deep lake bottoms we know very little about. Seiches could, however, have produced wave/storm features at depths well below those of continental shelves. Nevertheless, I am becoming increasingly convinced that the apparent storm and wave features seen in the Bude sandstones can be attributed to reflected flows caused by the incidence of turbidity currents upon flow obstructions (Edwards *et al.*, 1994; Kneller *et al.*, 1997). If the latter is true, there is no need to invoke periods of shallowing for the formation of such features.

**2** Both are agreed that the sandstone beds were emplaced by turbidity flows and that most of the succession was formed by a series of 'events'. Differences of opinion arise on two major accounts.

Firstly, whether the 'event beds' were essentially 'river-fed' and deposited during catastrophic 'storm-floods' **above** wave base (Higgs) or whether they formed as turbidites initiated from a marginal slope, probably by slumping **below** wave base.

Secondly, whether the very abundant thin-bedded 'mixed/slurried' beds and thick-bedded 'contorted/slump' beds were all the result of seismic events that shook the sediments after deposition (Higgs) or were the consequence of either the initiating and transport process itself (slumped beds) or syn- and postdepositional processes (slurried beds) (Burne).

Higgs' idea that the turbidity currents were initiated by river floods is important, especially by comparison with the deep-water systems of many of today's mud-rich deltas in equatorial regions (Congo, Magdalena), and most of the 'event beds' were probably river-generated. Nevertheless a 'slump' origin cannot be ruled out, and this conflict raises the important question, at present unresolved in modern delta/deep-sea systems, of how far deep-water 'turbidites' are the result of really instantaneous events such as slumping off the delta front or of longer-lived, lower density hyperpycnal river-generated flows.

With regard to the thin-bedded 'mixed/slurried' beds, Burne documents ample evidence that many of these formed during deposition, or very shortly after. It is clear that loading of ripples, fragmentation of clay layers, and formation of sand volcanoes occurred during deposition of the bed and was not due to a later seismic shock. The thicker 'contorted/ slump' sandstones are another matter. Higgs draws attention to a very important question, that is whether we need to, or are correct in invoking, lateral emplacement for such beds. I believe that, on balance, Higgs' ideas of postdepositional disruption of a packet of previously deposited turbidites by a seismic shock is the correct one. Too often, 'disrupted' strata are interpreted as slumps or debrites, transported from upslope, invoking therefore a nearby slope and the consequential environmental implications. If the strata can be seen clearly to be composed of sediment different from the overlying and underlying strata, then a transported origin is correct. However, if the disturbed strata are identical to the beds immediately above and below, then doubts must arise. If a 'slump' origin is invoked, then the slumped sediments must have originated in an area where the depositional processes were similar to those at the place we observe them. In the Bude Sandstone, the lateral extent of the 'contorted/slump beds', and the lateral passage into undeformed strata, as well as the similarity of both slumped and enclosing strata, point to postdepositional seismicity as the origin of most of the disrupted strata, which therefore, have experienced negligible lateral transport.

## Environmental interpretation

As usual with Palaeozoic and older turbidite systems, there is no positive evidence for water depth. However, the idea that the Bude Formation was deposited on a 'storm-influenced lake shelf' is neither supported by the positive evidence for storm and wave action in the sediments, nor by the negative evidence. There are so many features that one would expect to find if it were a shelf, but which, in fact, are not seen. As I pointed out earlier (Reading, 1963), the reason for concluding that the Bude Formation was deposited in relatively deep water is the complete absence of any emergent features and only equivocal evidence for shallow water over a thickness of about 1300 m of sediment deposited in a largely landlocked basin over a span of about 5 Myr. During this time lake levels rose and fell substantially as seen in the alternations of fully freshwater conditions and brackish to marine episodes because glacio-eustasy was rampant and there were significant fluctuations in freshwater input. Higgs' comparison of the Jura Quartzite and Lower Sandfjord Formation is both misleading and irrelevant because these are almost 100% sand, are marine and are Precambrian. It is still very difficult to distinguish between even fluvial and shelf sediments in such successions, let alone determine shorelines, and they were interpreted in the days when autocyclic rather than allocyclic mechanisms were the order of the day. The Upper Carboniferous basins with which we are dealing here were virtually tideless. The only physical effects they could have felt were those due to waves and storms. Wherever one sees Lower Westphalian lake margin sediments in north-west Europe (e.g. in the neighbouring time-equivalent Bideford Group at Westward Ho! (de Raaf *et al.*, 1965; Eagar & Xu Li, 1993), there is abundant evidence for shallow water in the form of wave ripples, *Teichichnus* burrows, etc., but only rare evidence of hummocky cross-stratification or extensive sorting of the coastal sediments, which are poorly sorted. All the evidence points to a basin or basins in which both storm and wave activity were relatively impotent. Had there been regular wave/storm activity at the basin margins, sandy beaches would have developed. These are never seen in the Lower Westphalian.

Thus the sedimentary evidence and the likelihood that the Bude basin was a wide, largely enclosed, gently subsiding sag basin, suggests water depths were considerable, though just how deep it is impossible to say. It certainly never emerged.

Having argued that Higgs' shallow shelf environment is not supported by the data and that deposition took place in a basin of some depth, the question is 'what sort of deep-water model is appropriate?' Before I argue for a combination of mud-rich, distal ramp (tentatively suggested by Hartley, 1991) and basin plain, I should discuss the extent and size of channels and the degree that cycles and sequences are developed in the Bude Formation.

There are almost certainly no deep, steep-walled channels in the Bude Formation, although tectonic deformation (duplexing/thrusting) wherever a thick sandstone occurs within this dominantly parallel-bedded succession would hinder observation of such channel margins. However, there are many small-scale channelled/erosive bases which cut down a few centimetres or even a metre into the underlying strata.

There is clearly a cyclicity as a consequence of eustatic sea-level changes and alternations of thin and thick-bedded packets and sequences can be observed. However, thinning- and thickening-upward sequences are rare and mostly occur in or close to the black shale/mudstone facies. Try as one can to discern sequences, the principal feature is a *lack* of predictability in the succession and this is what needs to be taken into account in any environmental interpretation.

The subsea fan interpretation of Burne (1995) goes back to the days when the point-source fan was unique for turbidite successions and had only to compete with the contourite model. We now know that a simple point-source fan is a rarity and that multiple, fluctuating sources, exemplified by the ramp model of Heller & Dickinson (1985) are a feature of many deep-water systems. Mud-rich ramps commonly front mud-rich deltas with their switching river mouths (Reading & Richards, 1994). Typically, as in the Bude Formation, sequences and channels are poorly developed, suggesting sources were impersistent and migrated frequently.

In addition, though, the Bude Formation has many of the characteristics of a basin plain. Beds are dominantly sheet-like, channelling is minor, sequences are rare or poorly developed, and irregularities in thickness can mostly be explained by compensation features and fluctuations in flow, possibly the response to changes in supply and current flow within a confined basin. This concept of basin plain/basin floor sedimentation has been badly neglected in recent years at the expense of basin margin systems. For example the Namurian Ross Sandstone Formation of western Ireland has been described by Chapin *et al.* (1994) as a fan, although it is composed of dominantly sheet-like beds, with a few 'slumps', very minor 'channelling' and no sequences other than changes consequent upon glacio-eustatic sea-level changes, like those in the Bude Formation.

To sum up, my present preferred picture of the Bude basin is of a broad lake of considerable depth and almost flat basin floor onto which deep-water ramps occasionally penetrated from the west, north and east. To the south, in front of an advancing orogenic belt, was a broad, emergent swell that separated the lake from the open sea for much of the time, but was too far away to supply sediment. Passages in the barrier allowed the sea to penetrate the Bude basin at intervals, and sea-level changes to affect it. During major glacio-eustatic highstands, marine waters and fauna penetrated the basin and clastic supply was almost eliminated. During lowstands salt water was flushed out by inflowing river waters and deep-water ramps penetrated the basin, fed by a complex pattern of fluctuating deltas from three sides of the basin. However, there are still many uncertainties, the true nature of the 'contorted/slump' beds, whether the 'event beds' were derived from relatively long-lived river-generated flows or 'slumps', whether the 'hummocky' cross-stratification and symmetrical ripples do reflect phases of shallowing and whether the basin plain/distal ramp model is appropriate. These uncertainties still need to be addressed.

## REPLY

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## INTRODUCTION

The Bude Formation of south-west England was deposited between about 312 Ma and 311 Ma (Jones, 1995). The relatively thick (1300 m) sequence was deposited along the northern margin of a foreland basin (Franke & Engel, 1988; Hecht, 1992), the Culm Basin, that developed north of the advancing tectonic front during the Variscan thrusting that began earlier than 330 Ma and continued until about 300 Ma (Ahrendt *et al.*, 1983).

It is well established that the Bude Formation consists largely of turbidites (Ashwin, 1957; Reading, 1963; Walker, 1963; Lovell, 1964; Burne, 1969; Melvin, 1986; Higgs, 1991). I concluded (Burne, 1969), and Melvin (1986) agreed, that the turbidites were deposited as subsea fan turbidite systems on the basin floor. Higgs (1987) proclaimed the Bude Formation to be 'The Fan That Never Was', and interpreted it as the deposits of a wave-affected shelf.

Recently (Burne, 1995), I reviewed my earlier conclusions (Burne, 1969) regarding the tectonic setting, palaeogeographical relationships and facies of the Bude Formation in the light of claims by the British Geological Survey (Edmonds *et al.*, 1979) that there was continuity between the Bude Formation and the contemporaneous paralic sequences of the Westward Ho! and Bideford region and Higgs' suggestion (Higgs, 1991) that the Bude Formation itself had a shelf origin. I concluded that, while paralic deposits of equivalent age to the Bude Formation coexist in the Culm Basin, there is no established depositional continuity between the two tectonically distinct successions (Reading, 1963; Burne & Moore, 1971; Cornford *et al.*, 1987; Eager & Xu Li, 1993), and, after thorough consideration, reaffirmed that the Bude Formation was deposited as subsea fans on the northern passive margin of a land-locked, foreland basin.

Higgs (1998) has offered a discussion of this review. Reading (1998), in turn, provides a discussion of Higgs' discussion, and concludes that Higgs' shallow shelf model is not supported by the data. This note provides a brief response to the significant points raised in both these discussions.

### The invalidity of Higgs' storm emplaced shelf-sand model

I concluded that there was no unequivocal evidence for shallow water structures in the Bude Formation (Burne, 1995). Nevertheless Higgs (1998) continues to advance the argument that structures interpreted as Hummocky Cross Stratification (HCS), symmetrical ripples, and signs that the tops of massive sandstones have been reworked, provide evidence for shelf sedimentation.

The point that Higgs misses is that neither HCS nor ripple-form are diagnostic of a particular environment, instead they reflect depositional processes. Higgs (1998) provides no additional evidence to justify the conclusion that the structures interpreted as HCS, symmetrical ripples, or quasi-symmetrical ripples were formed on a wave affected shelf. There are several reports of structures satisfying the descriptive diagnosis of HCS occurring in turbidite sequences (see references in Burne, 1995). Despite the claims of Higgs (1991, 1998) and Melvin (1987), I remain unconvinced that symmetrical ripples (of whatever origin) occur within the Bude Formation. The concept of reworking of the tops of turbidites by residual currents (Middleton, 1967; Burne, 1969) is now well established (Edwards *et al.*, 1994; Kneller *et al.*, 1997).

This succession has characteristics recognised as typical of turbidite sequences. Higgs (1998) reconciles this with his shelf interpretation by invoking a model of combined flow, in which high river run-off during storms generates unidirectional currents which are both accelerated and reworked by storm waves. This model is illogical in that it requires that the major rainfall event in the river catchment *always* precedes the storm winds that affect the basin by a sufficient time to allow the catchment run-off to reach the basin *before* storm waves are generated. These waves are then required to both help impel the depositing currents and to rework the tops of the beds deposited by them. In fact storm waves will precede the deposition of sediment carried to the basin by rivers swollen by precipitation from the same storm event. The temporal lag between the storm event and peak discharge by rivers is well documented (Pattison *et al.*, 1977), and has been experienced by all who have endured a tropical storm.

## Slurried & slump beds vs. seismites

Higgs (1998) makes much of the suggestion that the disrupted units of the Bude Formation are seismites, and Reading, while agreeing with my interpretation (Burne, 1970, 1995) that 'slurried beds' are frozen high density turbidity current deposits, surprisingly concurs with Higgs' suggestion that the 'slump beds' are 'seismites'. The field evidence is incompatible with this hypothesis. Seismic liquifaction of sediments requires that there be a coincidence between seismic waves of the correct amplitude, the appropriate number of cycles of shaking, and a water-saturated silty-sand or sandy-silt layer which is confined by an overlying clay layer (Ambraseys & Sarma, 1969; Ambraseys, 1988). These conditions can only develop patchily, where local conditions are suitable (Seed, 1970). Both Higgs (1998) and Reading (1998) fail to appreciate the significance of these conditions, and appear ignorant of distinctions I made (Burne, 1970) between the units of the Bude Formation that *have* been disrupted *in situ*, presumably by seismic waves, and those disturbed beds, termed 'slurried beds' and 'slump beds', that record the impact of high density turbidity currents on a muddy substrate, and the subsequent de-watering of the resultant rapidly deposited sediments. The name 'slump beds' was used for the thicker disrupted units. It is an established term for these characteristic units that form widespread basin markers (King, 1967; Freshney *et al.*, 1972). In this usage the term has no genetic significance. The beds are certainly not allochthonous debris flow deposits (debrites) as all the contained clasts above fine-sand size were derived either from close proximity to the place of deposition or, in the case of sand volcanoes, from the depositing bed itself. The extensive lateral extent of these 'slump beds' clearly indicates that their origin was as catastrophic emplacement events, and certainly discounts an origin as a result of seismic liquefaction which develops only patchily and on a local scale (Grantz *et al.*, 1964; Coulter & Migliaccio, 1966; Walsh *et al.*, 1994). On the other hand the sediments that are believed to be seismically disrupted (Burne, 1970) appear to have been water-saturated fine silty-sands that were capped by a substantial thickness of clay when disturbed by seismic waves, at which time sandstone dykes were emplaced into the overlying sediments, feeding sand volcanoes which erupted at the sea floor. This was a relatively local occurrence that has some parallels with the effects of the Great Alaska Earthquake of 1964 (Combellick *et al.*, 1995). It should also be noted that Eager & Xu Li (1993) also misunderstand the description by Burne & Moore (1971) of tectonically disrupted beds in the Westward Ho! Formation as 'tectonised beds having the appearance of a slump bed', they too are certainly not debrites.

## Bude Formation channels

The form and scale of subsea fan channels is far greater than the scale of the cliff and wave cut platform outcrop of Bude. They may attain widths of several kilometres, and are not necessarily incised into the fan sediments but may be accretionary features growing through the vertical accumulation of levee deposits (e.g. Shepard *et al.*, 1969; Shanmugam & Moiola, 1988). The features I illustrate (Burne, 1995; fig. 34) are interpreted as the accumulations of minor channel systems within such a larger fan channel complex. While these sediments have been affected by tectonics, the existence of duplexes is not as common as Reading (1998) suggests. The important thing is that the tectonic structures affect originally lenticular beds that are associated with what are interpreted to be channel complexes.

### The depositional sequence

Despite Reading (1998) despairing that there is a lack of predictability in the succession, sequences can be observed in the Bude Formation. In fact the terms 'thickening upward sequence' and 'thinning upward sequence' were first applied to sequences recognised in these rocks (Burne, 1970). Reading (1998) is mistaken in suggesting that my interpretation of this sequence dates back to a time when 'the point-source fan was unique for turbidite successions'. In fact the debate concerning turbidite successions prior to 1969 centred on determining evidence for the relative proximity to or distance from the source of the turbidity currents (Walker, 1967). I introduced (Burne, 1970) the concept that variation within turbidite successions might arise from lateral facies variation in a fan complex. This concept, taken together with the palaeocurrent data, necessarily implied the existence of fluctuating sources for the fan sediment. The questions then arose as to what extent the vertical variation in facies observed in the Bude Formation is due to lateral migration of environments, deepening or shallowing of the basin, or variations in rates of sediment supply due to, for example, glacial and interglacial variations in equatorial rainfall?

### Evidence for the depositional environment

The tectonic setting of the Bude Formation provides some constraint on the depth of the basin in which it was deposited – it is not an ocean basin, but neither is it a sag basin (as has been suggested by Reading, 1998). The biotic evidence supports the conclusion that the basin was relatively deep, with obviously shallow water elements, characteristic of other Westphalian basins, absent from the Bude Formation.

Reading (1998) concludes that 'there is no evidence for a storm-influenced lake shelf'. However, despite warning against the adoption of simplistic models, Reading (1998) characterises the Bude Formation according to jejune classification systems based on grain size distributions (Reading & Orton, 1991) and fan type (Reading & Richards, 1995). Leeder has recently pointed out that such systems of classification are 'lazy intellectually and deny the great potential richness of the sedimentary record' (Leeder, 1997; p. 374). Nevertheless Reading's conclusions as to the depositional setting of the Bude Formation (Reading, 1998) essentially mirror mine (Burne, 1970, 1996).

Both Reading (1998) and Higgs (1998) fail to appreciate the fact that I concluded that it is impossible to invoke the origin of the currents from the deposits, save that the conditions must have been suitable for the ignition of these currents. Reading (1998) seems to intuitively favour a river-generated underflow origin, but, as Higgs (1992) points out, hyperpycnal flow needs some extra propulsion to generate turbidity current ignition.

## CONCLUSION

The Discussions of Higgs (1998) and Reading (1998) provide neither data nor argument to justify modification of my conclusions (Burne, 1970, 1995) that the Bude Formation was deposited as a series of subsea fan turbidite-systems growing across the basin floor on the northern, passive margin of a foreland basin. Fans were fed with fine grained sediment from sources to the west, north and east. The basin was nonmarine for much of its history, though brief marine incursions occurred when high eustatic levels enabled links with the open sea to be established.

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In the Culm Basin of the south-west, carbonate turbidites of the Teign Valley Group (C1â€“4; lower part of the Culm Supergroup) were derived from the north and silicic turbidites from the south.Â  In the Solwayâ€“Northumberland and Tweed basins of the north, a river system that drained a large hinterland laid down mud, sand and carbonate as fluvial, alluvial fan and lacustrine deposits of the Ravenstonedale and Inverclyde groups (C1), during the Tournaisian when the climate was relatively arid.Â  The Holsworthy Group (C5â€“7) of south-west England was deposited as turbidite lobes on a delta front, and is similar to the lower part of the Millstone Grit of the Pennine Basin.