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Debris flow and slump deposits from the Upper Carboniferous Bude Formation of SW England: implications for Bude Formation facies models

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The Bude Formation of the Upper Carboniferous Culm Basin of SW England (Fig. 1) comprises a northerly derived, turbidite-dominated sequence deposited in brackish, shallow water (above storm wave base) in a subaqueous fan (Melvin 1986, 1987) or siliciclastic shelf depositional environment (Higgs 1984, 1986, 1987, 1991). Slumped beds occur throughout the Bude Formation (Ashwin 1957; Lovell 1964; King 1966; Moore 1968; Burne 1970; Freshney *et al.* 1972, 1979; Edmonds *et al.* 1979; Enfield *et al.* 1985; Higgs 1986, 1987; Melvin 1986, 1987) and account for 10% of its total thickness (Fig. 2). The slumped beds were originally interpreted as slump deposits by Ashwin (1957) and Lovell (1964). However, this interpretation was questioned by Burne (1970) followed by Freshney *et al.* (1979) who favoured an origin related to dewatering after deposition of a dense sediment flow. In contrast, Higgs (1986, 1987, 1991) and Melvin (1987) suggested an *in-situ* origin for the slumped beds related to liquefaction generated by seismic shock. An alternative explanation was favoured by Whalley and Lloyd (1986), who suggested a mixed sedimentary/tectonic origin where early thrust fault related deformation below the sediment-water interface followed deposition of a sedimentary slump. However, the detailed descriptions and interpretations of the slumped beds presented here, indicate that they did not originate by a single mechanism; the wide variety of internal structures resulting instead from deposition above the sediment-water interface by both slumps and debris flows. The presence of debris flow and slump deposits has important implications for the depositional setting within the Culm Basin during Bude Formation times.

The Culm Basin was initiated in early Namurian times following regional compression. It represents a foreland basin formed to the north of the developing Variscan Orogen and south of the cratonic Wales-Brabant Massif (Hartley and Warr 1990). However, it is unclear whether basin configuration was controlled by the structural inversion of previously thinned crust (Hartley and Warr 1990; Warr 1991) or though lithosperic loading related to thrust nappe emplacement south of the basin (Thomas 1988) or possibly a combination of both.

The Culm basin-fill sequence is extensively deformed (eg. Sanderson and Dearman 1973; Sanderson 1979; Shackleton et al. 1982; Coward and Smallwood 1984). It ranges from early Namurian to early Westphalian C in age (see Thomas 1988 and Hartley 1991, for further details). In addition to the early Westphalian A to early Westphalian C Bude Formation the basin-fill includes: 1) the distal turbidites of the early Namurian-early Westphalian A Crackington Formation (Ashwin 1957; Mackintosh 1964; Freshney *et al.* 1979), which display E-W palaeocurrent indicators reflecting an axial transport system (Melvin 1986), and 2) the northerly derived deltaic sediments of the late Namurian to late Westphalian A Bideford Formation (Elliott 1976; Edmonds *et al.* 1979; Li 1990).

The distribution and occurrence of slumped beds in the Bude Formation is shown in Fig. 2. Detailed examination of coastal exposures of the Bude Formation in northern Cornwall and Devon has revealed the presence of two types of slumped bed.

Type A beds form approximately 80% of the slumped beds in the Bude Formation. They consist of beds 0.5 to 22m thick comprising rounded intraclasts (up to 20m or more in diameter) of sandstone, siltstone, mudstone and interbedded sandstone and mudstone isolated within a matrix of contorted siltstone and mudstones (Fig. 3). The percentage of clasts to matrix varies considerably (even within single beds) from virtually clast-supported to almost totally matrix. Examples of type A beds showing differences in clast concentrations are exposed to the north of Sandymouth between SS 2015 1037 and SS 2015 1067. The matrix comprises an original bedding fabric with a ragged ('slurried') appearance. Both the matrix and intraclasts show evidence of a preferred direction of shear parallel to regional bedding, including fold axes (commonly open and curved) and stretched intraclasts. The amount of shear varies within and between different beds. In two examples (Duckpool SS 1985 1140 and Hartland Point SS 2269 2729) boudinaged intraclasts and extensive internal shear planes were observed. The tops of the beds may be either sharp, load-deformed by an overlying bed or overlain by sand volcanoes (Burne 1970). The bases may be sharp or show evidence of loading into underlying strata. Laterally, type A beds generally cannot be traced over distances of more than a few kilometres, although the limited stratigraphic control and complex structure of the Bude Formation makes lateral correlation of slump beds difficult to constrain.

Type B beds comprise 20% of slumped beds in the Bude Formation. Beds are up to 17m thick and composed of randomly distributed rounded or ragged intraclasts of sandstone, siltstone and mudstone and clasts of interbedded sandstone and mudstone (Fig. 4). Clasts may be up to 8m plus in diameter and float in an homogenous muddy, coarse siltstone matrix commonly rich in plant material. Clast long axes commonly lie parallel/sub-parallel to regional bedding. No lateral gradation into uncontorted sedi-

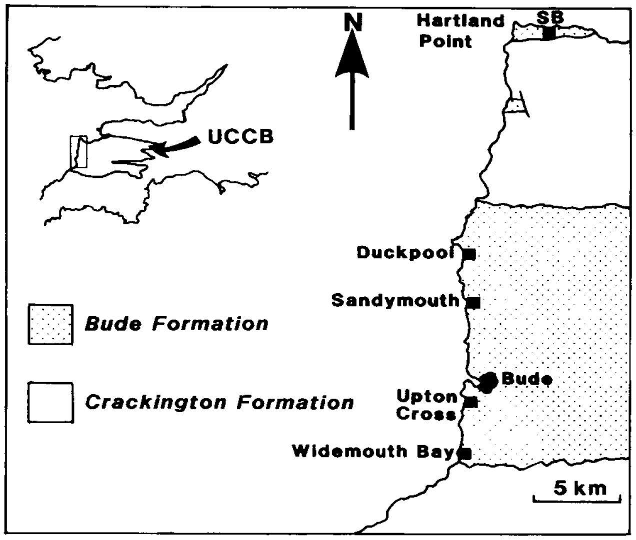

Figure 1. Geological map of north Devon and Cornwall, illustrating the studied coastal sections in the Bude Formation, SB = Shipload Bay. UCCB = Upper Carboniferous Culm Basin.

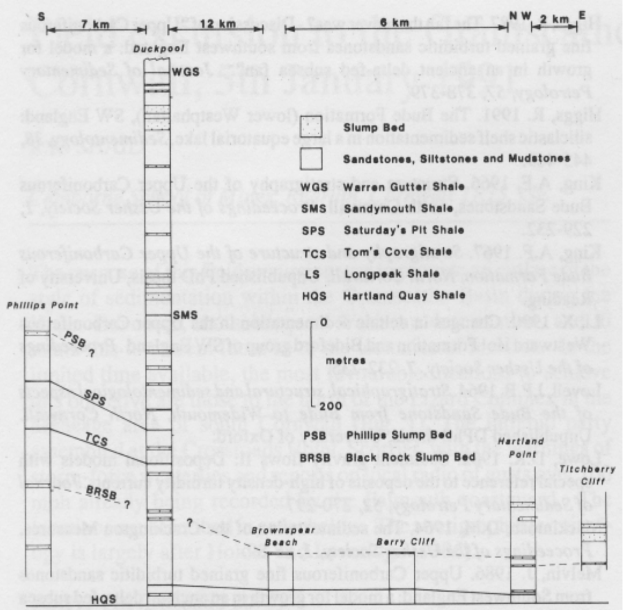

Figure 2. Position of the slump beds in the preserved stratigraphy of the Bude Formation across the Culm Basin, based on Freshney *et al.* (1972, 1979) and Edmonds et al. (1972). Note the possible basin-wide correlation of the Black Rock Slump Bed and the limited extent of most slump beds. (Warren Gutter Shale and the Hartland Quay shale are equivalent to the A. *aegiranum* and G. *amaliae* marine bands of the south Wales coalfield (Edmonds *et al.* 1979).

ments, internal stratification or bedding fabric is present. Tops and bases are usually sharp although load structures may be locally present. The Black Rock Slump Bed (King 1967) exposed at Widemouth Bay (SS 1950 0197) and Upton Cross (SS 2001 0533) is a good example of a type B bed.

Type A beds are interpreted as gravity driven slump deposits supporting the original interpretations of Ashwin (1957) and Lovell (1964). The presence of bedding-parallel fold axes and stretched intraclasts indicates that some internal deformation took place within the semi-lithified sediment during downslope movement, noting that the amount of shear varies both within and between flows. Only in the two examples at Duckpool and Hartland Point was movement sufficient to result in extensive internal bedding parallel shear, producing boudinaged intraclasts and numerous internal shear planes. Differences in the clast and matrix concentration of type A beds are thought to reflect original differences in the ratio of sand to mud in the sediment source area. The absence of criteria indicative of extensive internal shear (eg. boudinage intraclasts and shear planes) from the majority (approximately 90%) of type A deposits, coupled with the fact that the majority of the slumped beds in the Bude Formation can not be traced for more than a few kilometres (Fig. 2), suggests that the deformation responsible for type A beds was relatively localised.

The type B chaotic matrix-supported conglomerates are interpreted as cohesive debris flow deposits or debrites (sediments transported as a dense slurry in a matrix with a significant yield strength, Lowe 1982). Modern examples of debris flows are known to have travelled over 1000km (Simm and Kidd 1984) and it is possible that the debris flow deposits extended across much of the Culm Basin, as suggested also by the possible correlation of the Black Rock Slump Bed from north to south across the basin (Fig. 2).

The presence of slump and debris flow deposits in the Bude Formation has important implications for facies models of the Culm Basin during Bude Formation times. Two contrasting models have been presented recently for the depositional setting of the Bude Formation. Melvin (1986, 1987) favours a shallow subaqueous fan environment where turbidites are supplied from a delta to the north Higgs (1986, 1987, 1991) suggests a shallow siliciclastic shelf environment with turbidites (underflowites of Higgs 1987) supplied by river flood events to the north. This latter model requires a shelf environment with a very low gradient (less than 0.5°). Slump and debris flow deposits generally require a slope of at least 1° (Stow 1986), although they are known to move on slopes as low as 0.5° (Coleman 1981). The presence of repeated slump and debris flow deposits in the Bude formation suggests a palaeoslope gradient of probably greater than 1°, and not less than 0.5° as inferred by Higgs (1987, 1991). Thus facies models for the Bude Formation must include a significant southerly dipping palaeoslope (slope direction indicated by palaeocurrent data from associated turbidites, see Freshney *et al.* (1979) and Melvin (1986) for further details) supporting either a fan environment (Melvin 1986) or possibly the ramp facies model proposed by Heller and Dickinson (1985). The latter model may be applicable in view of the absence from the Bude Formation of a well developed feeder channel system (see Higgs 1987).

In contrast to the slump deposits, the debris flow deposits are thought to be much more laterally extensive, possibly ranging across the central part of the Culm Basin (Fig. 2). The amount of material involved in a basin-wide debris flow would require a substantial source area of unstable sediment, which regional palaeocurrent data suggest lay to the north. Regional paleogeographic reconstructions tentatively suggest a northerly-lying deltaic system during Bude Formation times possibly in the Bideford area (Melvin 1986, 1987; Higgs 1991; Hartley 1991). On this hypothesis, debris flows may have been sourced by delta front collapse, a process known to occur elsewhere in the geological record (eg. Nemec *et al.* 1989).

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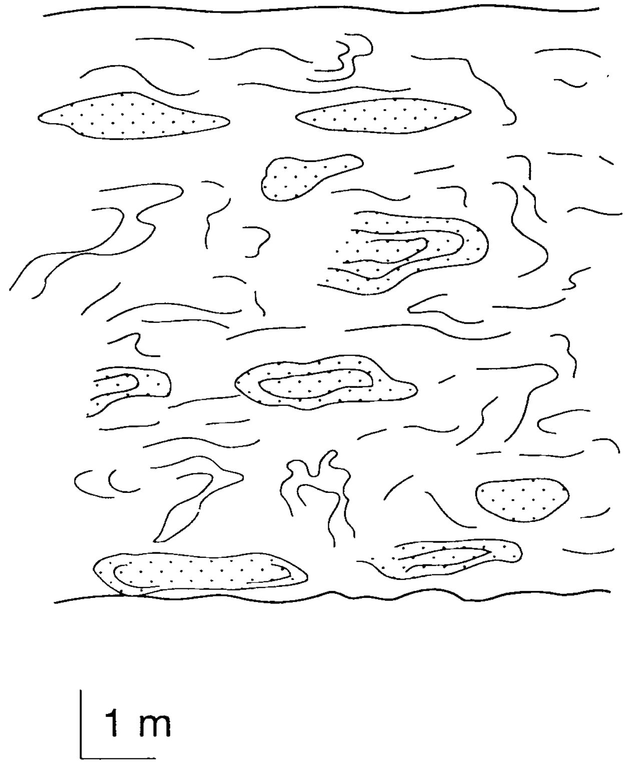

Figure 3. Generalised sketch *of* a type A slump bed based on field observations from north *of* Sandymouth *(SS 2015 1067* and *SS 2091 51042).* Note the elongate sandstone clasts (stippled) oriented parallel to regional bedding), and the well defined bedding within the matrix *of* thinly bedded siltstones and mudstones.

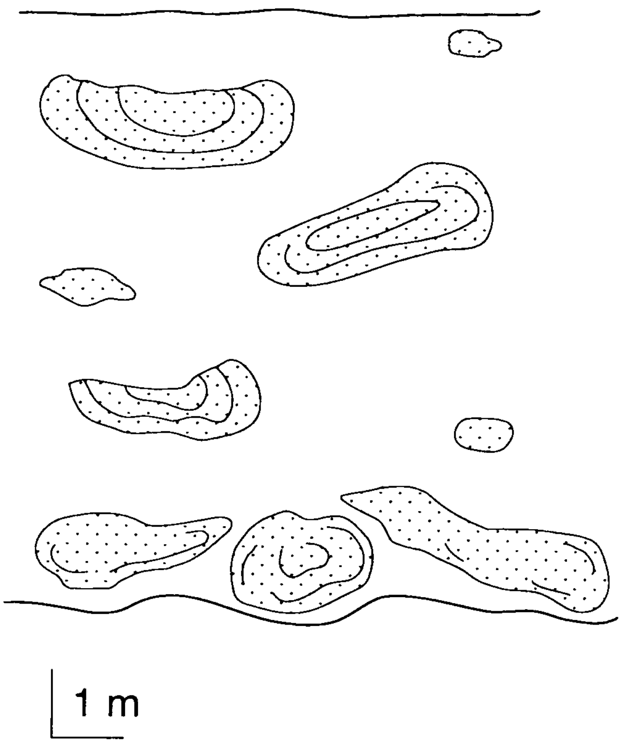

Figure 4. Generalised sketch of type B slump bed based on field observations from the Black Rock Slump bed at Black Rock (SS 1950 0197) and from the west side of Shipload Bay (SS 2450 2725). Note the folded and generally rounded nature of sandstone clasts (stippled) and the homogenous nature of the matrix.

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