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The Bude Formation, SW England—a three-dimensional, intra-formational Variscan imbricate stack?

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Abstract

The deformation of the Upper Carboniferous Bude Formation, SW England, is re-interpreted in terms of a sedimentary multilayer sequence, which represents a compromise between mechanically competent and mechanically incompetent behaviour. The chevron folding that characterises the sandstone–shale multilayer sequence is shown to be only a part of a more complex, regional scale, polyphase deformational history that developed at high structural levels in the Late Variscan orogeny. The major tectonic features are thrust faults, which are responsible for the imbrication of the original sedimentary pile. Six distinct thrust sheets are recognised in the ~5 km coastal section studied. Northerly directed thrusts pre-date chevron folding, whilst structurally necessary southerly propagating back-thrusts both pre- and post-date folding. Where they post-date folding, they impose a southerly shear onto the rocks, leading to modification of existing folds. The significance of these thrust structures has previously been ignored due to their tendency to develop parallel to bedding and to be overprinted by flexural slip features during chevron folding. A model is presented that views the Bude Formation as a three-dimensional intra-formational imbricate stack, which is, at any single locality, an instantaneous representation of an orogenic front propagating into its own foreland basin.

Keywords: Sedimentary multilayer sequence; Thrust faults; Chevron folding

1. Introduction

Multilayer sequences (e.g. alternating beds of sandstones and shales) are common features of many sedimentary environments. However, their behaviour during deformation must represent a compromise between a mechanically competent component (e.g. sandstone) and a mechanically incompetent component (e.g. shale). It is likely that whilst the competent component controls the overall deformation, most of the strain accommodation occurs within the incompetent component. The large-scale deformation style therefore may tend to be controlled by the multilayer-parallel geometry. In monotonous multilayer sequences with few distinctive marker horizons any layer-parallel displacements will be difficult to recognise. In this contribution, a detailed structural and sedimentological analysis is presented of a classic sedimentary multilayer sequence, the Upper Carboniferous Bude Formation of SW England, deformed under upper crustal (near surface?) conditions during the Variscan Orogeny.

The northern coastline of SW England (Fig. 1) has been the subject of considerable study. Its sedimentology is important in terms of both Upper Carboniferous stratigraphy (e.g. Lovell, 1965; King, 1966, 1967; Burne and Moore, 1971; Freshney et al., 1972, 1979; Thomas, 1988) and also sedimentary processes (e.g. Burne, 1970; Higgs, 1984, 1986, 1987, 1991; Melvin, 1986, 1987; Hartley, 1991). The structures observed are important in terms of Variscan (Hercynian) tectonics (e.g. Wilson, 1951; Zwart, 1964; Dearman, 1970; Freshney et al., 1972, 1979; Coward and Shackleton, 1982; Isaac et al., 1982; Rattey and Sanderson, 1982; Sanderson, 1982; Shackleton et al., 1982; Turner, 1982; Coward and Smallwood, 1984; Selwood et al., 1985; Selwood and Thomas, 1986a,b, 1988a; Seago and Chapman, 1988; Warr et al., 1991; Andrews, 1993). They are also important in terms of the evolution of individual structural elements (e.g. Dewey, 1909; Freshney, 1965; Dearman and Freshney, 1966; Gauss, 1967, 1973; Mackintosh, 1967; Dearman, 1969a,b; Roberts and Sanderson, 1971; Sanderson and Dearman, 1973; Beach, 1975, 1977; Hobson and Sanderson, 1975;

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Edwards, 1984; Selwood and Thomas, 1984, 1985, 1988b; Primmer, 1985; Andrews et al., 1988, 1996; Durning, 1989; Warr, 1989; Jackson, 1991; Thompson and Cosgrove, 1996). In particular, the folds present have played a prominent role in the development of the classic flexural slip model for chevron style folding (Ramsay, 1974; Sanderson, 1974; Tanner, 1989, 1992). However, it is these superficially regular and simple folds (e.g. Fig. 2a) that have obscured a more complex history.

For example, Freshney et al. (1972) treated the Upper Carboniferous Bude Formation, a thick and typically monotonous sandstone–shale multilayer sequence, as a folded but otherwise largely undisturbed sedimentary unit. Sanderson (1979) recognised more complexity and argued that the progressively overturned nature of the chevron folds from north to south (Fig. 2a–c) was due to their development during an increasing southerly-directed simple shear deformation (see also Ferguson and Lloyd, 1982). Subsequently, significantly more complex deformational histories have also been proposed (e.g. Enfield et al., 1985; Lloyd and Whalley, 1986, 1997; Whalley and Lloyd, 1986, 1991; Mapeo and Andrews, 1991). Such complex deformation histories are central to the regional scale tectonic interpretations presented here.

In spite of the interest shown in the sedimentological and structural aspects of the Bude Formation, the relationship between stratigraphy, sedimentation and deformation has received comparatively little attention. This probably reflects the *superficial* monotony of the rocks and the classification of the formation as a *continuous* sandstone–shale sequence interspersed with the occasional black shale (colloquially referred to as 'marine bands') and slump horizons (Fig. 3a). However, when the geology is studied on the scale of tens of metres and less, rather than kilometres, features become apparent that are inconsistent with the Bude Formation being a simple vertically continuous stratigraphic sequence that has suffered deformation via chevron folding during southerly directed shearing. It is clear then that considerable syn-sedimentary, syn/post-lithification and pre/post-chevron folding deformations have occurred, including listric normal growth faults, thrusts, refolding and late normal faults (Fig. 2). Such features have previously been recognised on the scale of individual or several beds (e.g. Enfield et al., 1985; Lloyd and Whalley, 1986; Whalley and Lloyd, 1986) but their significance on the formational or regional scale remains unknown.

In this study, it is shown that the small scale thrusting and imbrication observed in individual bedded units within the Bude Formation can be extrapolated up to the regional

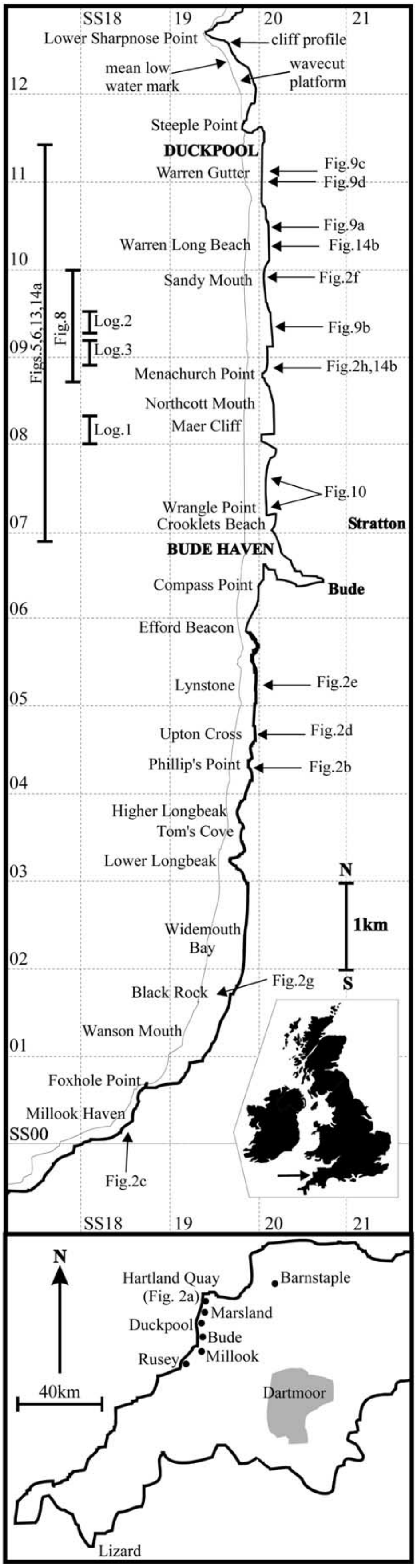


Fig. 1. Above: location map of the study region between Duckpool and Millook Haven, with positions of individual localities, maps and figures indicated (inset: position of study region in the context of British Isles). Below: positions of other locations outside of main section studied.

scale. This conclusion is based on detailed and integrated sedimentological, stratigraphical and structural mapping of a 4.5 km coastal section (Fig. 1) between Bude (UK GR SS203065) and Duckpool (SS201115). This section is almost completely exposed in both the horizontal (wavecut platform) and vertical (cliff profile) planes and therefore offers the opportunity for a three-dimensional investigation. Furthermore, the section runs approximately north–south, perpendicular to the regional tectonic trend of the chevron folds but parallel to the overall movement sense(s) of Variscan thrust and normal faults. The suggestion that regional scale thrusts should occur within the Upper Carboniferous rocks of SW England should not be surprising given the role thrusts have played in the Variscan evolution of SW England in general (e.g. Coward and Shackleton, 1982; Isaac et al., 1982; Shackleton et al., 1982; Turner, 1982; Coward and Smallwood, 1984; Selwood et al., 1985; Selwood and Thomas, 1986a,b, 1988a; Seago and Chapman, 1988; Warr et al., 1991; Andrews, 1993).

2. The Bude Formation

2.1. Lithologies

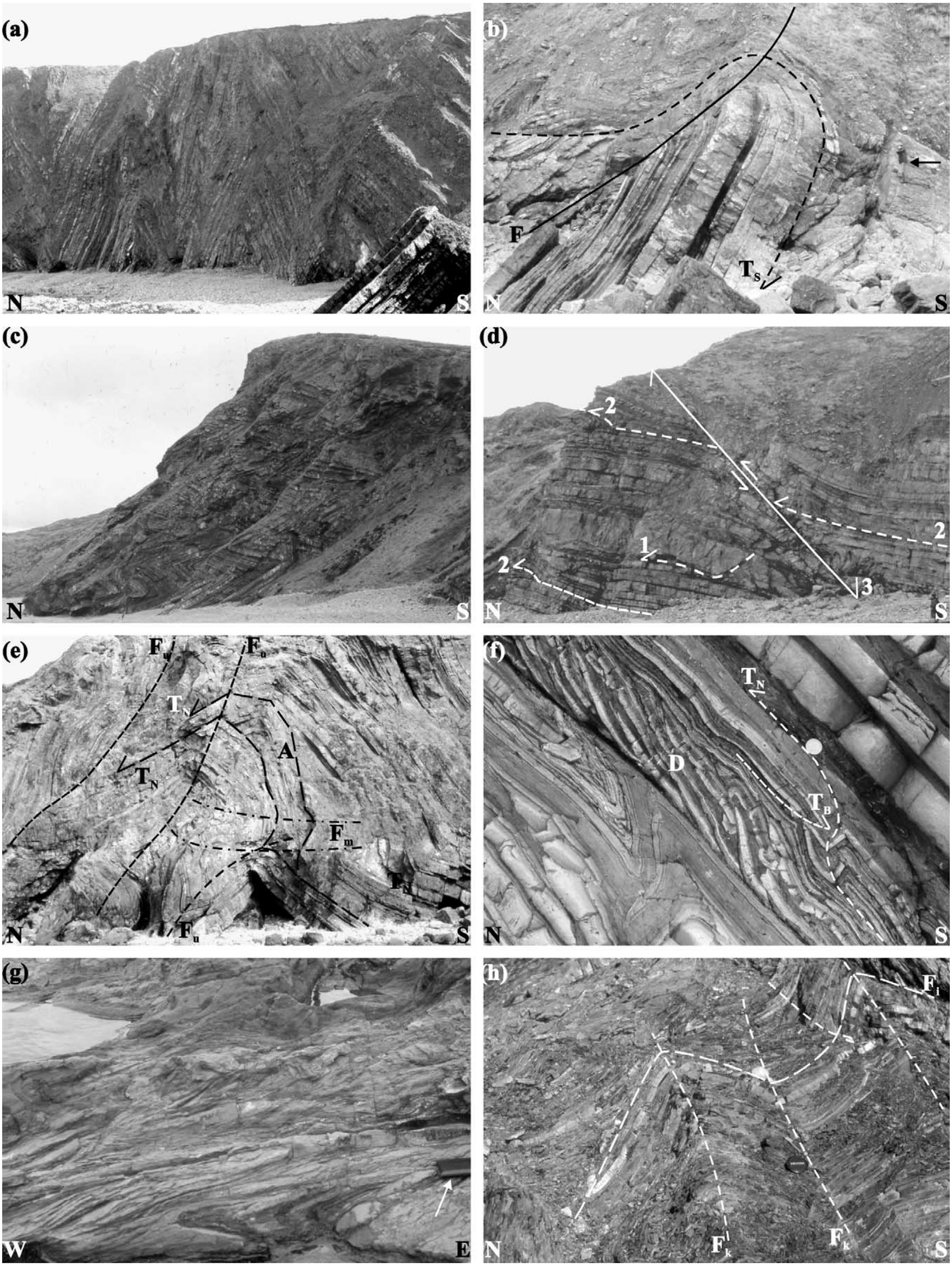
The Bude Formation consists of five lithologies (e.g. Figs. 3a and 5): sandstones, siltstones, shales, marine bands (black shales) and 'slump' beds. These lithologies suggest that the formation represents a coastal flood plane environment where slow moving rivers occasionally flooded before reaching the sea in a delta front (e.g. Higgs, 1991; Hartley, 1993). The mud flats were commonly overwhelmed by coarser, sediment-laden waters, whilst instability at the delta front led to sedimentary slumping. There is evidence of emergence (rain spots) and proximal plant life. Using the carbon:sulphur ratio technique of Berner and Raiswell (1984), the shales have a low organic content and appear to be freshwater in origin (Fig. 3b). This suggests that the Bude Formation is essentially non-marine with only rare marine incursions (i.e. the black shale marine bands), in contrast to the underlying Crackington Formation, which is clearly a marine sequence. This indicates a shallowing of the depo-region with time from the Crackington to Bude Formations, in agreement with recent palaeogeographic reconstructions by O'Mara and Turner (1997), based on the variation in uranium enrichment characteristics of Upper Carboniferous marine bands from northern England. These show that pre-*subcrenatum* (i.e. Crackington) marine bands (see Fig. 3a) represent marine anoxic black shale events. In contrast, *vanderbeckei* (i.e. mid-Bude) marine bands result from shallower water depths and poorly developed anoxic events, whilst Westphalian B/C (i.e. Upper Bude) and younger (i.e. post-Bude) marine bands are more marginal and/or brackish with an abundance of land-derived plant fragments and abundant terrigenous matter. The presence of 'slump beds' with both sedimentary and tectonic affinities, together with growth faults and bedding parallel thrust faults (see below), suggests that sedimentation did not precede deformation by a significant amount of time. They were probably partially contemporaneous, at least in different parts of the Bude basin. Finally, a high vitrinite reflectance from the shales (Cornford et al., 1987) suggests maximum burial to a depth of ~6 km.

2.2. Stratigraphy

The Bude Formation is exposed only discontinuously in a series of sections between Hartland Quay and Widemouth Bay (Fig. 1) and questions remain regarding the detailed stratigraphic succession. King (1966, 1967) proposed the original succession, with a total thickness of ~600 m (Fig. 3a), but this was subsequently extended to ~1250 m by Freshney et al. (1979). However, considerable structural interpretation has been made based on the *assumed* validity of either of these successions and in particular the correlation through the section of various marine bands (e.g. Fig. 4).

The Bude Formation appears to young from both the north and the south (see Fig. 4) towards a synclinal axis at Duckpool (Freshney et al., 1979). It extends (Fig. 3a) from the Langstettian (Westphalian A) to at least the Duckmantian–Bolsovian (Westphalian B–C) boundary (e.g. Rippon, 1996). The lowermost unit is the Hartland Quay Shale (*G. amaliae* horizon), whilst the youngest units observed (i.e. Bolsovian) are sandstones, siltstones and shales immediately above the Warren Gutter Shale (*A. aegiranum* horizon). The total age span is at least 1.4 Ma, based on ages from Hess and Lippolt (1986) and Claoué-Long et al. (1993).

The only named horizons common to both the King and Freshney successions are the Tom's Cove and Saturday's Pit shales (Fig. 3a). Based on their relative positions, King's succession includes only the lower part of the Bude Formation (i.e. the Langsettian), perhaps including the boundary between the Bude and Crackington Formations. In fact, the Bude Formation extends for at least 820 m above the Saturday's Pit Shale, which King (1967) suggested was the top of the formation, and ~70 m below the slump bed he suggested was the base. In addition, King's succession between the Tom's Cove and Saturday's Pit shales is ~110 m compared with 75–80 m for Freshney et al. It is also difficult to correlate many of the laterally continuous slump bed horizons between King (1967) and Freshney et al. (1979). Perhaps the only common horizon is the composite 'Phillips slump bed', which is nominally the top of King's succession, but represents a zone of intense deformation with evidence for both (early) contractional and (later) extensional deformations. These differences arise because King based his succession on the section between Widemoth Bay and Northcott Mouth, *in which he noted considerable disruption due to faulting*, whilst


(a)
N
S
(b)
F
T_S
N
S
(c)
N
S
(d)
2
2
1
2
3
N
S
(e)
F_u
F_u
T_N
T_N
A
F_m
T_N
F_u
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S
(f)
T_N
D
T_B
N
S
(g)
W
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F_i
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F_k
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S

Freshney et al. (1979) used the considerably less faulted section between Marsland (SS208173) and Duckpool (see Fig. 1 for locations). However, both acknowledged that faulting rendered stratigraphic interpretation and correlation north of Northcott Mouth difficult.

It is not the intention of this contribution to provide a revised stratigraphy for the Bude Formation. This will require extensive and detailed palaeontological and sedimentological analysis. However, it is suggested that the established stratigraphic succession (Fig. 3a) and disposition (e.g. Fig. 4) is potentially seriously flawed due to its basis on the comparison and equivalence of *apparently* similar marine band horizons. For example, whereas Rippon (1996) recognises only four marine bands within the stratigraphic extent of the Bude Formation, Freshney et al. (1979) recognise at least six, with only two (i.e. the *amaliae* Hartland Quay Shales and *aegiranum* Warren Gutter Shales) common to both successions (Fig. 3a). Unfortunately, the marine bands, although collectively representing a distinctive sedimentary facies, are typically very similar in appearance, except where obviously deformed. Furthermore, their individual faunas are far from being unique. In contrast to the (top of) the Crackington Formation, there is a scarcity of fossil occurrences in the Bude Formation marine bands and shale horizons, with zonal fossils restricted to the Sandy Mouth and Warren Gutter shales towards the top of the formation (see Freshney et al., 1979). The other shale horizons (e.g. Longpeak, Tom's Cove and Saturday's Pit) *contain no zonal fossils*. This has critical implications for the stratigraphic correlation involved in the structural section (see Fig. 4) proposed by Freshney et al. (1979).

In this contribution, new stratigraphic, sedimentological and structural observations are presented that cast doubt on previous stratigraphical successions. It is argued that significant 'additional' stratigraphy has been added to the successions via tectonic thickening of the Bude Formation due to the affects of previously unrecognised (often bedding parallel) thrusts, which repeat the largely monotonous sedimentary succession. Potential sites for these thrusts are the (thick) shales and/or slump bed horizons (e.g. see Fig. 13 below). Local support for the existence of regional scale thrust displacements within the Bude Formation is provided by rocks to the north of the studied area, where Cornford et al. (1987) used vitrinite reflectance to show that major Variscan thrusting has occurred within the slightly older (possibly partly laterally synchronous?) Bideford Formation.

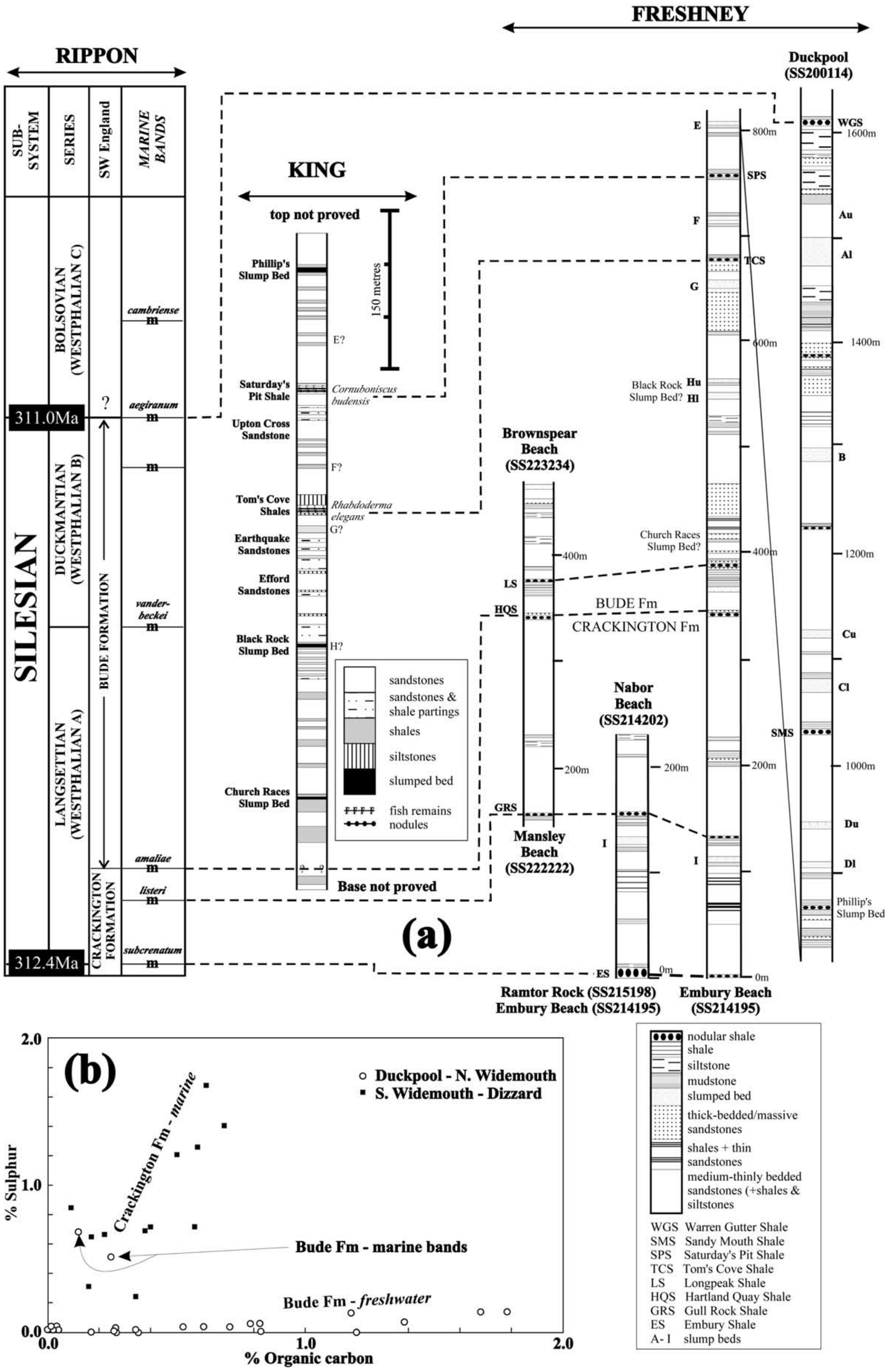
3. Evidence for regional-scale thrusts

3.1. Deformation in the Bude Formation

It is important when studying the Bude Formation to consider the *preferred* style of deformation. This is determined primarily by the lithologies. In simple terms the Bude Formation consists of relatively regularly interbedded sandstones and shales. There is a tendency for the former to be thicker than the latter, except for the few notable exceptions that are generally interpreted as marine bands. Such lithological variations are ideal for flexural slip chevron folding in which displacement occurs on bedding planes, particularly within the shale horizons. The chevron folds are geometrically rather simple (Fig. 2a), except close to fold hinges where a variety of accommodation structures may need to develop (Ramsay, 1974; Sanderson, 1974).

Bedding plane detachment is also evident in small scale thrusts within the Bude Formation (Enfield et al., 1985; Lloyd and Whalley, 1986; Whalley and Lloyd, 1986). Tanner (1992) interpreted such 'duplex' structures from the Hartland Quay section, typically formed by thin (<5 cm) sandstone or siltstone beds, as accommodation structures developed during flexural slip chevron folding. This interpretation is certainly valid for many examples, although the use of nearby flexural slip lineations (slickenfibres) that are parallel to the displacement direction of the roof/floor thrusts as a criterion for their recognition is likely to be equivocal in regions that have suffered successive N–S flexural slip deformations. However, for many other examples (e.g. Fig. 2f) it is inconsistent with the sense of vergence exhibited. Irrespective of the fold limb (i.e. north- or south-dipping) on which these structures occur, vergence is generally top-to-the-north rather than towards the local fold hinge. On north-dipping limbs, this leads to a 'down-dip' sense of imbrication. This geometry is consistent with a pre-folding, northerly directed thrust-related origin (e.g. Enfield et al., 1985; Lloyd and Whalley, 1986; Whalley and Lloyd, 1986). Furthermore, contrary to Tanner's (1992) morphological description, antiformal stacks are

Fig. 2. Examples of structures important in determining Variscan evolution of the Bude Formation. See Fig. 1 for locations. (a) Vertical chevron folds, Hartland Quay (height of cliffs ~75 m; SS 225250). (b) Southerly directed thrust (T_S) subsequently folded by an initially upright chevron fold (F) now overturned towards the south by southerly directed shearing, North of Phillips Point (figure, arrowed, for scale; SS 199043). (c) Horizontal chevron folds, Millook Haven (height of cliffs ~50 m; SS 185002). (d) Complex deformation history at Upton Cross (height of cliffs ~20 m; SS 200046)): 1. listric normal syn-sedimentary growth faults; 2. bedding-parallel northerly directed thrusts with small ramps; 3. late normal fault down throwing to S, exploiting an earlier northerly thrust ramp structure (indicated by shear arrows). (e) Complex deformation history at Lynstone (height of cliffs ~50 m; SS 200053): 1. pre-chevron folding northerly directed thrusts (T_N) and imbrication (A, antiformal stack); 2. initially upright chevron folds (F_u) now overturned towards the south; 3. modification folds (F_m) on southerly dipping (contractional) limb. (f) Small-scale duplex (D) associated with northerly directed Sandy Mouth Thrust; note local back-thrust, T_B, folding earlier fore-thrust, T_N (coin for scale; SS 200099). (g) Tight to isoclinal folding of thin silt/sandstones in slump band horizons, Black Rock Slump Bed, S. Widemouth Bay (notebook, arrowed, for scale; SS 197017). (h) Polyphase deformation of siltstones in thick shale/marine band horizon, N. of Menachurch Point (lens cap for scale; SS 200088): initial isoclinal fold (F_i) subsequently refolded by kink-like open folds (F_k).


FRESHNEY
RIPPON
SUB-SYSTEM
SERIES
SW England
MARINE BANDS
SILESIAN
BOLSOVIAN (WESTPHALIAN C)
DUCKMANTIAN (WESTPHALIAN B)
LANGSETTIAN (WESTPHALIAN A)
BUDE FORMATION
CRACKINGTON FORMATION
?
cambriense m
aegiranum m
m
vanderbeckei m
amaliae m
listeri m
subcrenatum m
311.0Ma
312.4Ma
KING
top not proved
150 metres
Phillip's Slump Bed
E?
Saturday's Pit Shale
Cornuboniscus budensis
Upton Cross Sandstone
F?
Tom's Cove Shales
Rhabdoderma elegans
G?
Earthquake Sandstones
Efford Sandstones
Black Rock Slump Bed
H?
Church Races Slump Bed
Base not proved
sandstones
sandstones & shale partings
shales
siltstones
slumped bed
fish remains
nodules
Brownspear Beach (SS223234)
400m
200m
LS
HQS
GRS
Mansley Beach (SS222222)
BUDE Fm
CRACKINGTON Fm
Nabor Beach (SS214202)
200m
0m
I
ES
Ramtor Rock (SS215198)
Embury Beach (SS214195)
E
800m
SPS
F
TCS
G
600m
Black Rock Slump Bed? Hu Hl
Church Races Slump Bed?
400m
200m
I
0m
Embury Beach (SS214195)
Duckpool (SS200114)
WGS
1600m
Au
Al
1400m
B
1200m
Cu
Cl
SMS
1000m
Du
Dl
Phillip's Slump Bed?
(a)
nodular shale
shale
siltstone
mudstone
slumped bed
thick-bedded/massive sandstones
shales + thin sandstones
medium-thinly bedded sandstones (+shales & siltstones
WGS Warren Gutter Shale
SMS Sandy Mouth Shale
SPS Saturday's Pit Shale
TCS Tom's Cove Shale
LS Longpeak Shale
HQS Hartland Quay Shale
GRS Gull Rock Shale
ES Embury Shale
A- I slump beds
(b)
○ Duckpool - N. Widemouth
▪ S. Widemouth - Dizzard
Crackington Fm - marine
Bude Fm - marine bands
Bude Fm - freshwater
% Sulphur
% Organic carbon
2.0
1.0
0.0
0.0
1.0
2.0

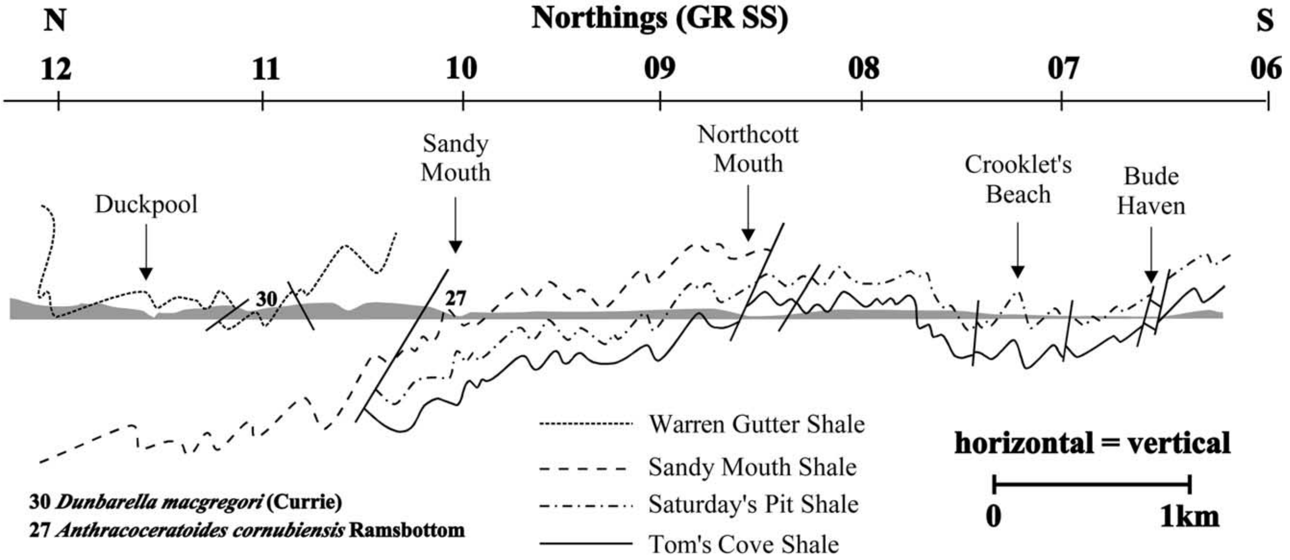


Fig. 4. Bude–Duckpool section taken with permission from the British Geological Survey structural profile (Freshney et al., 1979; Fig. 2; see Fig. 1 for location), emphasised by the four marine bands indicated. However, only two zonal fossil localities (numbered after Freshney et al., 1979) occur in the section. The relatively simple structural style indicated contrasts with that shown in Fig. 6 (see also Fig. 12). See text for discussion.

also observed in these duplex structures (e.g. Fig. 2e), which again is inconsistent with a fold-related origin.

The development of thrust structures in the Bude Formation should be of no surprise given the dominantly sandstone-shale lithologies and contractional style of deformation. They should be able to propagate easily along the shale horizons, especially if the fluid pressure is high, and continue for considerable distances, particularly in an *unfolded* rock unit, until some obstacle forces the displacement path to migrate out of the shale horizon. Thus, thrust *ramps* are expected to be relatively rare structures. However, the much more common thrust *flats* tend to be very difficult to recognise because of their bedding parallelism and affinity for shale horizons. Furthermore, as both thrusting and folding result in disruption within the shale horizons, early thrust plane structures will tend to be overprinted by subsequent flexural slip deformation during chevron folding. This suggests that even large (regional?) scale thrusts could be difficult to recognise, particularly in cliff-platform sections that are almost parallel to the transport direction.

Although thrust structures are expected to be difficult to recognise, close examination of shale and marine band horizons often reveals intense deformation (Fig. 2g and h), usually associated with the occurrence of ‘slump beds’ (Enfield et al., 1985; e.g. see Fig. 13 below). Intercalated thin cherty sandstones are isoclinally folded and even refolded but the edges of the units typically remain parallel to bedding and seem to maintain sedimentary contacts. The shales/marine bands also exhibit an intense cleavage that is both bedding-parallel and axial planar to the isoclinal folds. Where refolds occur, an axial planar second cleavage can be detected and the first cleavage is folded. All of these features testify to an intense deformation that is confined to the shale horizons and missing from the adjacent sandstones. Furthermore, such deformed shale horizons are laterally extensive throughout the section and are clearly folded by the chevron folds. Thus, they could represent pre-chevron folding decollement horizons associated with thrusting. These observations suggest that detailed sedimentological (e.g. Fig. 5) and structural (e.g. Fig. 6) field mapping on the tens of metre scale on both cliff profile and wavecut platform sections is required to identify the positions of large-scale thrust structures.

3.2. Stratigraphic sequences

In this section, several examples of sedimentary logs (e.g. Fig. 5) are described that emphasise specific aspects of the sedimentology and thrust fault structure of the Bude Formation. None of the logs cross chevron fold structures.

Log 1 (Fig. 5a) samples a section of stratigraphy around one of the four marine bands that outcrop between Northcott Mouth and Maer High Cliff (Fig. 1). The strike and dip of the beds is consistent (typically 110–115°/35–40°S). From 0–7 m is mainly sand dominated with subsidiary shales and

Fig. 3. Bude Formation stratigraphy (see Fig. 1 for locations). (a) Stratigraphic successions proposed for the Bude Formation. Left: generalised UK Upper Carboniferous stratigraphy (after Rippon, 1996). Centre, King’s (1967) ‘restricted’ composite succession between Northcott Mouth and S. Widemouth Bay. Right: Freshney et al.’s. (1979) ‘complete’ succession. See text for further details. (b) Results of carbon:sulphur content analysis, Duckpool–Dizzard Point, based on the method of Berner and Raiswell (1984). The Bude Formation (Duckpool–N. Widemouth) is mainly ‘freshwater’ with rare ‘marine’ incursions. The Crackington Formation (S. Widemouth–Dizzard) is entirely ‘marine’.

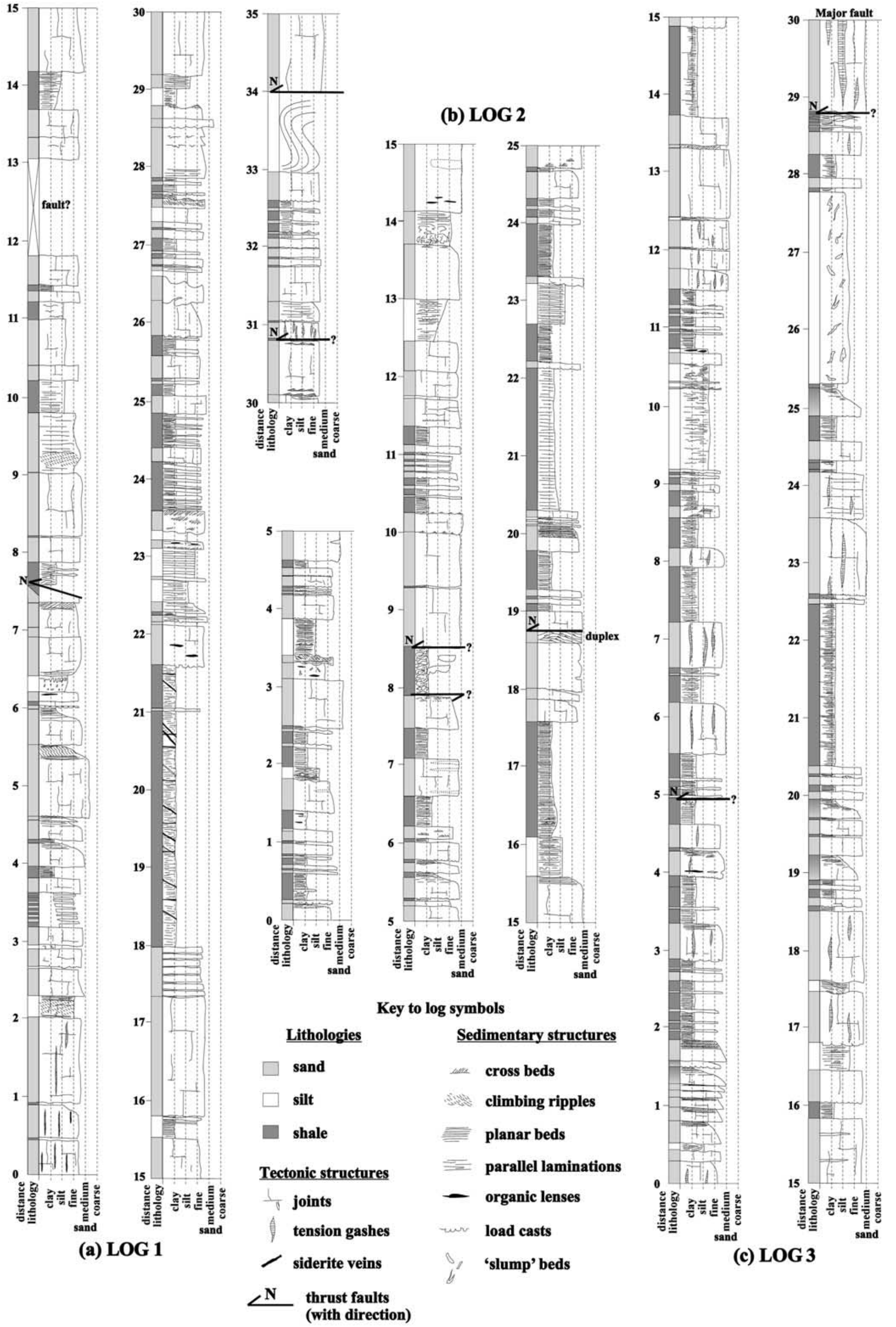


Fig. 5. Sedimentary logs; the relative positions are shown in Fig. 1. (a) Log 1: chosen to sample a section of stratigraphy around one of the four marine bands (Tom's Cove Shale) seen to outcrop between Northcott Mouth (SS 202083) and Maer High Cliff (SS 202080); it shows a mainly sand dominated sequence. (b) Log 2: a section with no marine bands but also one where sands are less dominant: north of Sarshall's Pit (SS 201093) to south of Long Rock (SS 201095). (c) Log 3: chosen to examine the stratigraphy adjacent to a slump bed, particularly the contacts above and below: north of Menachurch Point (SS 201089-201092).

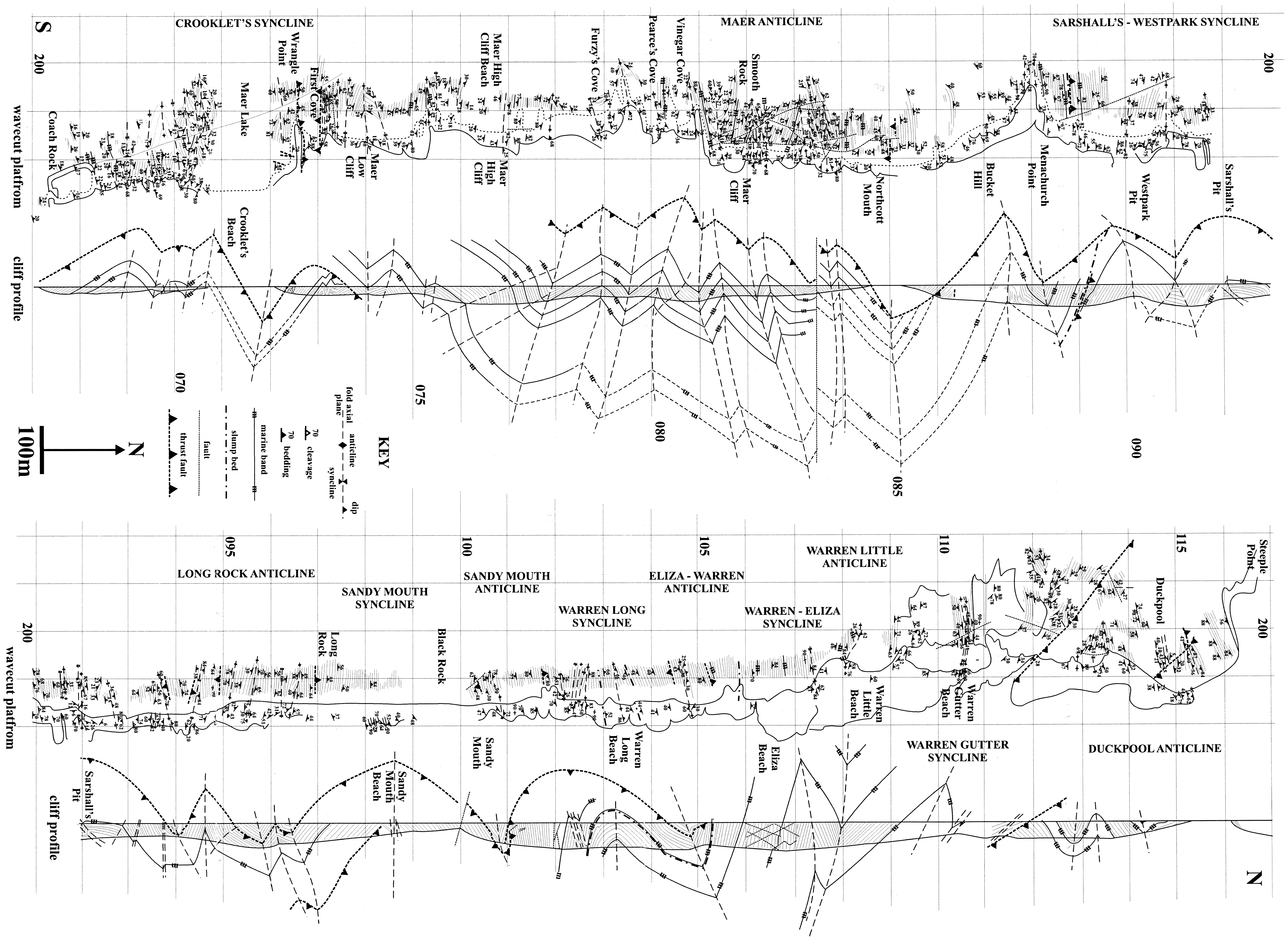


Fig. 6. Detailed field observations for the Bude–Duckpool section. The maps combine wavecut platform (horizontal) and cliff profile (vertical) observations and were used to construct the three-dimensional section shown in Fig. 12. Compare with Fig. 4.

siltstones. At 7.5 m a sandstone bed is truncated in a footwall ramp and the shales in the hanging wall immediately above this are very disturbed. From 8–18 m the sequence is again sandstone dominated, although the lack of exposure and accentuated erosion at 12–13 m may be interpreted as a (thrust?) fault. A marine band occurs between 18 and 21.5 m. Above this until 28 m the sequence is more evenly sandstone–shale, although it does coarsen upwards and towards the top sandstones are again dominant. However, at 31 m a sandstone bed is very disrupted and contains many vertical tension gashes that indicate localised deformation, possibly in the shale bed immediately below. The major structural feature in this section occurs at 34 m, where a bedding parallel fault terminates the sequence. The footwall is highly sheared for ~1 m, indicating a northerly component of displacement on the fault, but the hanging wall appears to be relatively undisturbed. The fault is interpreted therefore as a northerly propagating thrust structure.

Log 2 (Fig. 5b) covers a section between Sarshall's Pit and Long Rock (Fig. 1) with no marine bands but also one where sands are less dominant. Although the strike of the beds is consistent (112°), the dip is more variable ranging from vertical to moderately southwards. From 0–8.5 m consists of sandstones, siltstones and shales in approximately equal proportions. However, the shale horizon at 8 m is very disturbed and contains inclusions of sandstone up to 30 cm in size. This horizon is interpreted as a bedding parallel thrust structure that has exploited an incompetent shale plus thin sandstone unit, possibly also subjected to high fluid pressure. From 8.5–15.5 m, sandstones begin to dominate the sequence, although shales are still relatively common. This is in turn terminated by a 2 m thick laminated shale unit above which is a 1 m thick sandstone. The top of this sandstone is distinguished by a top-to-the-north flexural slip duplex structure, consistent with either thrusting or chevron folding. From 19–24.5 m the sequence consists of black shale with ancillary siltstone and sandstone layers, which is terminated by a thicker sandstone bed.

Log 3 (Fig. 5c) was chosen north of Menachurch Point (Fig. 1) to examine the stratigraphy adjacent to a slump bed and also to illustrate the association of slump beds and tectonic deformation. The strike and dip of the beds is consistent (typically 080–085°/70–75°N). From 0–4.5 m consists of sandstones, siltstones and shales, although the middle is shale dominated. Between 4.5 and 5 m there are distinct indications of bedding parallel fault movement in a shale unit. From here to 9 m, the beds become thicker but sandstone and shale remain in approximately equal proportions; the sandstones contain vertical tension gashes. The sequence becomes siltstone dominated between 9 and 11.5 m, with thin sandstones and a shale top. From 11.5–18.5 m the sequence is sandstone dominated, but includes a thick, hard shale horizon at 14–15 m, with the topmost units again having vertical tension gashes. Shales become equally common between 18.5 and 20.5 m, where a 2 m thick marine band (black shale) occurs that contains laterally extensive bedding parallel siderite veins, possibly indicative of high fluid pressures (i.e. 'beefing' structures). A sandstone dominated sequence with thin shales then occurs until ~25.5 m, where it is replaced by a 2.5 m thick 'slump' bed containing sandstone 'balls' and detached fold hinges of a pale sandstone similar to that which occurs immediately below. The 'slump' bed has sharp boundaries both above and below and includes thin, laminated shale layers. At 28.75 m there are distinct indications of bedding parallel faulting in a shale unit immediately below a 3 m thick sandstone that contains numerous vertical tension gashes. Above this bed, the succession is terminated by a major fault structure.

The sedimentological logging approach described above allows a number of new structural interpretations in the Duckpool–Bude section. In particular, it shows the effects of thrusting on the stratigraphic sequence, as well as other structural relationships. These are described in the following sections.

3.3. Effects of thrusts on stratigraphy

Logging the sedimentary sequences provides a true test of whether the existing structural geometry is correct or whether a new explanation is required. The significance of this procedure on the kilometre scale is shown in the following example (Fig. 7).

According to Freshney et al. (1979) (see also Fig. 4), the sequence between Bucket Hill and Long Rock (SS 202 087 and 202 097; see Fig. 6) is continuous, based on a simple geometrical construction involving three of the marine bands (the Tom's Cove, Saturday's Pit and Sandy Mouth shales). However, in detail (Fig. 7) the sequence is not continuous but is broken up by several zones of 'tectonic disruption'. Unfortunately, these are poorly exposed and obscured by erosion and landslip, a feature of many of the structurally complex but critical localities along the whole section that might be considered as indirect evidence for the existence of major faulting. In fact, two distinct stratigraphic sequences can be recognised: a northern sequence (Fig. 7e and f) and a southern sequence (Fig. 7a–c), with the Sandy Mouth Shale restricted to the former and the other two shale horizons restricted to the latter. A broad zone of 'tectonic disruption' separates the northern and southern sequences. It is possible, but unlikely given the thickness of the two sequences, that these are their natural extents. It is more likely that the two sequences have been juxtaposed tectonically. In terms of the model present later, juxtaposition by thrusting is preferred, with two hanging wall cut-offs postulated, one beneath location a and the other between locations f and a (Fig. 7). It is shown below that these features define the northern 'tip' of the 'Maer thrust sheet', wedged between the 'Northcott thrust sheet' (or autochthon) beneath and the 'Sandy Mouth thrust sheet' above (see Fig. 12).

It has already been shown that the Bude Formation

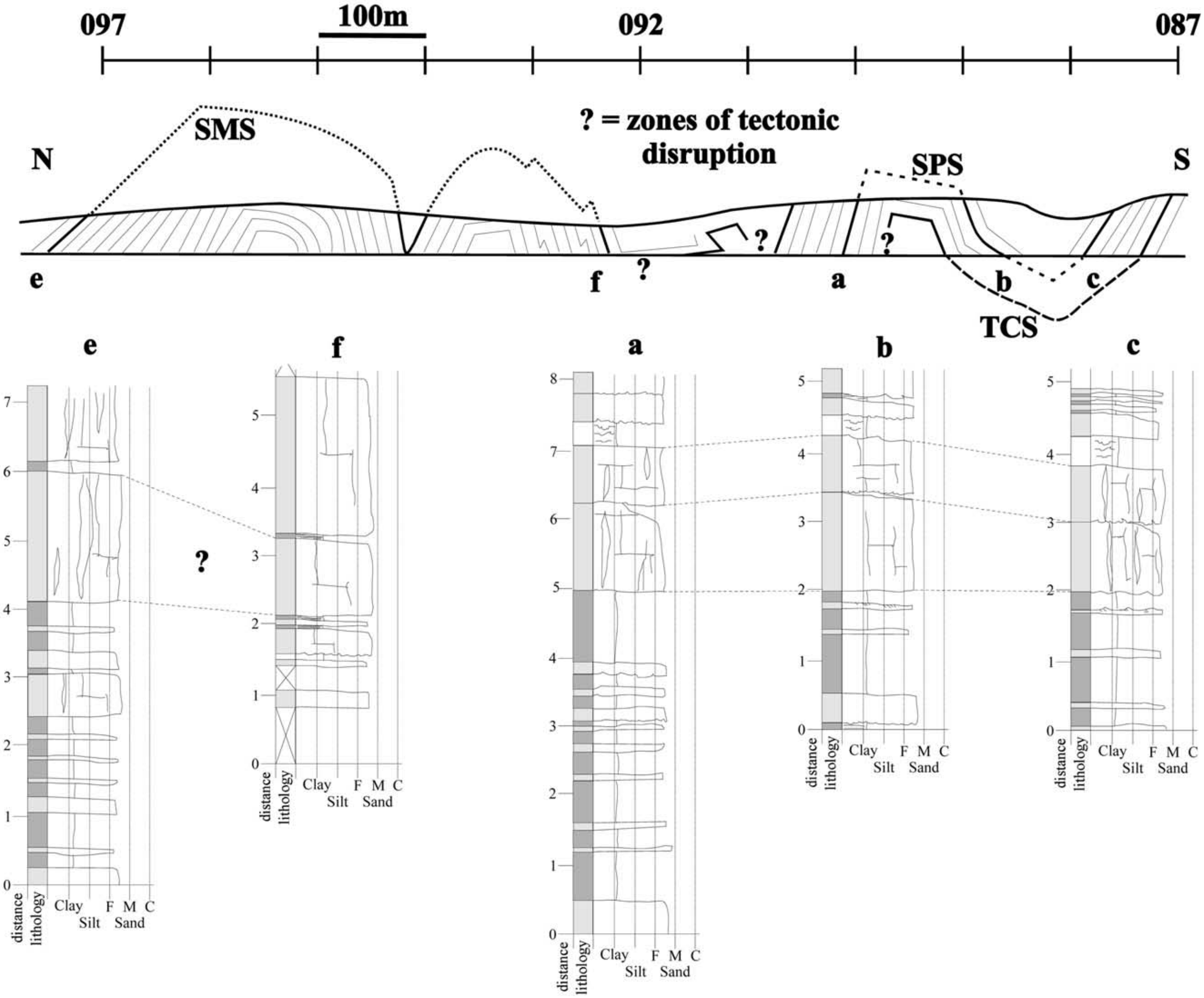


Fig. 7. Example of bed tracing from Bucket Hill to Long Rock (SS 202 087 and 202 097). Two distinct sequences are observed: a–b–c, is restricted to the south; e–f is only observed in the north (symbols as for Fig. 5). The two sequences are most likely to have been omitted due to structural reasons between sections a and f. See text for details.

is dominated by essentially similar coarsening upward sandstone–shale sedimentary cycles (Figs. 3a and 5). However, more distinctive horizons, such as thick marine bands and slump beds, also occur sporadically. According to Freshney et al. (1972) (see Fig. 4), such bands can be traced on the kilometre scale and can be followed through the chevron folded outcrop trace. Thus, the disappearance of a marine band across a single chevron fold structure would not be expected on stratigraphical grounds. However, as the following example illustrates, marine bands frequently cannot be traced across chevron fold structures and a structural explanation (e.g. pre-folding thrust ramps) is required for their disappearance.

Between Maer Low Cliff and First Cove (SS 20170700 and 20180729; Figs. 1 and 6), a stratigraphic sequence containing two *closely* spaced marine bands is observed on the southern limb of an overall synclinal structure (Fig. 8). However, the northern limb of the fold has a different sequence containing two *widely* spaced marine bands. Although there is no obvious evidence of faulting at Maer Low Cliff, there is evidence of faulting sub-parallel to bedding at nearby Wrangle Point (SS 20130726). If faulting pre-dated the synclinal chevron fold structure, the fault at Wrangle Point would be expected to continue at Maer Low Cliff. Furthermore, the localised irregular folding immediately to the north of the *closely* spaced marine bands is consistent with the effects of an early ramp–flat thrust geometry on the nucleation and propagation of chevron folds (see below and Fig. 10). A solution to this structure is that the stratigraphy that includes the two *closely* spaced marine bands ramps down onto a footwall flat (Fig. 8). It is shown later that this locality represents the boundary between the ‘Crooklet’s thrust sheet’ above and the ‘Maer thrust sheet’ below (see Fig. 12).

Similar examples of the loss (i.e. marine bands) and/or change of recognisable stratigraphy across chevron folds are

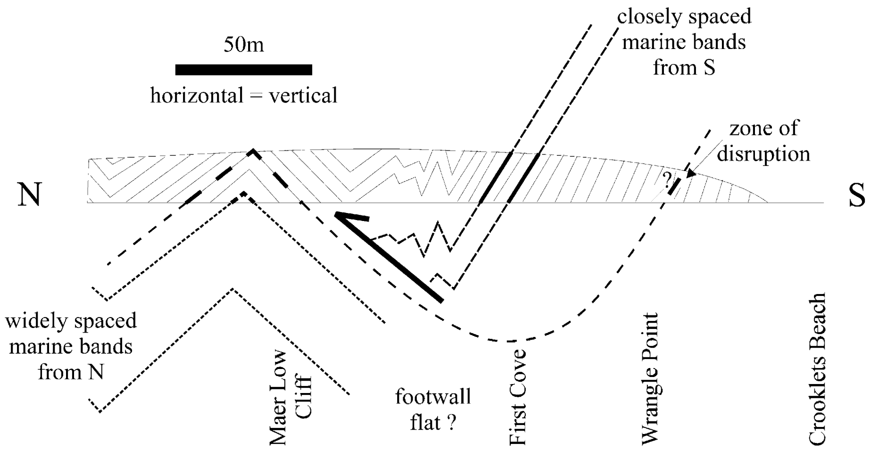


Fig. 8. Stratigraphic evidence for major thrust displacements (see Fig. 1 for location). Two narrowly spaced marine bands on the southern limb of an overall syncline between First Cove and Maer Low Cliff do not reappear on the northern limb but are replaced by two more widely spaced marine bands (the Tom's Cove and Saturday's Pit shales of Freshney et al., 1979). See text for further details.

also observed (Fig. 6) at Warren Long Beach (SS20171022) and Northcott Mouth (SS202085). It is shown below that in all such cases the preferred explanation involves intra-formational thrusting (see Fig. 12). The displacement on the thrusts can be of the order of hundreds of metres, making them regional scale structures within the Bude Formation.

3.4. Structural relationships

So far, the existence of significant pre-chevron folding thrust structures within the Bude Formation has been based on purely sedimentological evidence. In this section, evidence based on structural relationships is presented to support the existence of these thrust structures (Figs. 9–11).

3.4.1. Cleavage development

It is generally believed that cleavage did not develop during deformation of the Upper Carboniferous rocks of SW England. However, careful examination, particularly of the shale horizons, reveals the existence of up to three different cleavages (e.g. Enfield et al., 1985; Lloyd and Whalley, 1986, 1997; Whalley and Lloyd, 1986; Mapeo and Andrews, 1991). According to Lloyd and Whalley (1997) these cleavages are associated with northerly thrusting (S_1), vertical chevron folding (S_2) and southerly shear (S_3). Thus, recognition of the S_1 cleavage within the Bude Formation between Duckpool and Bude would provide strong support for the existence of early northerly directed thrusting. Unfortunately, it is often difficult to distinguish between the three cleavages.

In principal, S_1 should form subparallel or slightly steeper to bedding, with a southerly dip, although the occurrence of early back-thrusts would lead to the opposite configuration (Fig. 9a). S_2 should form subvertical, parallel to the axial planes of upright chevron folds, which fold S_1 such that on southerly-dipping limbs it is slightly steeper than bedding whilst on northerly-dipping limbs it is slightly shallower than bedding (Fig. 9b). Where S_1 is associated with southerly back-thrusting, these relationships are reversed. S_3 is related to the modification of initially upright chevron folds due to southerly shear (e.g. Lloyd and Whalley, 1986, 1997; Whalley and Lloyd, 1986). This deformation caused rotation of the chevron folds about horizontal E–W axes, with extension (e.g. normal faults, boudinage) on northerly dipping limbs and contraction (e.g. recumbent chevron folds, with S_3 parallel to the axial planes) on southerly dipping limbs. Thus, on the normal limbs of recumbent chevron folds, S_1 should be slightly steeper than bedding and south-dipping, whilst on inverted limbs it should be slightly shallower than bedding and north-dipping (Fig. 9c). Where S_1 is associated with southerly back-thrusting these relationships are again reversed.

It should be mentioned that the 'Lloyd–Whalley' chevron fold modification model conflicts with the earlier view (Sanderson, 1979) that southerly shear was simultaneous with chevron fold development. A consequence of this model is that the upright, overturned and recumbent chevron folds observed from Hartland to Millook (Figs. 1 and 2) are contemporaneous and differ in orientation solely due to the amount of shear strain involved. However, the Lloyd–Whalley model is supported by structural relationships at several localities (e.g. Welcombe Mouth, north of Marsland, and Lower Longbeak; see Fig. 1) where S_2 has clearly been rotated on the modified limbs of initially upright chevron folds (see Lloyd and Whalley, 1986, 1997).

It now remains to identify examples of the S_1 cleavage in order to support the existence of northerly thrusting. However, as shown schematically in Fig. 9a–c, both S_1 and S_2 can have similar orientations on fold limbs. This similarity is exacerbated because S_2, rather than being axial planar, more usually transects the upright folds in a fanning configuration. Plotting poles to cleavages for all localities that have not been affected by chevron fold modification provides a potential solution to this problem

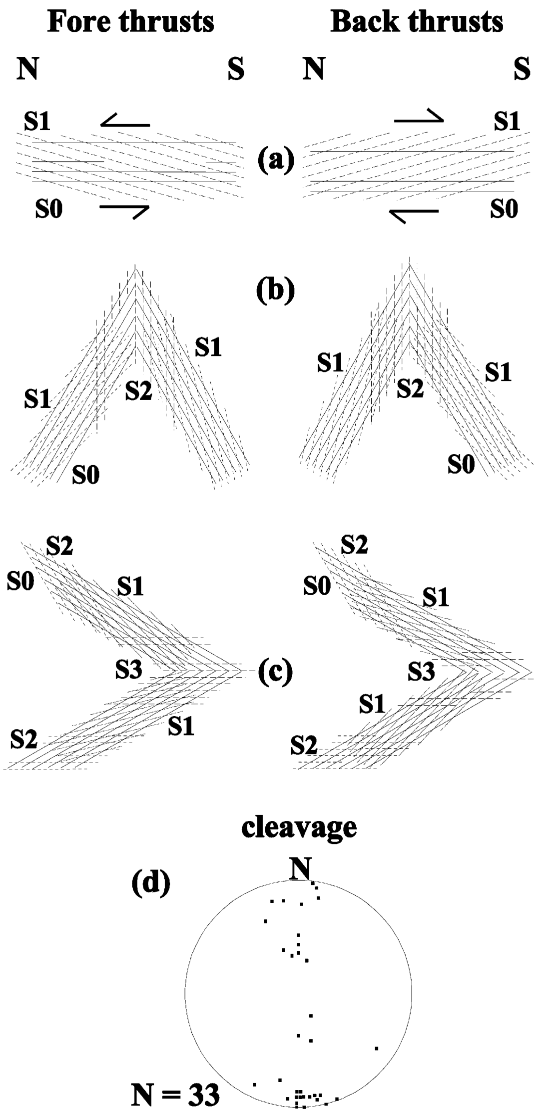


Fig. 9. Schematic representation of cleavage formation and interpretation in the Bude Formation (based on Lloyd and Whalley, 1997). (a) S_1: related to early northerly (left) or southerly (right) thrusting (S_0, bedding). (b) S_2: related to upright chevron folding; note reorientation of S_1. (c) S_3: related to modification of upright chevron folds by southerly directed, horizontal shear; note reorientation of S_1 and S_2. (d) Actual orientations of S_1 and S_2 cleavages (not differentiated) in localities not affected by southerly shear; see text for discussion.

(Fig. 9d). If these cleavages resulted only from subvertical chevron folding, they should define subhorizontal clusters oriented north and south. In fact, they define a girdle distribution oriented N–S. This distribution can be explained if some of the cleavages are S_1 and hence have been reoriented by the chevron folding. Poles that are moderately northerly-dipping are associated with a southerly dipping S_1 cleavage and hence northerly thrusts. Poles that are moderately southerly-dipping are associated with a northerly dipping S_1 cleavage and hence early (i.e. pre-chevron folding) southerly back-thrusts.

3.4.2. Existence of thrust ramps

Although the Lloyd–Whalley model of chevron fold modification was developed on sections immediately to the south (i.e. Bude–Widemouth–Millook; see Fig. 1), it was found that it could not always be used to adequately explain the geometry of fold structures observed between Bude and Duckpool (e.g. Fig. 6). In most cases, this is because the northerly-dipping 'extensional' limbs are too steep. However, one of the main assumptions of the model is that the folds are symmetrical and upright before modification. This assumption is not valid if there has been regional scale thrusting prior to chevron folding because any ramp–flat geometry produced would have been folded into a variety of orientations that depart significantly from the ideal assumed in the model (e.g. Fig. 10). If a horizontal southerly directed shear is then applied, complex fold modification structures occur because of the different limb orientations relative to the shear direction. Thus, the presence of 'extensional' limbs of chevron folds that are too steep to fit the Lloyd–Whalley model can be explained by the existence of thrust ramps at least on the scale of the amplitude of the chevron folds observed today (i.e. ≥100 m). The actual displacement achieved on thrusts with ramps of this size can be much greater than the ramp length (e.g. Fig. 11a and b).

3.4.3. Regional back-thrusts and local lateral ramps

Not all the medium to large scale thrust structures observed between Bude and Duckpool have a northerly sense of vergence. A large scale thrust was recognised at Duckpool (see Figs. 6, 11c and d and 12) that verges towards the south (see below for description). However, such thrusts are much rarer than the northward propagating examples. On purely geometrical reasoning, the presence of thrusts with an opposite (i.e. back-thrust) sense of vergence, would argue for even larger scale fore-thrusts (e.g. Jones, 1982; Vann et al., 1985).

Small to medium scale thrusts that verge approximately towards the east or west have also been recognised. These structures are interpreted as lateral ramps. Their presence explains the orientation of cleavage (i.e. S_1) that depart significantly from an E–W strike (Fig. 9d).

4. A model for the deformation of the Bude Formation

Previous stratigraphic correlation within the Bude Formation (e.g. Freshney et al., 1979) is based on the occurrence of a few fossiliferous shale and marine band horizons and a geometry that assumes a simple chevron folded and normal faulted sequence (Fig. 4). However, many of the fossil species (e.g. fishes) are not particularly diagnostic for the time scale involved. Furthermore, Freshney et al. (1979) acknowledged the broken up nature of parts of the Bude Formation outcrop, particularly in the Duckpool to Northcott Mouth section (Fig. 1), where

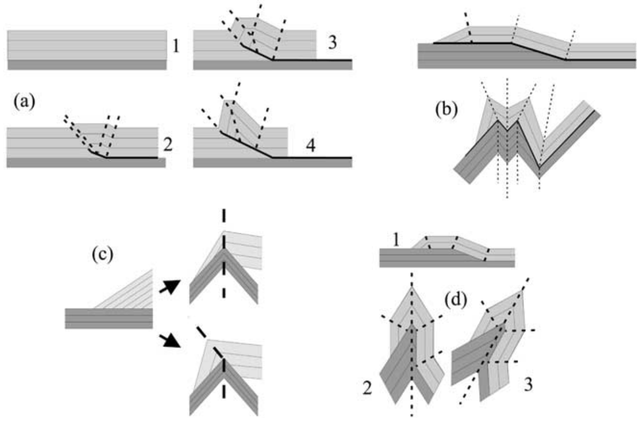


Fig. 10. Effects of early ramp–flat thrust geometries on subsequent chevron folding. (a) Suppe's (1983) model for the development of fault propagation folds at thrust tips. The fold geometry is chevron-like and similar to some of the chevron fold geometries observed in the Bude–Duckpool section. (b) Open, 'chevron-like' folds associated with early ramp–flat thrusting geometry act as nucleation sites for subsequent chevron fold development due to horizontal shortening. Note changes in axial plane orientations. (c) Chevron folds nucleated at thrust ramp–flat structures exhibit changes in axial plane orientations due to the need to maintain bed thickness across the fold hinge and to bisect the fold interlimb angle. (d) Composite deformation model: 1. Incipient chevron folds associated with thrust ramp–flat structures; 2. Nucleation of upright chevron folds with variable axial plane orientations; 3. Rotation of folds due to southerly (dextral) shear.

several large scale thrust structures have been recognised (Figs. 6 and 11). The recognition of fore-, lateral- and back-thrust systems described above has serious implications for any stratigraphical and structural interpretation of the Bude Formation. It is argued therefore that the correlation inherent in Fig. 4 can be unreliable. In contrast, the correlations presented here are based on structural mapping incorporating the comparison of stratigraphic *sequences* rather than individual horizons that are only equivalent if a *simple folded* sequence is assumed. In the description that follows, the stratigraphic names for individual horizons given in Figs. 3a and 4 are not used, except where it is absolutely certain that they are correct and distinct (i.e. in type localities, such as Warren Gutter, Sandy Mouth, Saturday's Pit, etc.). It is not surprising therefore that this new interpretation of the Duckpool to Bude section (summarised in Fig. 12) conflicts markedly with the established section given in Fig. 4 (Freshney et al., 1979).

4.1. A 3D profile

The stratigraphic, sedimentological and structural observations (compiled in Figs. 5 and 6) made between Bude and Duckpool (Fig. 1), which supposedly comprises most of the known Bude Formation, allow the construction of a three-dimensional profile (Fig. 12). This profile commences at the south of the section at Bude Haven (Fig. 12, N0675—such grid references refer to *northings* only) and works progressively northwards. It clearly illustrates the structural complexity of this hitherto assumed simply deformed sedimentary sequence (e.g. Fig. 4). The structural details used to construct this section are listed in Appendix A, but can be summarised as follows.

Using the criteria described above for the recognition of large scale thrusts within the Bude Formation (e.g. Figs. 7–11), it has been possible to identify several major thrust sheets in the Bude–Duckpool section (Fig. 12). The dominant movement sense of these thrust sheets, together with the medium scale lateral ramp structures that have also been recognised, suggest that the tectonic transport direction *prior to the formation of the more obvious chevron fold structures* was towards the north. However, at least one major southerly directed back-thrust is also present. The fore-thrusts pre-dated chevron folding, but most back-thrusting seems to have post-dated these folds and acted to modify them in terms of a southerly directed shear deformation (Fig. 13). This behaviour is compatible with the chevron fold modification model proposed by Lloyd and Whalley (1986, 1997) provided that the initial orientation of the chevrons is taken into consideration.

4.2. Warren Gutter: a test of the 3D profile

The structure at Warren Gutter (SS N1100-1110), which includes the youngest exposed Bude Formation strata (i.e. the Warren Gutter Shale, the boundary between Westphalian B and C; Fig. 3a) provides a good test of the interpretation presented in this contribution. Freshney et al. (1979, Plate 3) (see Fig. 14a) highlighted Warren Gutter for the presence of tight, overturned anticlinal and thrust out synclinal chevron folds. However, these folds mask the existence of earlier thrust structures compatible with the model presented here.

Warren Gutter is situated in the footwall to the Duckpool South back-thrust (Fig. 11c). The sheared through syncline is in fact a hanging wall cut-off (Fig. 14a, h_1) associated with a southerly directed back-thrust (T_B), presumably related to the main Duckpool South back-thrust. This feature is in fact recognised on the cross-section drawn by Freshney et al. (1979) (Fig. 2; see Fig. 14b) but was interpreted as a wrench fault (as were several other similar faults throughout the whole section). Nevertheless, based on this section there is at least 50 m of reverse displacement on the fault. Such a figure constrains the main Duckpool South back-thrust to substantially greater displacement. If the section (Fig. 14b) is followed north beyond the Duckpool South back-thrust, several other back-thrust faults are indicated, including the Duckpool North back-thrust (DNB) hypothesised above and two other structures (B_1 and B_2) outside the section studied.

Although Duckpool appears to be a zone of concentrated back-thrust deformation, there is also evidence for northerly directed (i.e. fore) thrusting. Plate 3 of Freshney et al. (1979) shows a thin sequence of sandstones and siltstones (Fig. 14a, s) within the Warren Gutter Shale (W) that terminates abruptly in the core of an antiformal chevron fold (A_1) in the hanging wall of the back-thrust

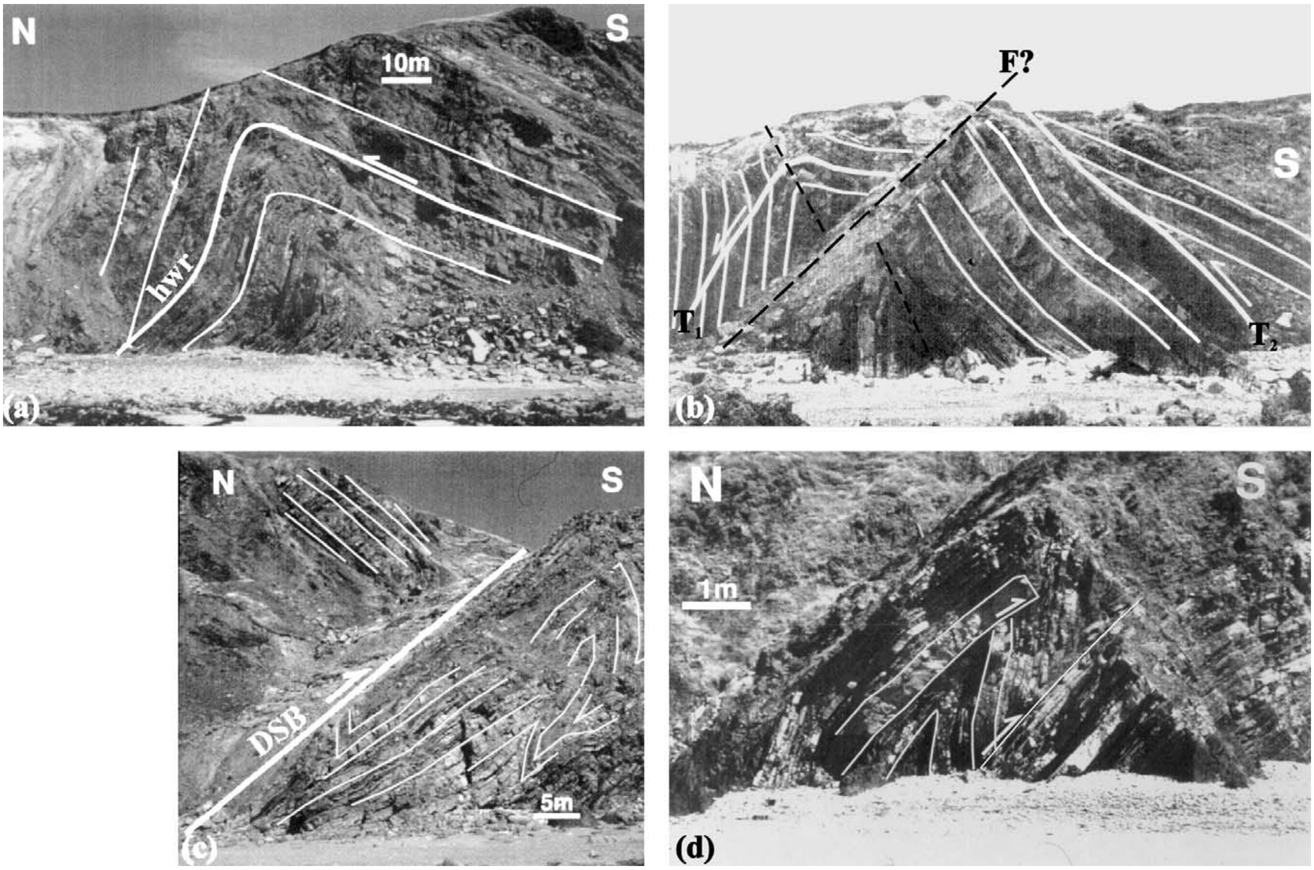


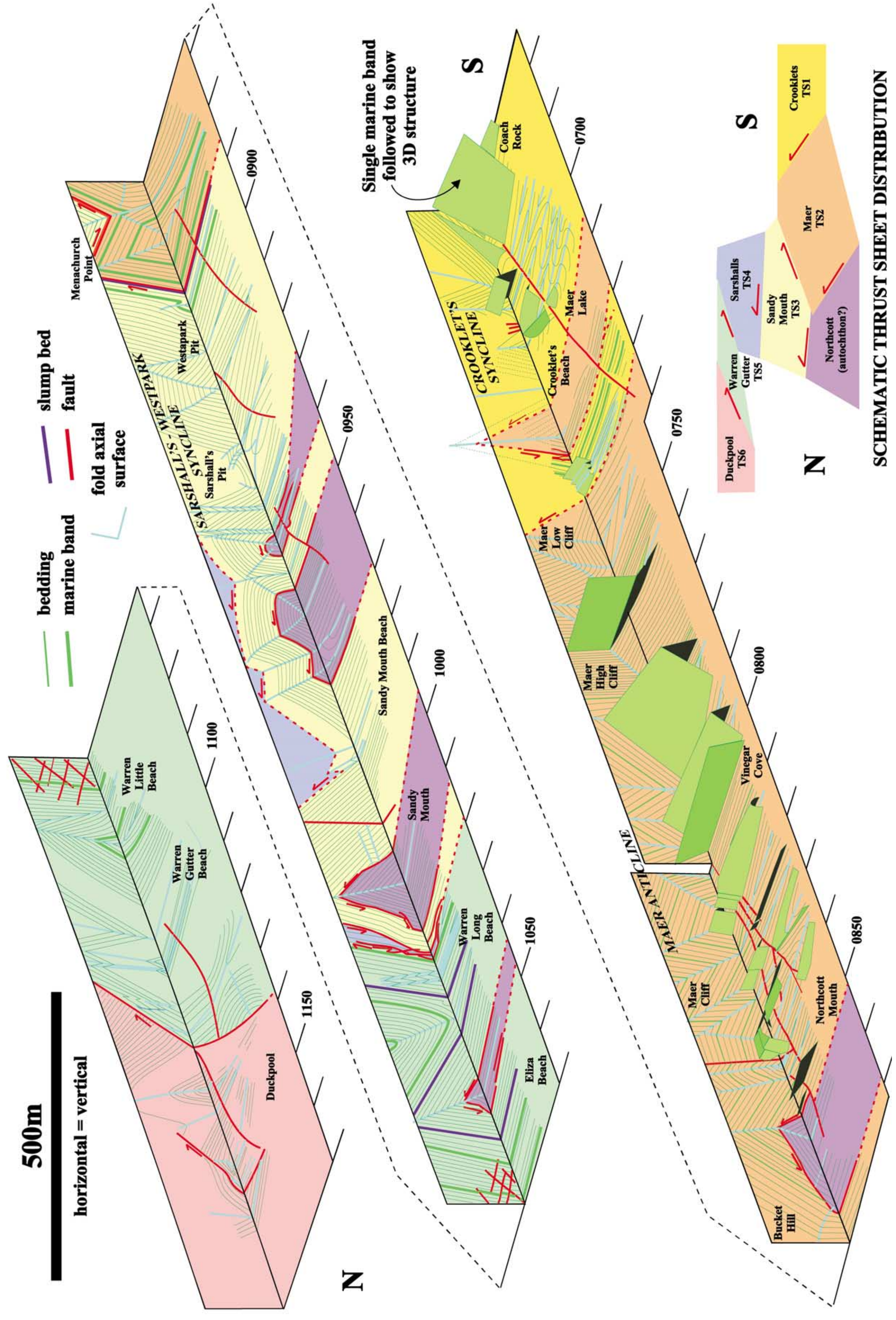
Fig. 11. Examples of relatively large scale thrust structures observed between Bude and Duckpool. See Fig. 1 for locations. (a) Warren Long Beach (SS 2016 1047). Only the hanging wall ramp (hwr) is observed, which requires an offset of at least 130 m to keep the footwall ramp out of the field of view. This thrust is clearly folded by the upright chevron fold. (b) North of Sharshall's Pit (SS 2019 0940). Either two separate thrusts (T1, T2) or a single thrust (T1–T2) subsequently offset by a normal fault (F) obscured by scree debris can explain this locality. The thrust(s) is/are clearly folded by a northerly verging chevron fold (see Fig. 10 for an explanation of this apparently anomalous vergence sense). (c) Duckpool (SS 2006 1117). A landslip obscures the southerly verging Duckpool South back-thrust (DSB). However, footwall beds show top-to-south vergence (see Fig. 14 for further discussion), whilst hanging wall beds are relatively undeformed. (d) Warren Gutter (SS 2008 1104). Folds with tight interlimb angles and hinges have been thrust through with a consistent southerly sense.

(T_B). This termination can be interpreted as another hanging wall cut-off (h_2), but in this case associated with a northerly directed thrust (T_N) that runs along the base of the thin sequence of sandstones and siltstones. The local extent of this thrust can be gauged by matching stratigraphy. The Warren Gutter Shale also occurs in the footwall to the back-thrust (T_B), in the core of another anticlinal chevron fold (A_2), and contains the same sequence of sandstones and siltstones. Presumably, therefore, the base of this sequence is the same northerly directed thrust (T_N). Unfortunately, the displacement accommodated on this thrust cannot be determined. However, the relationships shown in Fig. 14a indicate that northerly directed thrusting pre-dated back-thrusting at Duckpool, whilst chevron folding (e.g. A_1 and A_2) is either synchronous and/or post-dates back-thrusting (Fig. 14c).

4.3. An intra-formational imbricate stack

Using the three-dimensional profile described above and summarised in Appendix A, there may be up to five distinct northerly directed thrust sheets (TS1–5) in the Bude–Duckpool section (Fig. 12), although TS1 and TS3 may be equivalent. In addition, TS6 is clearly carried southwards on the Duckpool South back-thrust and there is evidence to suggest that it may be bounded further north by another (i.e. the Duckpool North) back-thrust (TS7?). It is possible that TS3 and TS5 have been thrust over the thrust sheets immediately to their south (i.e. TS2 and TS4, respectively), in a back-thrust sense. In addition, due to subsequent chevron folding, TS4 reappears as a klippe surrounded by TS3 on Sandy Mouth Beach (N098-099) and may represent a minor structural unit that formed as an imbricate fore- or

Fig. 12. Three-dimensional section from Bude to Duckpool based on detailed structural and sedimentary mapping (Figs. 4 and 6 and Appendix A) showing the effects of northerly thrusting, chevron folding and southerly shear due to back-thrusting on the wavecut platform and cliff profile outcrop patterns. The geology is markedly non-cylindrical, even over a structural strike length of ~100 m.


500m
horizontal = vertical
bedding
marine band
slump bed
fault
fold axial surface
N
S
Duckpool
1150
Warren Gutter Beach
Warren Little Beach
1100
Eliza Beach
1050
Warren Long Beach
Sandy Mouth
1000
Sandy Mouth Beach
0950
SARSHALL'S / WESTPARK SYNCLINE
Sarshall's Pit
Westapark Pit
Menachurch Point
0900
Single marine band followed to show 3D structure
Bucket Hill
0850
Northcott Mouth
Maer Cliff
MAER ANTICLINE
Vinegar Cove
0800
Maer High Cliff
Maer Low Cliff
0750
Crooklet's Beach
CROOKLET'S SYNCLINE
Maer Lake
Coach Rock
0700
Duckpool TS6
Warren Gutter TS5
Sarshalls TS4
Sandy Mouth TS3
Northcott (autochthon?)
Maer TS2
Crooklets TS1
SCHEMATIC THRUST SHEET DISTRIBUTION

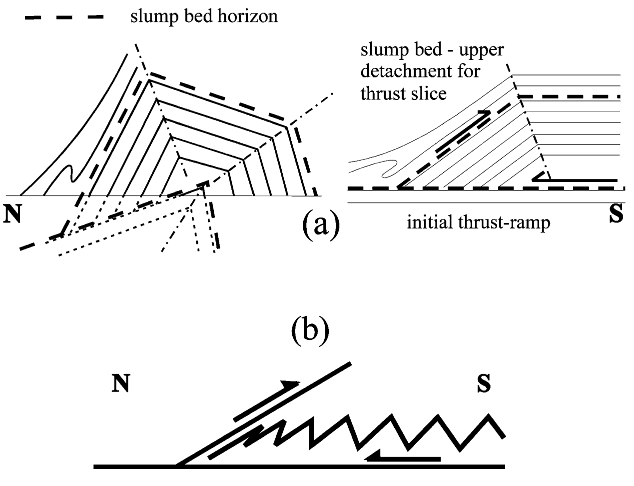


Fig. 13. Schematic representation of the relationship between, fore- and back-thrusts and chevron folds, including the role played by slump bed horizons. See Fig. 1 for locations. (a) Left, final profile. Slump bed horizon exploited by fore- and back-thrust structures and then subsequently chevron folded; note how the chevron fold orientation varies with position. Right, unfolded restoration. Structures such as these are observed at SS 20290892 and 20161028. (b) Effect of back-thrusting due to southerly shear on earlier chevron folding: the folds are tightened and/or progressively overturned. Structures such as these are observed between SS N1140 and N1150 (e.g. Fig. 11d and e).

back-thrust feature during the juxtaposition of TS3 and TS5. Structurally unattributed units also appear in chevron fold cores at several localities along the section (e.g. N104-105, N100-101, N095-097, N094 and N084-085). The reconstruction (Fig. 12) suggests that these are windows of a structurally lower thrust sheet or perhaps even autochthonous Bude Formation.

The observations described here demand that the Bude Formation has been thickened tectonically by thrusting between Duckpool and Bude (Fig. 1). The overall geometrical pattern is that of an intraformational imbricate stack (Fig. 12). However, to establish the actual original thickness will require more detailed stratigraphic work. For example, careful sampling of microfossils (e.g. spores) might be able to define a more detailed stratigraphy in this generally monotonous succession. However, careful examination of the descriptions given in Freshney et al. (1979) lends independent support for these new interpretations. They quote numerous examples of sheared and/or contorted beds, tectonic repetition, structurally expanded and/or sheared out sequences, and bedding parallel faults, many of which coincide with the locations of the thrust structures identified in this contribution.

4.4. Variscan evolution of the Bude Formation

The stratigraphic, sedimentological and structural observations made between Bude and Duckpool permit the proposition of an evolutionary model for the Bude Formation. Such a model may be applicable to the high structural level deformation of many sandstone–shale sequences or sedimentary basins. The essential steps in this evolution are as follows (Fig. 15; refer also to Figs. 6 and 12).

Step 1. Sedimentation in a coastal flood-plane/delta-front environment with rare marine incursions and associated sedimentary and tectonic instability (e.g. slumping, listric normal growth faults; Fig. 15a, see also Fig. 2d).

Step 2. Northerly directed thrusting associated with the northward and upward propagation of Variscan tectonics. Such deformation may have been penecontemporaneous with sedimentation, but certainly occurred at high structural and stratigraphic levels. Consequently, thrusting exploited relatively high pore fluid pressures that favoured bedding parallel ‘flat’ movements along shale-dominated horizons with only rare ‘ramp’ propagations (Fig. 15b; see also Figs. 2d–f, 4, 6 and 12). Where ramp–flat geometries did develop they produced incipient chevron folds with variable axial plane orientations (see Fig. 10). A weak but regionally pervasive northerly verging cleavage (S_1) also developed, subparallel to, but slightly steeper than, bedding (S_0), especially in shale horizons (Fig. 9a and d).

Step 3. Horizontal compression developed behind the thrust front(s), resulting in bulk shortening (Fig. 15c). The sandstone–shale multilayer sequence was ideal for flexural slip deformation and vertical chevron-style folding (Fig. 2a and b). It can be demonstrated that folding post-dated *northerly* thrusting *at any one locality* because, whereas, folded thrusts are common (e.g. Fig. 11a and b), folds thrust through with a northerly sense of vergence are rare (except for minor accommodation thrusts in the hinge zones of chevron folds). Furthermore, where ramp–flat geometries had developed prior to folding, they acted as nucleation points for chevron fold formation, resulting in chevrons with variable geometries and axial plane orientations. Thus, the classic vertical chevron folds were perhaps only rarely developed, with initially upright and northerly or southerly verging folds being more typical. A local cleavage (S_2) developed in the hinge zones of the chevrons (Fig. 9b and d), especially in shale horizons, and verged either northerly, southerly or neutrally depending on the individual geometry of the fold (Fig. 10).

Step 4. Structurally necessary back-thrusts (i.e. southerly propagating) developed to accommodate volume increases, particularly at structurally high levels (Fig. 15d). Such structures can either pre- or post-date the chevron folding and earlier back-thrusts obviously can be folded by the chevrons. However, in general the back-thrusts post-date the chevron folds and therefore tend to superpose a (local) southerly shear regime (Fig. 11c and d). This results in the classic modified chevron folds described by Lloyd and Whalley (1986, 1997), due to the tightening and overturning to the south of the essentially upright folds (e.g. Fig. 13). Originally southerly dipping fold limbs are in the compressional field of this shear regime and develop subhorizontal chevron folds via flexural slip (e.g. Fig. 2c).

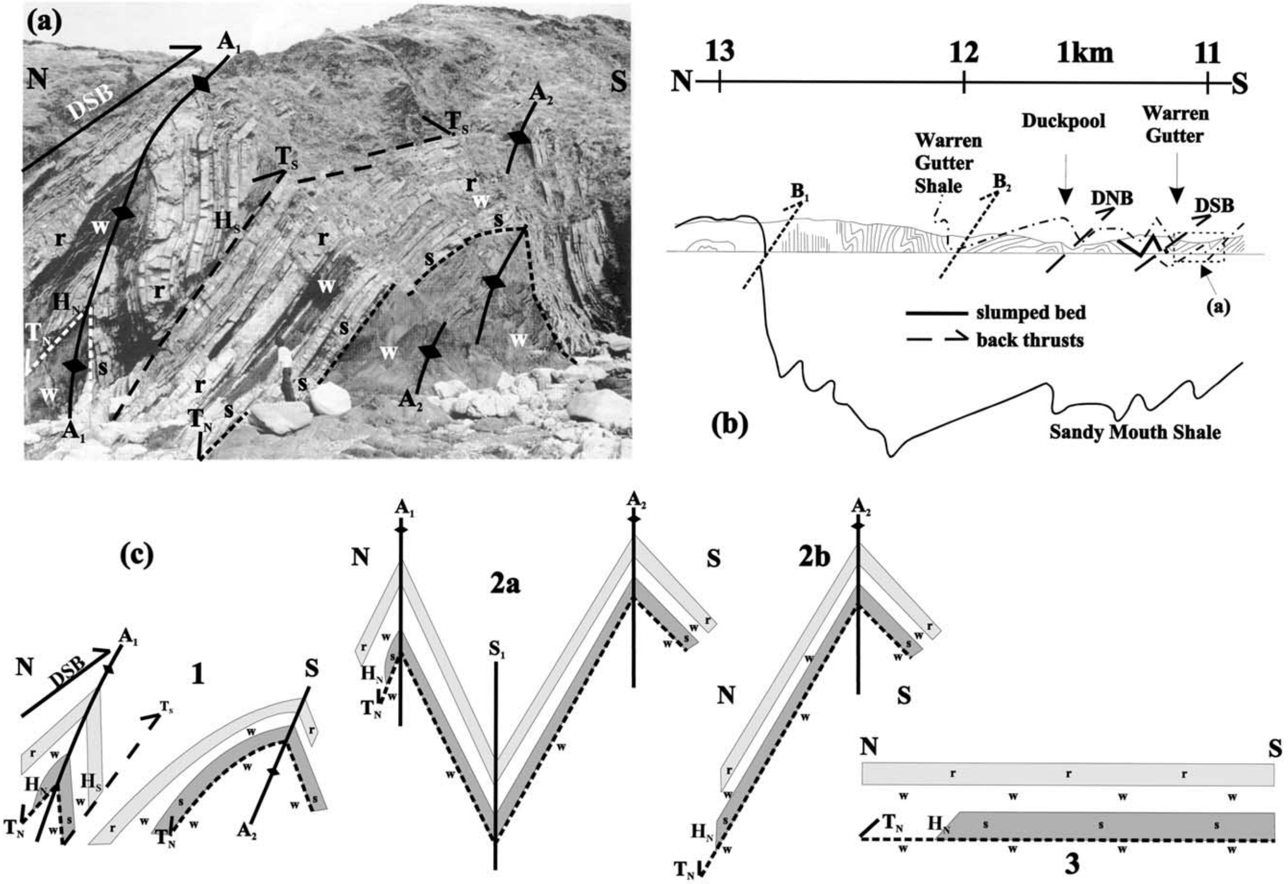


Fig. 14. A reinterpretation of the structure at Warren Gutter (SS N1100-1110) in terms of the thrust-fold model presented here. See text for discussion. (a) Plate 3 of Freshney et al. (1979) reproduced by permission of the British Geological Survey (© NERC. All rights reserved. IPR/22-25C). etc. Nomenclature: H_S, hanging wall cut-off associated with back-thrust, T_S; H_N, hanging wall cut-off associated with fore-thrust, T_N; r and s, marker horizons traced through the structure; W, Warren Gutter Shale; A_1 and A_2, anticlinal chevron folds; DSB, Duckpool South back-thrust (see Fig. 11c). (b) Detail of Fig. 2 of Freshney et al. (1979) (see also Fig. 4), including outcrop shown in (a). Note the reverse offset of the Warren Gutter Shale by the DSB. This permits the reinterpretation of this section in terms of a series of back-thrust faults (DNB, Duckpool north back-thrust; B_1 and B_2, other probable back-thrusts north of the study section). (c) Schematic evolution (nomenclature as above). 1. Present configuration. 2. Removal of southerly back-thrust and shear modification of A_1 and A_2. Two possibilities are envisaged: (2a) incorporation of a synclinal chevron fold (S_1), subsequently thrust through by T_S; or (2b) interpretation of A_1 as a hanging wall ramp associated with T_S, which, therefore, can also be removed. 3. Removal of vertical chevron folding to reveal a single northerly directed thrust (T_N) that repeats part of the W stratigraphy.

A subhorizontal, southerly verging cleavage (S_3) may be associated with these folds (Fig. 9c). Originally northerly dipping fold limbs, together with axial planes, are in the extensional field of this shear regime and develop extensional structures, such as normal faults, boudinage of competent beds and veining. In addition, early thrust planes may also suffer reactivation as normal faults during this shear regime due to steepening, perhaps even overturning so that they now dip to the north. Indeed, several ‘complex normal fault zones’ (e.g. at Phillip’s Point and between S. Widemouth Bay and Wanson Mouth; see Fig. 1) exhibit contractional structures with northerly vergence (after correction) that are overprinted by extensional features (see also Enfield et al., 1985). Thus, many of the northerly-dipping apparently normal faults that occur in this section may be reactivated northerly propagating thrusts. Perhaps the most important of these are the Widemouth–Wanson Faults and the Rusey Fault further to the south. The former represents the *tectonic* contact between the Bude and Crackington Formations and the interpretation presented here implies that originally the Crackington Formation was thrust over the Bude Formation, although today the Bude Formation lies in the hanging wall of an apparently normal fault. The latter separates Upper and Lower (?) Carboniferous strata and appears to be a normal fault. However, it is likely that it was originally a northerly propagating thrust (see Andrews et al. (1996) and Thompson and Cosgrove (1996) for discussions) that emplaced the Lower Carboniferous (and Devonian?) metamorphic ‘infra-structure’ over the Upper Carboniferous non-metamorphic ‘suprastructure’ (Zwart, 1964).

Support for this interpretation is again provided by Freshney et al. (1979). They considered that folding occurred at a high structural level at a very late stage in the Variscan Orogeny, due to contractional forces that began in the Late Devonian much further to the south. These forces were also responsible for thrusting and overfolding immediately to the north and south of the

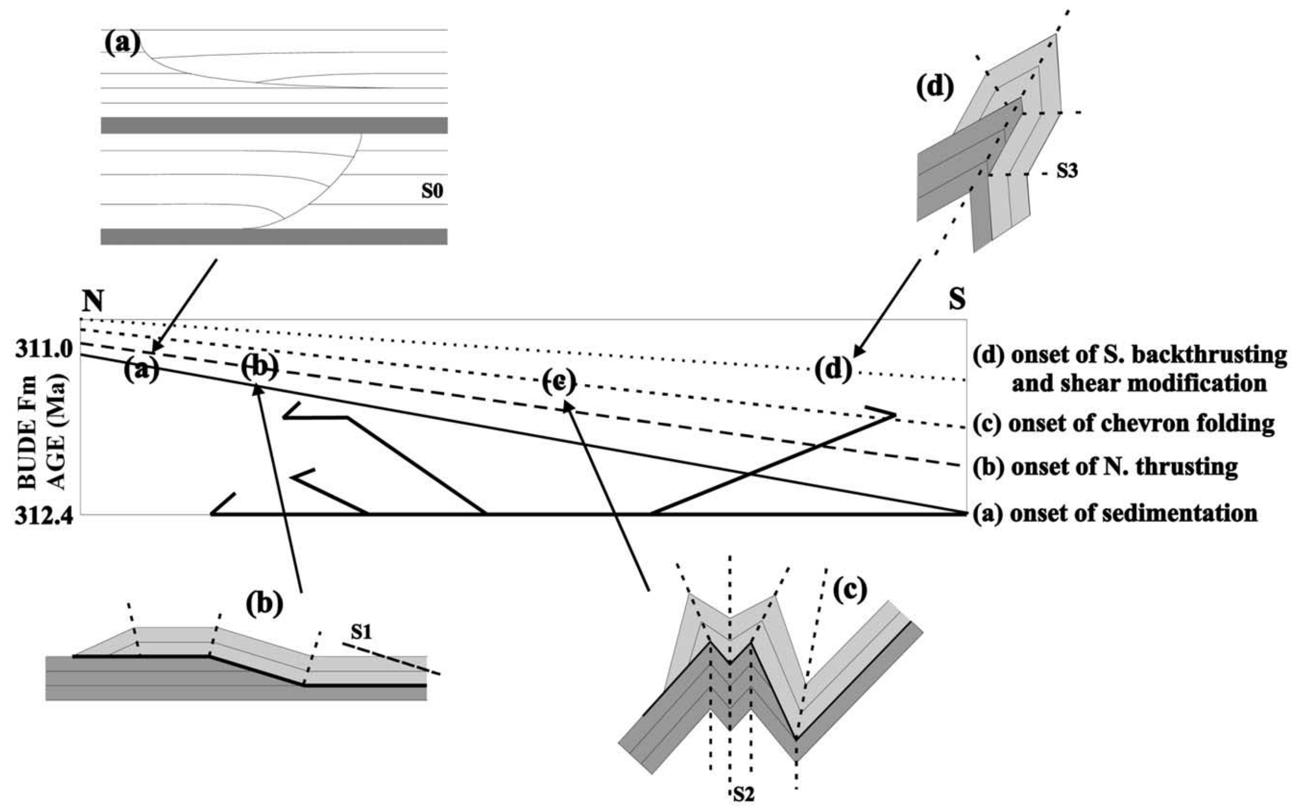


Fig. 15. A model for the Variscan evolution of the Bude Formation. (a)–(d) migrate progressively northwards and are potentially synchronous in time but not position. It is possible for back-thrusting to predate chevron folding. See text for details. (a) Onset of sedimentation in a coastal floodplane environment and listric normal growth faulting. (b) Onset of northerly thrusting, mainly bedding parallel, and incipient chevron fold-style fault propagation folds with variable geometries related to rare ramp–flat structures. (c) Onset of horizontal compression resulting in upright chevron folding, which nucleate at thrust ramp–flat structures and therefore may exhibit variable geometries, axial plane orientations and vergence senses; folding of early northerly thrusts. (d) Onset of southerly directed back-thrusts impose a southerly shear regime onto earlier structures, resulting in chevron fold modification and possible reactivation of earlier thrust structures as normal faults.

Duckpool–Bude region. However, why thrusting did not occur in this region was not explained. This is particularly surprising as Freshney et al. (1979) considered that the Upper Carboniferous rocks probably formed a thin sheet separated from the highly deformed rocks below by a decollement plane that possibly reaches the surface in the Rusey Thrust! This description is completely in agreement with the new interpretations. In addition, they suggest that the sense of overturning of folds is highly variable and appears to be related to the position on the flanks of major folds and within the structural belt as a whole. In other words, they are describing the Lloyd–Whalley model contracting limb modification folds that develop due to localised shear related to back-thrusts.

It is interesting to compare the 1.4 Ma stratigraphic time span for the Bude Formation (based on data in Claoué-Long et al. (1993) and Hess and Lippolt (1986)) with the estimate of the 'local' orogenic deformation time span obtained by Ferguson and Lloyd (1982) for the evolution of the 'Southern Culm Overfold'. This estimate was based on the mechanical analysis of small scale structures, including boudinage. The 'Southern Culm Overfold' apparently represents a major fold-thrust complex of Namurian and Westphalian rocks emplaced over Devonian and Lower Carboniferous strata. Geometrical reconstruction of the pre-folding/thrusting configuration of the rock units (see Ferguson and Lloyd, 1982; Fig. 2) supports the suggestion made above that the Rusey Fault Zone was originally a southerly propagating (back) thrust structure. The time taken for this structure to evolve was estimated to have been between 0.75 and 1.5 Ma, depending on temperature (and hence depth of burial), compatible with the 'stratigraphic' time span. Ferguson and Lloyd (1982) further argued that the age of evolution of the 'Southern Culm Overfold' was ~295 Ma, based on the radiometric isotope data of Dodson and Rex (1971) from slates in the Tintagel–Boscastle area. This age is clearly compatible with the model of penecontemporaneous sedimentation and deformation.

Finally, it is emphasised that the sequence described above (Fig. 15) can be *contemporaneous*, as both sedimentation and deformation proceeded from south to north. Thus, whilst back-thrusting and southerly shear were occurring in the south (i.e. the structurally deeper and older region), horizontal compression and chevron folding was occurring immediately north (i.e. structurally slightly higher and younger) of this. Further north (or higher/younger still), northerly thrusting was occurring, whilst sedimentation and growth faulting were occurring in the northmost (highest/youngest) region. *It is conceivable therefore that at any single locality, the Bude Formation is an instantaneous representation of an orogenic front propagating into its foreland basin*. This view of the deformation of the Bude Formation is broadly consistent with the overall picture of Variscan tectonics in Britain and Ireland (e.g. Freshney et al., 1979; Coward and Shackleton, 1982; Isaac et al., 1982; Shackleton et al., 1982; Turner, 1982; Coward and Selwood, 1984; Shackleton, 1984; Selwood and Thomas, 1988a,b; Thomas, 1988), which involved a northward propagating and waning deformation front at the end of the Carboniferous (see Hartley (1993) and Burgess and Gayer (2000) for further discussion of Variscan tectonics in SW England).

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Appendix A. Structural details used to erect 3D profile for the Bude Formation (Fig. 12)—LWM, Lloyd–Whalley chevron fold modification model; N, northings grid reference

N0675-N0740. Single marine band (Saturday's Pit Shale?) drawn as 3D object. First structure observed (N0690) is a syncline overturned to S. Extensional veins and normal faults on S dipping ('extensional') end compatible with S shear according to LWM. Wave-cut platform indicates effects of S shear with minor modification folds occurring on N dipping ('compressional') limb. Hinge region of several folds (N0700) exhibit normal and reverse faulting, compatible with LWM for low shear strains. Wrangle Point (N0720-0724) stratigraphy disturbed by complex array of bedding parallel faults, interpreted as part of major N propagating thrust system. Series of tight folds in otherwise relatively open fold train, and disappearance of two closely spaced marine bands across a large syncline (Fig. 9), interpreted as related to thrust ramp (see above). Prominent late NW–SE fault cuts a wide erosion channel across beach crop (N0680-0740).

N0740-0800. Relatively straightforward section, although a marine band (N0753) reveals an unusually cylindrical structural style. Between Maer High Cliff, Pearce's Cove (N0770-0800) and Northcott Mouth (N0855), a series of chevron folds, illustrated by 3D marine band, appears to exhibit slight modification due to S shear. However, comparison with LWM is poor, possibly because original fold geometry is related to thrust ramp structures associated with this thrust sheet, rather than initially vertical chevrons (Fig. 11).

N0800-0870. Relatively simple cylindrical structural style (shown by 3D marine band) continues to Northcott Mouth (N0855), where a late NW–SE normal fault is truncated by one of several even later faults trending subparallel to cliff profile section on wavecut platform. Throw on profile parallel faults increases to W but decreases to S (Fig. 12). Major thrust structure occurs between Northcott Mouth and Bucket Hill (N0870), defined by hanging wall ramp–footwall flat bedding geometry. Unfortunately, outcrop is generally poor, especially at N end, and most evidence is based on absence of marine bands at cliff base and further N.

N0870-0940. Structures become non-cylindrical N of Bucket Hill and at Menachurch Point (0880) a large anticline shows marked changes in plunge along strike. Fold structure seen at Sarshall's Pit (N0922) appears to follow LWM, but in detail is more complicated. It appears that fold(s) here were not originally vertical structures and therefore cannot follow precisely LWM during subsequent simple shear. Most likely explanation is that fold(s) nucleated with different geometries at an earlier thrust ramp–flat structure (Figs. 10 and 11). Apparent 'modification' folds on contracting limb of this fold are not subhorizontal but have a distinct N vergence and could be associated with an original N propagating thrust. At N0940 another late fault subparallel to cliff profile cuts the wavecut platform.

N0940-1000. Major N propagating thrust occurs N of Menachurch Point (N0940). This structure (Fig. 8b) is clearly folded by an upright chevron fold. Numerous lateral ramp structures outcrop in wavecut platform. S of Long Rock (N0965) a double anticline, single syncline structure is markedly non-cylindrical and periclinal, mimicking modification style suggested by LWM (1997; Fig. 6a). Exposure is lost S of Black Rock (N0990-0995) in lead-in to major Sandy Mouth structure, which is unconstrained in much of what is its hanging wall.

N1000-1060. Sandy Mouth Thrust (N1000-1010) is a large scale, N propagating feature, clearly folded by later, upright chevron folds. There are also numerous small–medium scale duplexes (Fig. 2f). Immediately to N (N1025) is a complex set of faults that are subparallel to essentially vertical bedding. Actual structure is difficult to determine, but is probably related to Sandy Mouth Thrust and may represent 'roof thrust' to Sandy Mouth 'thrust sheet' (Fig. 12). This 'roof thrust' reappears in Warren Long Beach (N1040-105; Fig. 8a), whilst numerous lateral ramps crop out on wavecut platform. Between N1025 and N1040 (i.e. structurally higher but presumably stratigraphically lower; Fig. 13a), a slump bed horizon has concentrated deformation and provides evidence (N1028) for pre- and post-chevron folding thrust deformation. Structure can be interpreted as an initial hanging wall ramp–footwall flat associated with a N propagating thrust (i.e. Sandy Mouth 'roof thrust'?). It has been folded subsequently into an essentially upright chevron fold and finally sheared to S by a S propagating back-thrust (see Fig. 13a), which has exploited the slump bed horizon. Same slump bed outcrops further N on both limbs of a large anticline (N1050), above reappearance of Sandy Mouth 'roof thrust'.

N1060-1110. At Eliza Beach (N1063-1072) faults occur on N dipping limb of a large anticline, indicating extension due to S shear according to LWM. At N end of Eliza Beach (N1074), a much tighter than normal syncline occurs, indicating horizontal shortening beyond theoretical 60° lock-up angle for chevron folding. Shortening begins to intensify in Warren Gutter (N1100) and from here to Duckpool (N1150) occurs most intensive deformation observed in entire Bude–Duckpool section. In Warren Gutter, folds with tight (20–30°) inter-limb angles occur, associated with a strong but consistently ~ESE oriented and N dipping cleavage (presumably S_2), especially in shales and marine bands. Hinges of these folds are typically thrust through in a consistent sense, indicating S transport (Fig. 8d). Folds become less tight (90–100°) along strike onto wavecut platform. Tightening of folds and intensification of deformation is associated with the first of two major back-thrusts that occurs S of Duckpool (Fig. 8c). Rocks in this section occur within the footwall to this thrust, but have also been affected by both N thrusting and chevron folding (see below).

N1110-1170. Duckpool structures show conflicting vergence sense, compatible with polyphase deformation. Duckpool South back-thrust (N1117; Fig. 8c) separates very highly deformed rocks in its footwall (see above) from relatively weakly deformed, S dipping rocks in its hanging wall. Overall structure is markedly non-cylindrical: small folds and faults are common and cleavages are present with variable orientations. Although outcrop trace of this thrust is NW–SE on wavecut platform (from N1117-1140), suggesting a SW propagation direction, variable geometry of footwall structures (e.g. folds and cleavage) suggest more irregular movements. A second thrust, Duckpool North back-thrust, may also be present (N1146) but it is difficult to be sure due to complexity of deformation and lack of outcrop.

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