Read at the Annual conference of the Ussher Society, January 1991

Pre-folding tectonic contraction and extension of the Bude Formation, North Cornwall

R.B.M. MAPEO and J.R. ANDREWS

Mapeo, R.B.M. and Andrews J.R. 1991. Pre-folding tectonic contraction and extension of the Bude Formation, North Cornwall. *Proceedings of the Ussher Society, 7,* 350-355.

Evidence of pre- and syn-folding extension is widespread in the Bude Formation between Wanson Mouth and Sandy Mouth beach, north Cornwall. Early faults with an extensional geometry are common throughout the section leading to omission of small packets of strata. The faults are clearly tectonic as the fault planes are characteristically mineralised by vein-quartz which displays slickenside striae. They also have a well constrained geometry and there is absence of any chaotic disturbed sediment associated with deformation of unlithified sediment. Some of the early extensional faults have classic listric geometries, their trajectories curving sharply and abruptly into bed-parallel detachments. Displacements on individual faults are small (cmm) but cumulatively they may reflect considerable extension, The faults are easily distinguished from the late low-angle normal faults, well documented in the BGS memoir. Pre- and syn-folding thrusts are also common and have features as above which suggest they are tectonic rather than syn-sedimentary but that they are not all simply accommodation structures to flexural-slip folding. The NNW-SSE transport of the early extensional faults and thrusts suggests contemporaneous development with extension due to thrusts transferring part or all of their displacement down section before eventually cutting back up again towards the surface.

R.B.M. Mapeo and J.R. Andrews, Department of Geology, The University, Southampton S09 5NH. (*also of Department of Geological Survey, Botswana.)*

Introduction

Upright to overturned chevron folding in the Bude and Crackington formations is spectacularly displayed in the cliff sections of north Cornwall. These decametric scale folds dominate the structure. Other less obvious but still significant structures have generally been ignored until relatively recently. Whalley and Lloyd (1986) and Enfield *et al.* (1985) described northerly directed contractional detachments, antiformal stacks, imbrication and duplex structures which they attribute to syndepositional deformation marking the earliest component of the tectonic history. Tanner (1989) concluded that duplexes at Hartland Quay were developed during the flexural slip folding process. This paper documents both early contractional and extensional structures within the Bude Formation between Wanson Mouth (SS 196 010) and Warren Gutter (SS 200 011) (Fig. 1). Following the criteria of Elliot and Williams (1988) and Maltman (1984) they are distinguished as tectonic rather than syndepositional in origin. Their relative age has been determined by their relationships with chevron folds (Fig. 2).

Geological setting

The Upper Culm Measures in SW England comprise three lithostratigraphic units, the Crackington Formation, the Bideford Formation and the Bude Formation. The spatial relationships of these three Namurian to Westphalian formations are obscured by the structural complexity of the Culm basin and poor inland exposure. The Bude Formation conformably overlies the Crackington Formation and is coeval with the top of the Bideford Formation (Edmonds *et al.* 1979). It crops out along the coast northwards from a major wrench fault, the Widemouth South Fault and comprises three main lithological types, black shales, thick massive sandstones and alternations of shales, siltstones and sandstones. It represents the uppermost stratigraphic unit in the area. The lateral continuation of some Bude Formation sandstones into the Bideford Formation is reported by Freshney *et al.* (1979). The distribution of the Bude Formation is shown in Fig. 1. More detailed descriptions of lithofacies of the Bude Formation are given by Freshney *et al.* (1972) and Melvin (1986). The structures described below occur in the Bude Formation and are exposed at Stowe Cliffs, Sandy Mouth Beach, Menachurch Point and Northcott Mouth.

The Bude Formation is the least deformed and metamorphosed of the Upper Palaeozoic sedimentary sequences along the Cornwall and Devon coastlines. Metamorphism attained only the diagenetic zone of the lower greenschist facies (Primmer 1985). The rocks display spectacular chevron folds of varying complexity. The folds are thought to have been formed by a process of flexural slip folding (Ramsay 1974). The flexural slip mechanism was reviewed by Tanner (1989) who identified discrete bed-parallel detachments at Hartland Quay and interpreted them as the slip surfaces accommodating folding. Lloyd and Whalley (1986) recognised that the south dipping limbs of some chevron folds have been modified to produce sub-horizontal angular folds which affect the syn-upright folding axial planar cleavage. They interpreted this in terms of a south directed simple shear rotating the primary chevron folds, modifying the hypothesis of Sanderson (1979). To avoid the subsequent rotations induced by modification of chevron folds, data used in this paper were obtained from sections displaying one episode of upright chevron folding.

Methodology

The identification of structures attributable to deformation which pre-dates a major folding event requires careful observation and mapping. Early faults are overprinted by the cleavage axial planar to the main phase chevron folds. Early thrusts are folded but in some cases this is by the development of piggy-back style thrust sequences. The antiformal stack at Upton Cross (Enfield *et al.* 1985) is an example where early thrusts have been folded by footwall collapse and also by subsequent chevron style folding. The sequence of structures deduced using these criteria is shown in Fig. 2. The term extensional fault is used in the sense of Norris (1958); the datum is bedding. Early listric extension of the bedding was often followed by contractional reactivation (inversion) of the extensional faults, which obscures much of the evidence.

The early structures are intraformational in nature and there is no significant difference in age in footwall and hangingwall strata other than relatively minor superposition or omission.

Data was collected from a total of 19 sites located along the north Cornwall coastline, from Foxhole Point south of Wanson Mouth (SS 185 005) to Warren Gutter (SS 200 110). The orientations of faults, nature of the fault surfaces, slip-directions and sense of transport were recorded, and for pre-folding structures these have been restored to their original orientations by rotating bedding to horizontal about the strike. Six sites are documented in detail below.

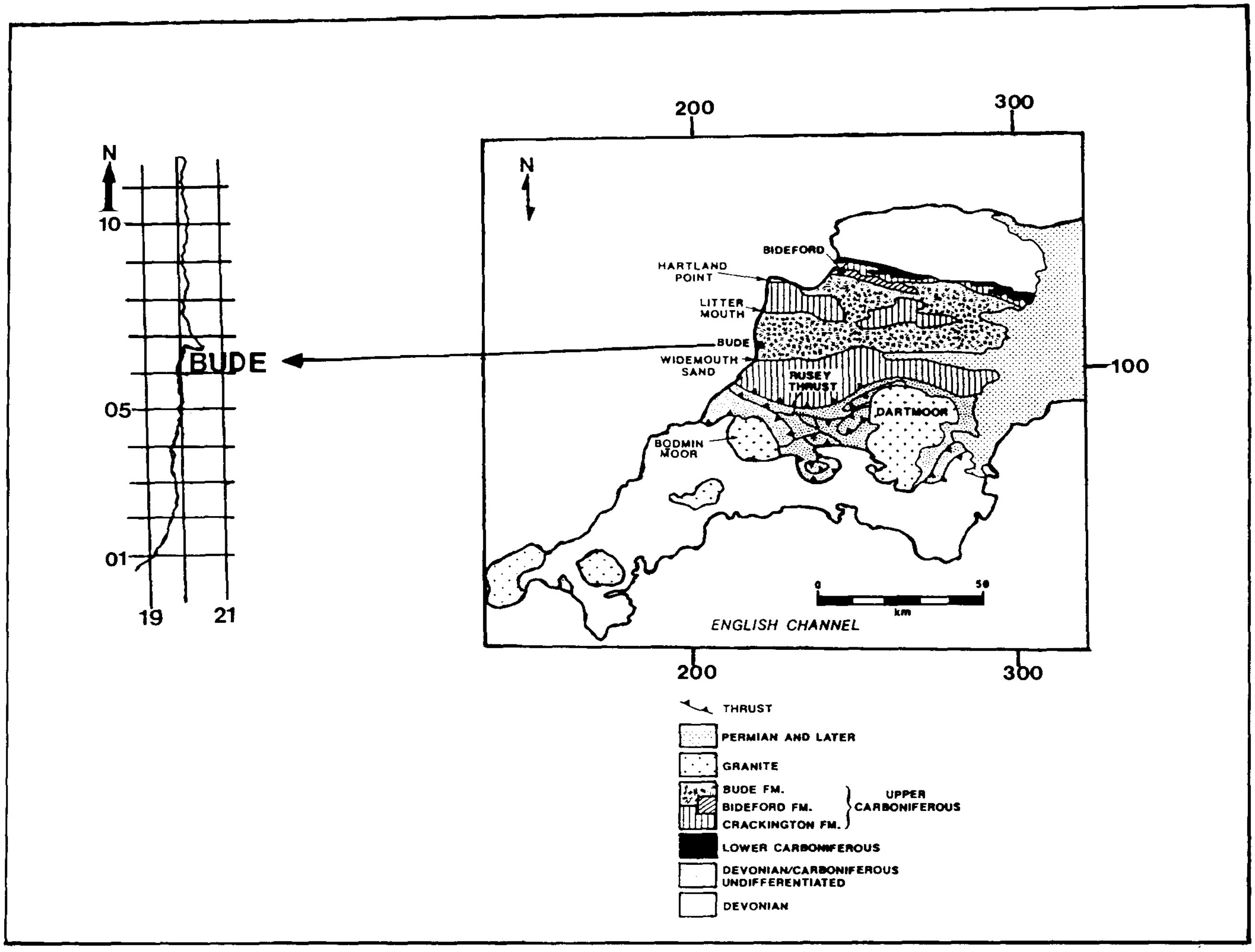

Figure 1. Geological sketch map of SW England with location of the area studied (after Melvin 1986 and O.S. Sheet 174).

Pre-folding extensional faults

Sandy Mouth (SS 201 101)

Several early faults can be observed in the cliff to the north and south of the entrance to the beach. Individual beds show a complex history of early extensional faulting, which preceded or was synchronous with northerly transporting contractional faults (of which the Sandy Mouth thrust described below is an example) and south transporting backthrusts. A typical example of some of these early structures is shown in Fig. 3. The early extensional fault is about 200mm in length where it cross-cuts the bedding and it extends more than a metre along the flat, parallel to bedding. This fault predates an overlying later contractional fault duplex which displays a northward sense of transport. The black shale preserved as a triangular shaped piece is all that remains of a more continuous layer which ran along the top of the thicker siltstone. Small lenses of the black shale can still be found adhering to the top of the siltstone. The remaining black shale has been transported away in the overlying thrust sheet and replaced by material from a lower stratigraphic unit. These early faults deform some syn-sedimentary structures, mostly slump folds. Fault planes, where there is only evidence of extension, are characterised by quartz-covered surfaces which show down-dip fibres. This indicates that the extension occurred in an environment where the rock was already lithified, probably at a depth of burial of several tens of metres or more. Syn-sediment fractures observed in oceanic sequences elsewhere are often mud-filled or occasionally carbonate-filled (see e.g. Pickering *et al. 1990).*

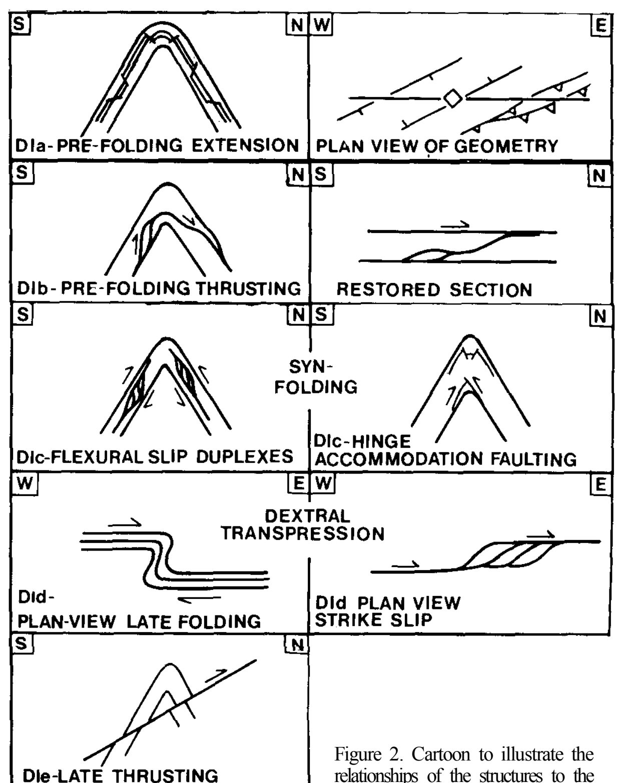

Figure 2. Cartoon to illustrate the relationships of the structures to the main phase chevron folding.

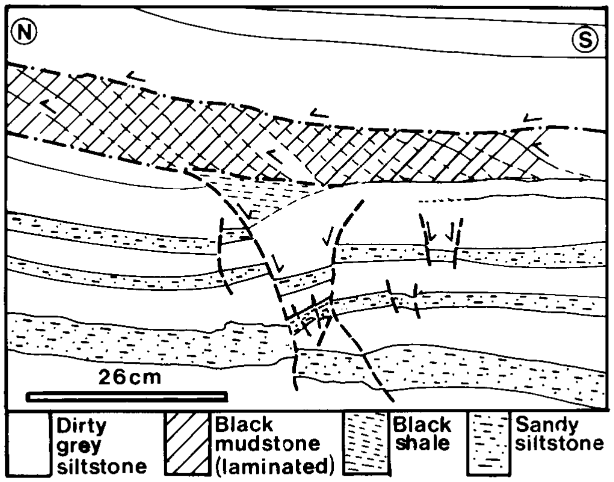

Figure 3. Extensional faulting predates northward directed thrust system which generated a duplex. The thrusting partially utilised pre-existing bedparallel extensional detachment surfaces. Sandy Mouth (SS 201 101).

Menachurch Point (SS 202 093)

The Menachurch Point section is located 600m south of Sandy Mouth beach. Bude Formation strata form upright chevron and box folds. At SS 202 093, a complex structure is exposed in the core of a box fold, stratigraphically below the Sandy Mouth Shale Member (Fig. 4). Sub-horizontal bedding consists of a sequence of sandstones, siltstones and shales all lying above a massive sandstone bed. The sigmoidal faults linking the horses in a footwall duplex indicate northwards transport, whilst hangingwall cutoffs against the roof thrust suggest southwards transport. The thrusts postdate early extensional faulting which comprises a number of conjugate sets seen in a section normal to the transport direction (Fig. 4b). These thin the massive sand layer beneath by developing a series of small horsts and graben. A whole unit of sandstone has been omitted over one horst. This omission is unlikely to be syn-sedimentary, because parts of the missing units occur as lenses along detachment surfaces and evidence for growth faulting has not been seen.

The roof to these bed-parallel detachments can be traced for about 2m where it becomes the bounding thrust of the adjacent duplex system. This suggests that the original extensional detachment has been utilized by later thrust and backthrust systems. When the structures are followed into the limbs of the box fold there is no evidence of very discordant cross-cutting thrusting which would be predicted by continued propagation of a post-folding thrust system and it is concluded that these structures are pre-folding.

Stowe Cliffs (SS 200 105)

The Stowe cliffs section is located about 500m north of Sandy Mouth beach. Lithologies in this section consist of siltstones, sandstones and black shales. These structures are in units stratigraphically above the Sandy Mouth Shale Member. Early extensional faults, folded thrusts and faults occur on both limbs of the Stowe Cliffs anticline. On the north-dipping fold limb, pop-up structures suggest some backthusting.

Early extension faults form conjugate sets: the majority occur on the south limb, both sets dipping gently to steeply to the SE or NW with most throwing to the NW. Where they cross-cut the bedding they range from 400-600mm in length, and the fault planes are marked by thin striated sheets of quartz fibres. Slickenside striae pitch steeply almost down dip. The extensional faults are postdated by both south directed and north directed thrusting.

Summary

The present-day geometry of the pre-folding extensional faults is shown in Fig. 5a and the slip directions in Fig. 5b. They strike ENE to NE and their conjugate nature is readily apparent on the stereograms. The fault planes are generally covered by a thin veneer of striated quartz. Reference to the results of deep sea drilling cores suggests that deposition of quartz in open fractures does not occur in the immediate sub-surface environment, which implies that the rocks were lithified during faulting and probably at a depth of burial of tens of metres or more.

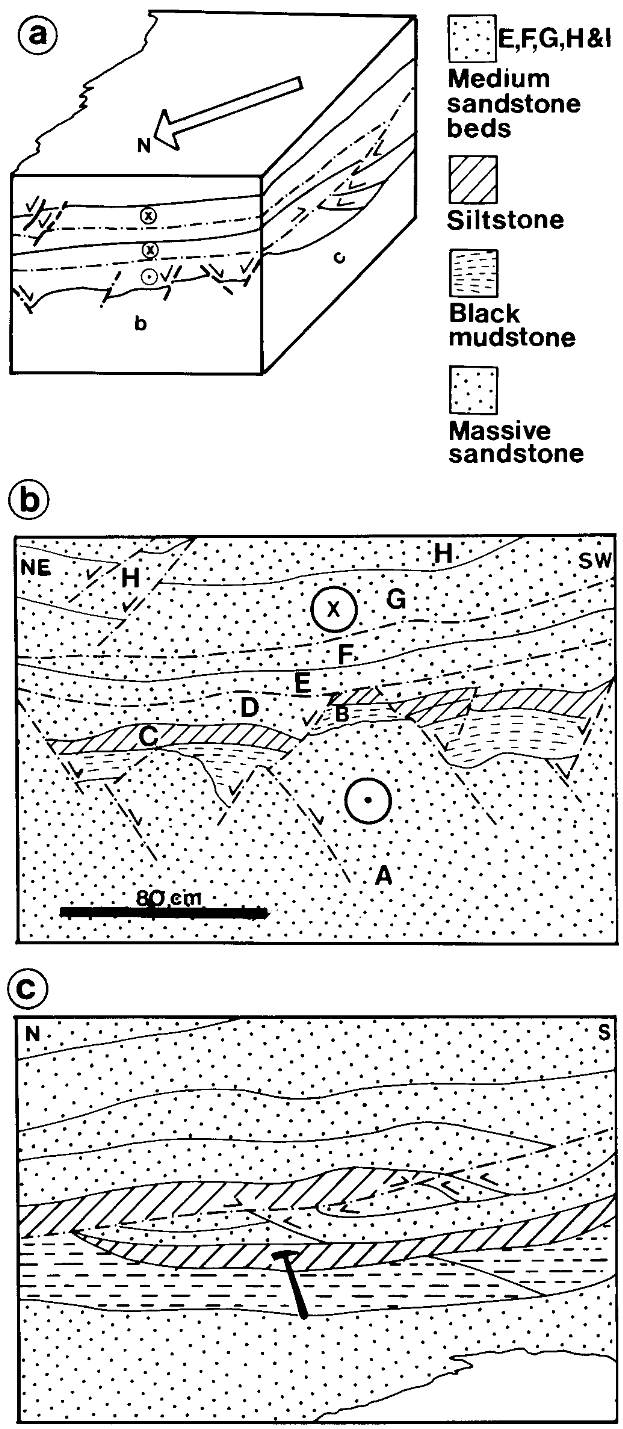

Figure 4. Block diagram and sections to illustrate the relationship between early extensional and contractional faults at Menachurch Point (SS 202 093). a) Block diagram. Higher level thrusts transport to the south whilst a footwall duplex indicates northwards transport. b) Section perpendicular to transport showing extensional faults which predate the southwards transporting thrusts. c) Section parallel to transport indicating opposing transport directions. scales: hammer 470mm.

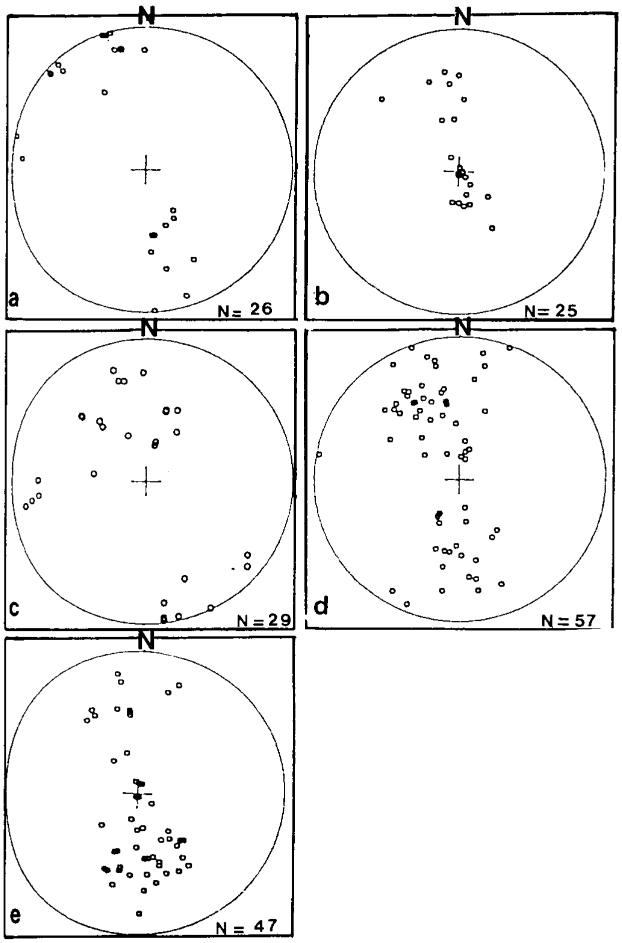

Figure 5. Data from prefolding extensional and thrust faults between Wanson mouth (SS 196 010) and Warren Gutter (SS 200011). a) Extensional faults. b) Slickenside striae on extensional fault planes. c) Extensional faults restored to pre-folding orientation by rotation about strike. d) Thrusts. e) Slickenside striae on thrust planes.

The extensional faults are not simply accommodation structures developed during folding because:

(i) They occur in fold limbs as well as hinges.
(ii) They strike anticlockwise of the main phase fold axial traces.
(iii) They occur earlier than or in association with pre-folding contractional faults.

Pre-folding thrusts

Northcott Mouth Thrust (SS 201085)

The Northcott Mouth Thrust is exposed on a 3m high and about 10m long ridge on the wave cut platform south of the beach at Northcott Mouth. The thrust can be studied during low tide. It occurs in a south dipping fold limb where it has developed a 2m long duplex (Fig. 6). The sense of transport on this duplex is southwards. The associated thrust is south dipping and cuts up section in the same direction, the ramp is well exposed where it cuts through a thick sandstone at a steep angle to bedding and the duplex is developed immediately on top of the sandstone.

As the sense of displacement on the duplex is inconsistent with the flexural slip duplex mechanism (Tanner 1989), this exposure provides critical evidence for pre-folding thrusting of the Bude Formation.

Sandy Mouth Thrust (SS 201 100)

The Sandy Mouth Thrust is exposed in the south dipping limb of an anticline which occurs in the cliff section immediately to the north of Sandy Mouth beach entrance. It has a planar profile

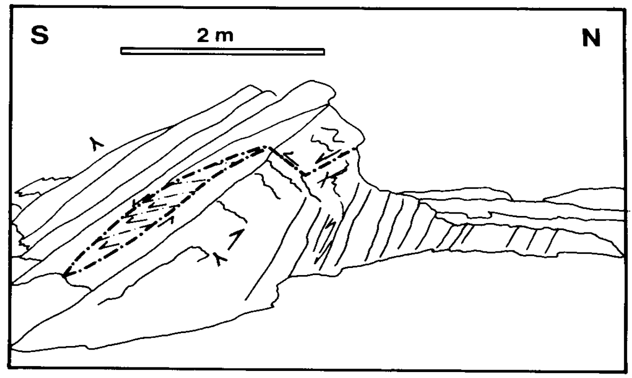

Figure 6. Thrust and small duplex south of Northcott Mouth. The thrust cuts upsection transporting to the south on a south-dipping fold limb and is consequently a pre-folding contractional fault. The outcrop is approximately 3m high.

dipping south at approximately 55° where a spectacular small duplex is developed as the thrust cuts up section across a thin (cm) bedded part of the sequence. To the north on the opposite limb of the anticline it reappears dipping about 75°-80° north (Fig. 7).

The fault can be traced for about 2-3m on both limbs in the cliff. The stratigraphic position of the fault on either limb suggests it can be traced around the anticline and is pre-folding in age. It cuts through Bude Formation rocks below the Sandy Mouth Shale Member on the south dipping limb, and its postulated extension can be picked up above the same shale member on the northern limb.

Bedding on the north limb is overturned and so also dips to the south and the thrust in this limb is downward facing (Lisle 1985) to the north. Displacement on the south limb is about 2m while on the north limb it is reduced to less than lm and the fault becomes bed parallel. This suggests that the thrust tip is only a few metres away. The angle between the fault and bedding varies, on the south limb it is about 5-10° and about 20° on the northern limb. Both the fault and the fold axial plane strike nearly E-W.

Menachurch Point (SS 202 096)

At SS 202 096 there is a small antiformal stack (Fig. 8) which affects three sandstone and four siltstone beds. It has resulted from northwards transport on a thrust system which utilised some of the thinner bedded shale rich lithologies. The horses have been stacked together above an earlier extensional fault system. Below this antiformal stack the extensional faults show two opposite slickenside directions plunging to the NW and SE. These slickensides are formed by thin quartz vein fibres on fault and bedding planes. Later sub-horizontal slickenside striae which plunge WSW are related to ENE transporting thrusts which have utilised the extensional faults as side wall ramps. Similar E-W directed contraction was recognised by Andrews et a[. (1988) and is probably a manifestation of an overall dextral transpressional regime in which these structures were generated.

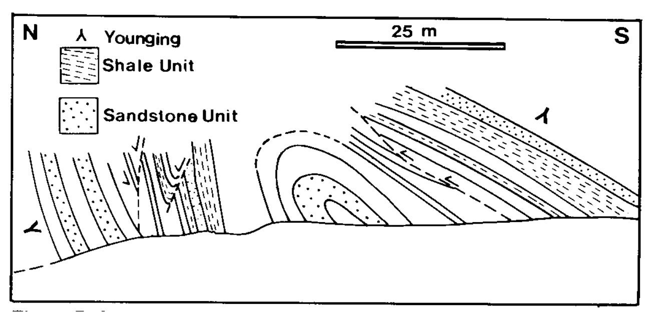

Figure 7. Schematic cross-section showing the folded thrust in the cliff immediately north of Sandy Mouth beach.

Summary

The present-day geometry of the pre-folding contractional faults is shown in Fig. 5d and the slip directions in Fig. 5e. They strike ENE to NE and their conjugate nature is readily apparent on the stereograms.

These thrusts pre-date the folding because:

i) They are folded by the upright chevron folds.
ii) They are associated with duplexes which have the wrong sense of transport for generation by the flexural slip mechanism and are in an unfavorable oriention for postfolding generation.

Dextral Transpression

There is growing documentation of continuing dextral transpression during the closure of the Culm Basin (Ramsay 1990; Jackson 1991). This is supported by an obliquity between the thrusts and extensional faults (Fig. 5) and the strike of the folds (the faults are anticlockwise of the folds).

Bed-parallel dextral slip on the steep limbs of folds is associated with strike-slip duplexing (Woodcock and Fischer 1986) and steeply plunging folds with dextral vergence. This provides clear evidence for post-folding dextral movement (to be described in detail elsewhere).

Discussion

The chevron folding event has been used as a datum in the establishment of a structural chronology. Though only pre-folding structures are documented above they are seen as part of a continuous or semi-continuous deformation sequence (Fig. 2):

Phase la: early extension.

Phase 1b:pre-folding contraction.

Phase lc: further bed-parallel contraction producing chevron folds and associated accommodation structures.

Phase 1d: dextral transpression producing some eastdirected shortening and post-folding bed parallel strikeslip movements.

Phase 1e: post-folding thrusting.

Phase 1 was preceded by syndepositional deformation producing slump folds, water escape structures and several slump beds. During Phase 1, fold amplification overlapped with dextral transpression, the development of strike-slip duplexes and a complex sequence of vein opening (Jackson 1991).

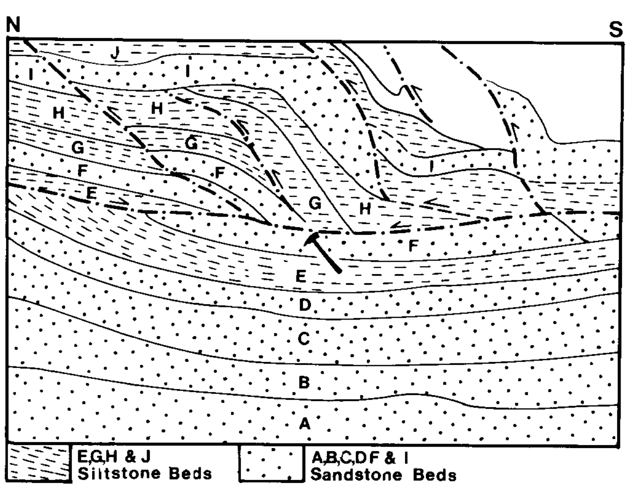

Figure 8. Antiformal stack at Menachurch Point. Most thrusts are northwards transporting with some backthrusting. The system overlies an earlier extensional fault (not seen). The hammer is 470mm long.

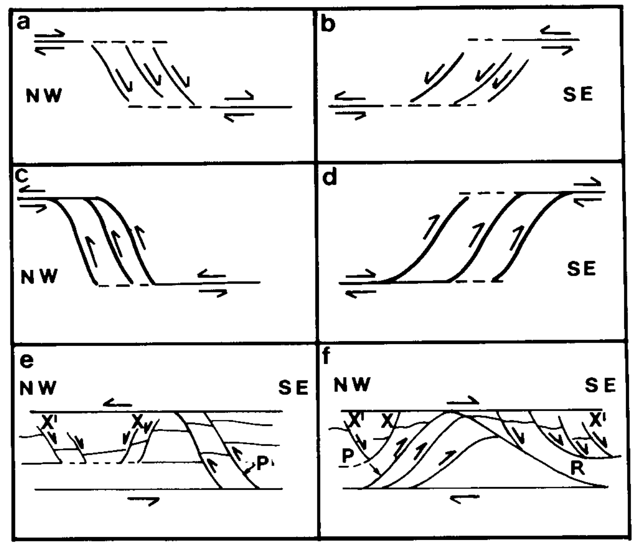

Figure 9. Kinematic model to illustrate the synchronous generation of extensional and contractional faults. a) and b) show SE and NW dipping extensional faults as thrust cuts down section in direction of transport. c) and d) show duplexes developed as thrusts cut up section. e) and f) combine the two sets of structures into one slab. P[1], R, P and X-X[1] are shears (after Swanson 1990).

The structures described by Enfield *et al.* (1986) and Whalley and Lloyd (1986) belong at least in part to Phase 1, and were envisaged by those authors as a continuum into the main tectonic phase. The structures described here are interpreted as clearly separated from syn-sedimentary tectonism. This is because the earliest faults demonstrate a common geometry over a wide area (Fig. 5), and were clearly lithified before deformation. Faults are mainly mineralised with crystalline material, either calcite or quartz or other minerals. The mineralisation of the fault planes is indicative of the ability of the sediments to sustain fluid-filled voids at the time of deformation. There is also no evidence of changes of sedimentary thickness across the extensional faults which might be expected if they were syn-sedimentary. Syntectonic quartz veins suggest deformation was accompanied by high pore fluid pressure, as suggested by Whalley and Lloyd (1986).

Origin of the extensional structures

After restoring bedding to the horizontal (Fig. 5c) early extensional faults form conjugate NE to ENE sets. Both pre-folding contractional and extensional faults have a similar geometry, and in particular the slip directions for both are common (compare Figs 5b and 5e). In addition, apart from two examples, all early extensional faults occur in the footwall of thrust planes. This spatial and geometric relationship suggests a kinematic link. Few examples of synchronous generation of extension of extensional and contraction faults are described in the literature. Two such examples are in the Makran accretionary prism in Pakistan (Platt and Leggett 1986) and in the Moine thrust zone (Coward 1988).

In the Makran accretionary prism extensional faults are confined to the footwalls of thrusts which show evidence for displacement being transferred downward into extension zones. That is to say thrusts cut up or down section in the direction of thrust transport. The removal of material during the extensional faulting phase is probably due in part to "footwall plucking" (Platt and Leggett 1986) where a thrust cuts down section then climbs back to its original stratigraphic level and accretes a lens of material into the hanging wall. Extensional zones consist of displacements on conjugate sets of normal faults below bed-parallel slip surfaces. The direction of thrust transport is parallel to that of displacement on the extensional faults. Furthermore these extensional faults also deform some of the thrusts.

In the Moine Thrust Zone Coward (1988) describes extensional faults which are regarded as synchronous with thrusting. They are both parallel and orthogonal to the thrust transport direction and are thought to form by decoupling on the sole thrust to the Moine Thrust System (Coward 1982*)*.

The extensional structures in the Bude Formation are thought to form by a similar process whereby movement on a thrust plane is transferred up-section or down-section in the direction of transport (Fig. 9). Downward transfer produces extensional faults with slip directions parallel to the direction of transport. The upwards transfer of motion produces contractional duplexes. Similar examples in a strike-slip setting are described by Swanson (1990). Climb of the thrusts back to the dominant slip surface will produce structures analogous to sidewall ripouts (Swanson 1989).

Conclusions

Early extensional faults in the Bude Formation developed in association with the beginning of thrusting by the local transfer of displacement to lower stratigraphic levels. Thrusts transferring to lower levels created extensional relay ramps but probably did not propagate for any great distances at these lower levels. The displacements then propagated onwards at the same stratigraphic level over the extensional zones, in many cases stacking material into duplexes which now overlie conjugate extensional fault systems.

The geometry of the faults and thrusts suggests that they have the same kinematic significance as envisaged by Enfield *et al.* (1985) and Whalley and Lloyd (1986), i.e. they are due to thrusting and backthrusting associated with the closure of the Culm Basin. The differences in interpretation reflect the depth of overburden under which the structures are thought to have developed, i.e. very near to the surface as proposed by the above authors or at a deeper level as envisaged here.

Acknowledgements. R.B.M. Mapeo is supported by a British Council Postgraduate Studentship award. The comments of an anonymous reviewer helped improve the manuscript.

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