A MAJOR SUBMARINE SLIDE IN THE LYNTON FORMATION (LOWER TO MIDDLE DEVONIAN) IN NORTH DEVON

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A major submarine slide is recognised in the Lynton Formation from structural analysis of bedding and cleavage relationships, supported by the sedimentology of the affected sediments. Corrected for tectonic deformation, the fold axis within the slide trends ESE, and the movement direction of the slide was towards the SSW. The trigger may have been seismicity on Early Devonian faults along the Bristol Channel. The Lynton slide sheet is one of the larger examples observed in the geological record.

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INTRODUCTION

Major submarine slides and slumps are a highly significant feature of modern ocean floors where they give rise to tsunami, whose effects may be of far-reaching consequence. Recently two sites have caught the public attention: New Guinea (Tappin, 2001; Tappin *et al.*, 2001) attributed to buildup of sediment at the shelf edge, and off the coast of Madeira (Satake, 2001) where upward growth and oversteepening of the volcanic pile led to collapse into the Atlantic Ocean. Our purpose here is to describe a large feature in the Lower - Middle Devonian Lynton Formation (Figures 1-3), exposed along the cliffs to the east of Lynmouth, North Devon (NGR SS 73 49), which is interpreted as a synsedimentary slide of considerable magnitude.

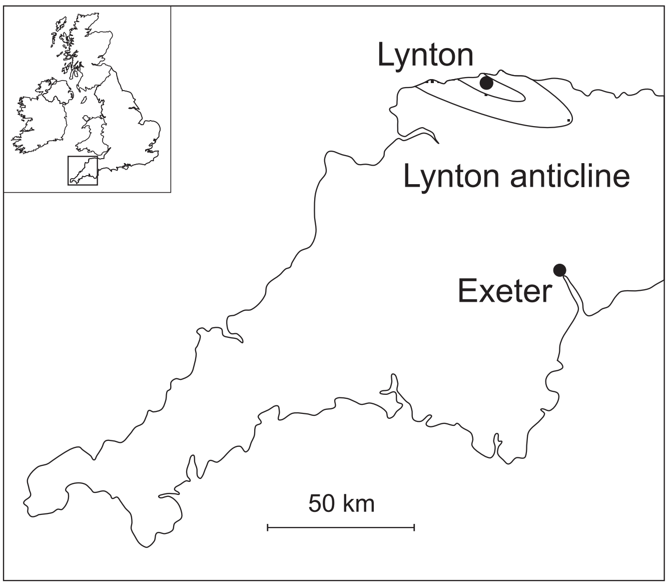

Figure 1. *General location map and position of the Lynton Anticline.*

GEOLOGICAL SETTING

The Lynton Formation is a thick (300-400 m) siliciclastic unit of mudrocks, siltstones and fine-grained sandstones (Edmonds *et al.*, 1985; Pound, 1996). It is the oldest unit of the Devonian exposed in North Devon, and represents the deposition of sand and muds of Late Emsian - Early Eifelian age into an offshore depositional environment, that was mostly muddy, but at times sandy. The Lynton Formation passes upwards by gradation into the dominantly non-marine, sandy Hangman Sandstone Formation. The Lynton Formation forms a complex anticlinal structure (Figure 2), referred to as the Lynton Anticline (Whittaker, in Whittaker and Edmonds, 1981). The base of the formation is not exposed and is moderately faulted, and only in recent years has the stratigraphy been elucidated with any degree of certainty (Pound, 1996). There is a well developed slaty pressure solution cleavage, and the structure interpreted as syn-depositional has been identified in respect of its independence of this cleavage.

STRUCTUAL SETTING

Detailed mapping, carried out by us jointly, of the coastal section east of Lynmouth (Figures 2, 3) between Lynmouth and Ninney Well (NGR SS 733 496) exposes some of the lowest horizons of the Lynton Formation, and has revealed the presence of a major pre-depositional fold. It lies within the northern (steep to overturned) limb of the Lynton or North Devon Anticline. The crestal area of the fold is associated with a major reverse fault, the Lynmouth - East Lyn Fault, dipping southwards at about 45° (Whittaker and Edmonds, 1981). The local development of extensive soft sediment deformation features in the rocks exposed between Lynmouth and Ninney Well, and the fact that the fold predates the first phase of Variscan deformation, suggests that the fold should be interpreted as a large-scale synsedimentary fold. Our structural interpretation is compatible with Miliorizos *et al.* (2004), which shows the Lynmouth-East Lyn Fault (or Lynton Fault) as a reverse fault displacing the major Lynton Anticline (or North Devon Anticline).

Figure 3 shows a structural map of the foreshore and cliffs east of Lynmouth, and a true-scale cross-section through the foreshore and cliffs. The location of the map and sections described are shown in Figure 2. In the cliffs on the western half of the map the bedding dips steeply northwards and youngs northwards, whilst near the base of the cliff the bedding becomes flat lying (NGR SS 7292 4962). On the eastern half of the map, high in the cliffs, the beds dip vertically to steeply northwards, but young southwards high in the cliffs, becoming flat lying near the base of the cliffs (Figure 4A). Further eastwards, the southerly younging beds low in the cliffs dip southwards. In a small cave (NGR SS 7317 4960) the southerly dipping beds pass around a fold hinge and become northerly dipping. This well-exposed fold axis trends 098°-278° with virtually no plunge.

It is clear that a major synform is present in the cliffs east of Lynmouth which has an east-west trending axis as shown on the map and profile through the structure (Figure 3). An equal-area projection of the bedding (Figure 5) demonstrates that the synform has a slight plunge towards 098° and has a maximum interlimb angle of 97°. Way-up evidence in the form of trochoidal wave-ripples, cross-bedding and graded rhythmites indicate that both limbs are the right way up. The northerly limb dips and youngs southwards, whilst the southerly limb dips and youngs northwards. Thus the synform is a syncline.

Cutting across and transecting the syncline, and apparently unrelated to it, is a well developed slaty pressure solution cleavage which typically dips at 25° to 35° southwards (Figure 3), regardless of the two limbs of the synform (Figure 6c inset). This is the only tectonic/metamorphic foliation in these rocks and is clearly unrelated to the main syncline, as shown in Figures 3 and 6c. Any axial planar foliation associated with the major syncline would dip steeply northwards, but in fact none is developed. A well-developed pressure solution cleavage is

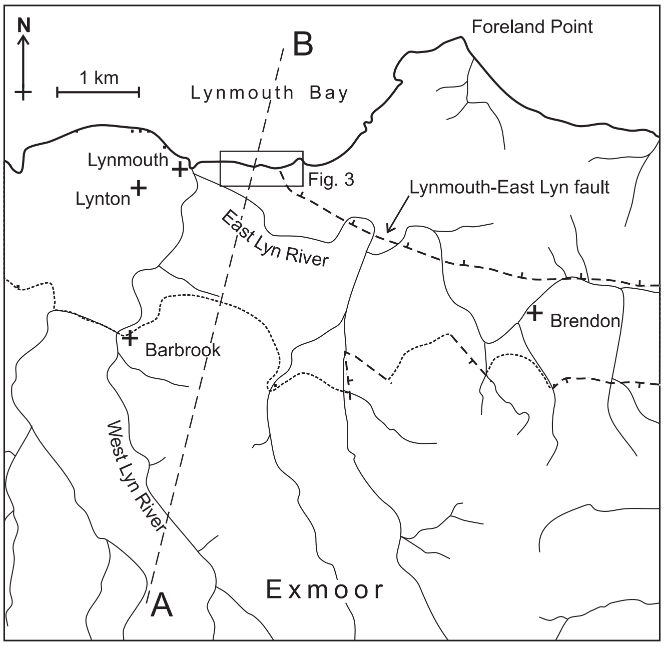

Figure 2. Location and geology of the Lynton area, showing the position of Figure 3 and section A-B shown in Figure 6.

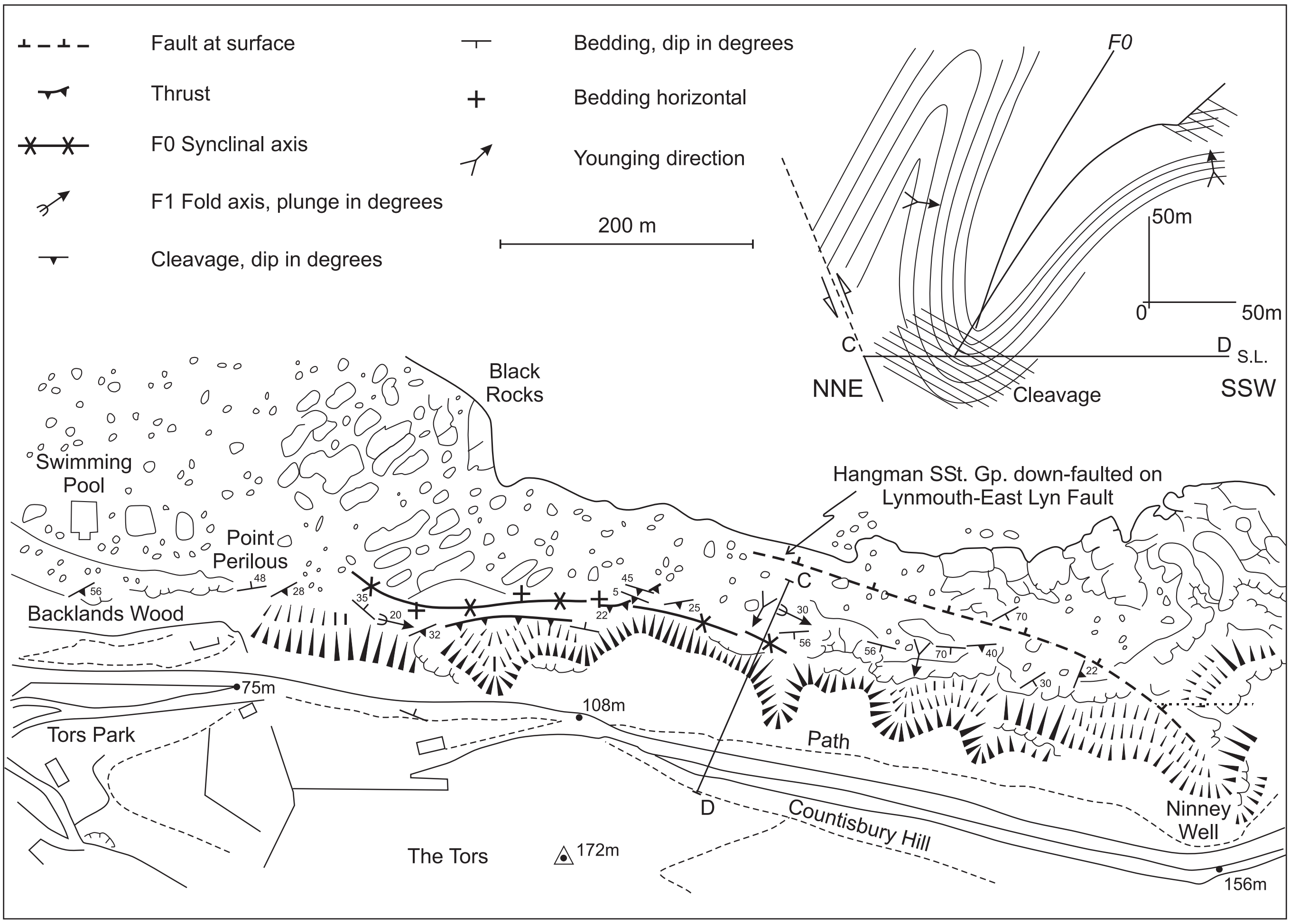

Figure 3. Geological structure east of Lynmouth, and diagrammatic cross-section through the cliffs east of Lynmouth. Position of section is marked on Figure 2. Bedding on cross-section shown by thick solid (actual) and dashed (interpreted) lines; cleavage by thin lines. The steep northern limb has been interpreted to turn back into an anticline so that the whole structure verges and faces to the SSW.

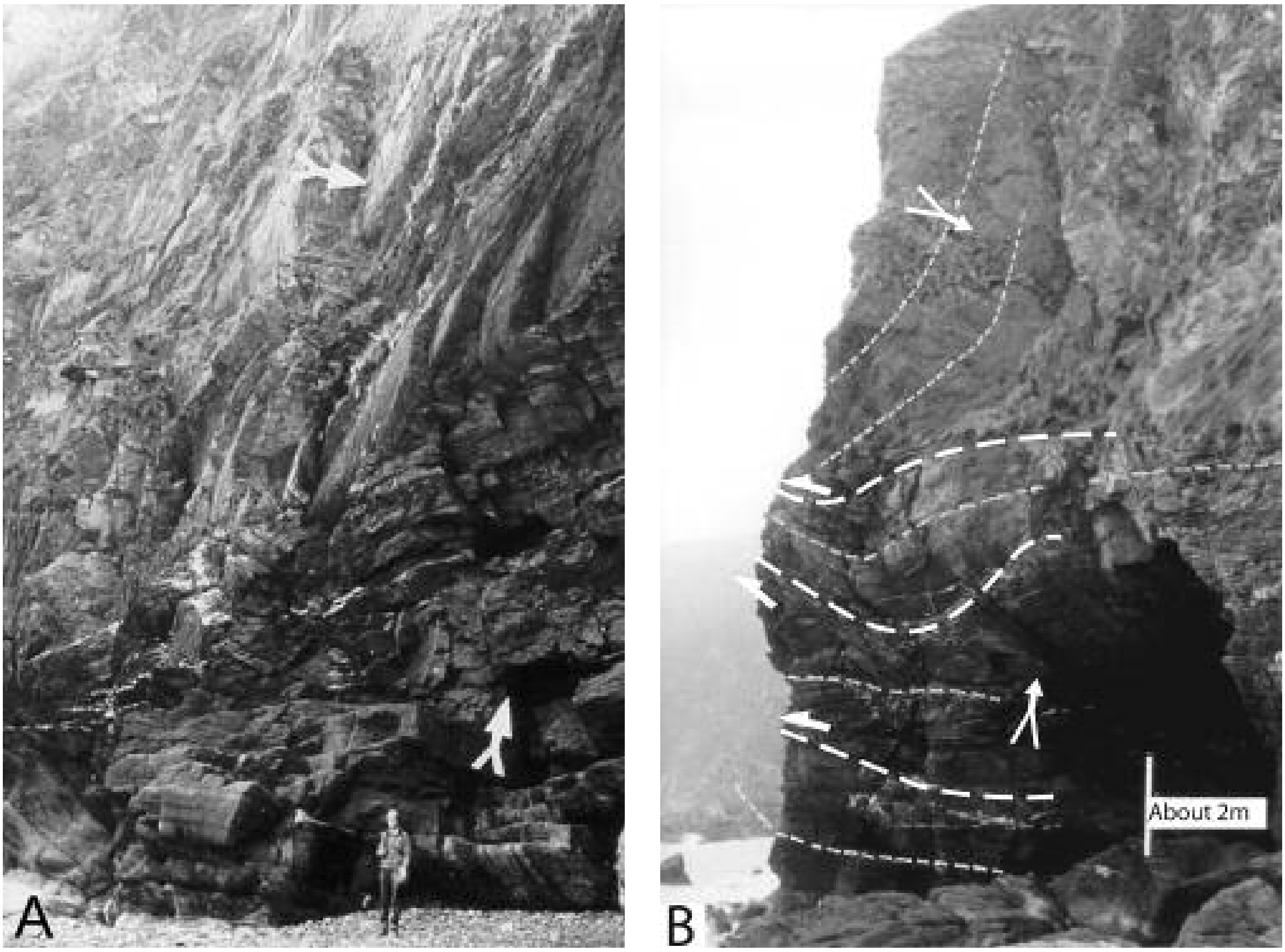

Figure 4. *Field photographs of the Lynmouth area. A. Cliffs east of Lynmouth (NGR SS 7310 4962), viewed eastwards showing the northern limb of the F_0 syncline. High in the cliffs the beds dip steeply northwards but young southwards (forked arrows) and are inverted. Towards the base of the cliffs they become flat-lying as they turn through the clearly visible syn-sedimentary F_0 axial surface to become the right way up. B. View eastwards (NGR SS 7311 4962) of beds dipping steeply northwards high in the cliffs (younging to the south), becoming flat-lying at the base of the cliffs. Three thrusts are arrowed (showing sense of movement). The upper thrust cuts through a small fold and is interpreted as a fold-thrust structure. The lower thrust is only minor in extent. (Thin lines indicate bedding. Thick lines and half arrows indicate thrusts. Forked arrows indicate younging direction). C. Gully (NGR SS 7323 4959) looking due south. The geologists are standing on an F_1 medium-scale fold plunging 30°ESE. A spaced cleavage in the sandstones is axial planar to this tectonic fold which deforms the northern limb of the large-scale F_0 syn-sedimentary fold. The dashed line indicates a bedding trace from which the sense of vergence of this F_1 fold can be determined. The F_1 fold verges to the south (to the right) as determined by the short limb in the centre of the photograph and is downward facing determined by the younging direction indicated by the forked arrow. The fold is plotted on the map of Figure 3 near the C end of the cross section.*

common in North Devon and is associated with small- and medium-scale folds overturned towards the north (e.g. at Combe Martin, Whittaker and Edmonds, 1981). This southerly dipping cleavage is axial planar, although fanning in relation to the main Lynton Anticline (Figure 6b). The major syncline in the cliffs east of Lynmouth is designated F_0 as it is pre-tectonic and probably syn-depositional in origin. The Lynton Anticline and associated small- and medium-scale folds with an axial planar cleavage are designated F_1 (Figure 4C).

Figure 6C (inset) shows the relationship of the cleavage and F_1 tectonic folds with the F_0 syncline. On the northern limb, the bedding is steeper than the cleavage, yet it is not inverted. The minor F_1 tectonic folds verge south and are downward facing (sensu Bell, 1982). On the southern limb, the cleavage and bedding dip at about the same angle, but in opposite directions. The minor F_1 tectonic folds still verge south, but are upward facing. Thus, the minor fold vergence and cleavage does not change across the F_0 fold axis, but the facing direction does not change. Notice that minor F_1 folds are only occasionally developed along the Lynmouth section (two are recorded on the map (Figure 3), one from each limb of the F_0 syncline). However, even if they were absent the same conclusions regarding vergence and facing could be made based on the cleavage/bedding relationships and way-up criteria (Bell, 1982).

The F_0 syncline is thus believed to be of syn-sedimentary origin. The cleavage and F_1 minor tectonic folds were produced later, on the steep northern limb of the Lynton Anticline, during the primary Variscan deformation in North Devon (Edmonds *et al.*, 1985). Prior to overturning in the north limb of the Lynton Anticline the F_0 syncline would have had a low-lying axial plane and would have verged and faced towards the south. To determine the vergence of the F_0 fold absolutely one would have to assess the relative limb lengths, and this is not possible due to the limited outcrop in a north-south direction. However, if the F_0 fold did not verge south, major inversion of the strata on a much larger scale would be implied, and this seems unlikely. It is suggested that the syncline must have had a corresponding anticline to the north of it, and it appears that this has been faulted out by the Lynmouth - East Lyn fault (Figure 3).

In addition to folding, the sequence east of Lynmouth is also disrupted by thrusting (see Figure 3). The most extensive thrust may be traced horizontally westwards from grid reference NGR SS 7294 4960 to 7305 4961 (marked on Figure 3) and creates a major step-like feature in the cliff face. Several small thrusts are shown in Figure 4B (NGR SS 7311 4962) and with associated folding complicates the relationship between the overturned steep limb and the flat axial region of the F_0 syncline. At grid reference NGR SS 7308 4962 a gently westerly dipping bedding-parallel thrust surface can be seen at beach level and has a well-developed thrust plane slickenside indicating a north-south sense of displacement, which is plotted on the stereogram in Figure 5. In summary, the thrusts developed in the sequence east of Lynmouth represent north-south shortening interpreted to have developed during the primary Variscan deformation of North Devon.

Origin of the F_0 syncline

Apart from the pre-tectonic nature of the F_0 syncline, a further line of evidence suggests a syn-depositional origin for the fold. The sedimentary sequence cropping out in the cliffs east of Lynmouth differs from Lynton Formation sedimentary rocks present elsewhere, with the exception of beds of the same age at Yellow Stone (NGR SS 7062 4497), in that it contains 'disturbed' sediments displaying evidence of lateral flowage, and in some cases where heterolithic lithologies are developed, loading. Discrete décollement surfaces are only rarely recognised. The tops of many of the units that have been disturbed are truncated by penecontemporaneous erosion surfaces, overlain by regularly bedded sediments. In some outcrops, multiple layers of erosionally-truncated disturbed units can be recognised.

Thus, a wide range of soft sediment deformation structures in the sequence east of Lynmouth suggests slope instability of the seafloor immediately adjacent to the Lynmouth - East Lyn Fault, suggesting that the F_0 syncline is syn-sedimentary in origin and probably represents a response to contractional strain in the leading edge of a major slide unit.

In conformity with the recommendations of Woodcock (1979a), the term slump is reserved for specific types of slide where backward rotation on a more or less horizontal axis parallel to the slope is recognised. No such backward rotation has been recognised within the sequence involved within the F_0 syncline. For this reason, the F_0 syncline is assigned to the broader category 'slide unit'. Initial triggering of sliding may have been related to a number of factors including seismic shocks, a build up of pore-fluid pressure, oversteepening of slopes, or cyclic loading by oscillating currents associated with a tsunami.

Any of the above processes may have been aided by bioturbation leading to slope destabilisation. A seismic shock

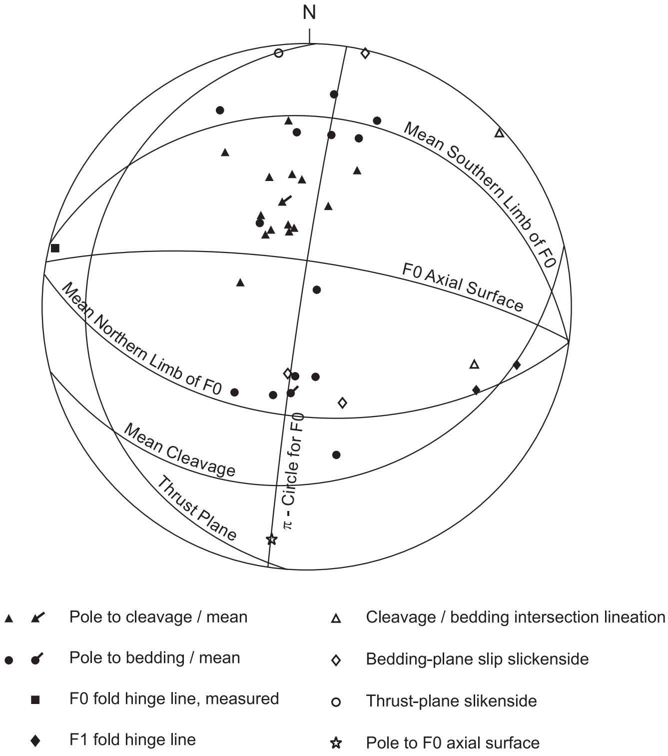

Figure 5. *Stereogram of eastern Lynmouth beach structural section.*

is shown as the trigger in Figure 6a. The conjectured evolution of the sedimentary sequence in North Exmoor is also shown in Figure 6.

Palaeoslope

The movement direction of the slide sheet is assumed to have been perpendicular to the mean axis of the slide sheet folding (F_0) (cf. Woodcock, 1979b). Thus, it is necessary to find the original orientation of the F_0 slide sheet fold. Its present orientation and direction as measured directly or as determined from poles to bedding (Figure 5) is a few degrees towards 098° i.e. slightly south of east. The slide sheet fold is now in a near vertical plane on the northern limb of the Lynton Anticline. If these beds are unfolded, it is clear that the slide sheet slid in a direction approximately towards the south or south-west.

The accurate determination of the original orientation of the F_0 fold was found by removing the plunge of the regional fold axis (F_1) and then rotating the steep limb back to horizontal. The regional fold axis (F_1) of the Lynton Anticline plunges approximately 22° towards the ESE as determined from a stereographic projection of bedding in the north Exmoor region. This ESE plunge is corroborated by the outcrop pattern and by the intersection of the cleavage and bedding east of Lynmouth. When the regional (F_1) fold axis is unplunged and the gross bedding east of Lynmouth is rotated about the F_1 axis back to horizontal, it is apparent that the F_0 axis plunges a few degrees towards the ESE. Thus the F_0 fold was formed during the translation of a slide sheet down a SSW dipping palaeoslope.

If faulting controlled the slope which collapsed to give the F_0 slide unit, then this is unlikely to have been the Lynmouth-East Lyn Fault as this cuts right through the slide sheet. It is more likely to have been one of the related sub-parallel faults developed further north in the present Bristol Channel. Early Devonian movements on these faults is now well established (Whittaker, 1978; Tunbridge, 1986; Miliorizos *et al.*, 2004).

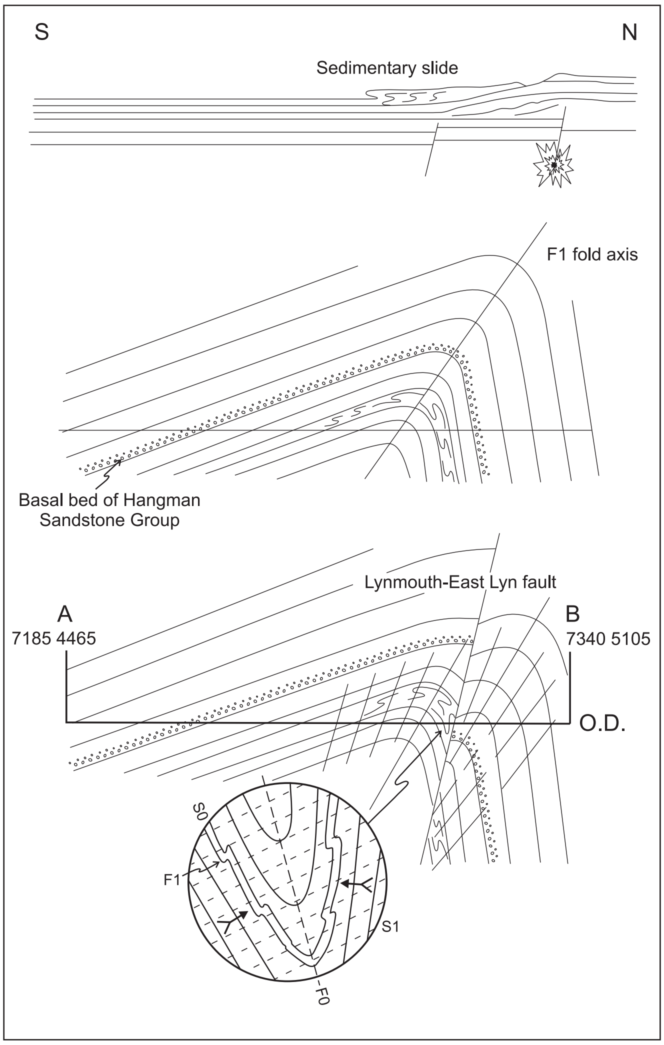

Figure 6. *Structure of the Lynmouth - East Lyn fault. A. Generation of the F_0 syncline in the compressional leading edge of a sedimentary slide unit. The rotational slump scar to the north in the extensional trailing edge of the slide sheet is conjectural. A seismic shock on a fault lying in the present Bristol Channel to the north is shown as the trigger for slide movement. A tsunami, build up in pore fluid pressure or oversteepening of slopes could all equally well have triggered the slide. B. Formation of F_1 major overturned fold during the primary Variscan deformation of North Devon. Note the fanning cleavage associated with the northward inclined Lynton/North Devon Anticline. C. Section along line A-B, Figure 2. Reverse movement on the Lynmouth - East Lyn Fault resulting in the cutting out of the complimentary anticline to the F_0 syncline. Simple trigonometric calculations indicate a movement in the order of 1600 m on the Lynmouth - East Lyn fault, compared to the 2000 m proposed by Whittaker (in Whittaker and Edmonds, 1981). Inset: the F_0 syncline shows the relationship of the cleavage and the F_1 tectonic folds within the F_0 syncline - see text for discussion. Note the fanning cleavage (shown schematically).*

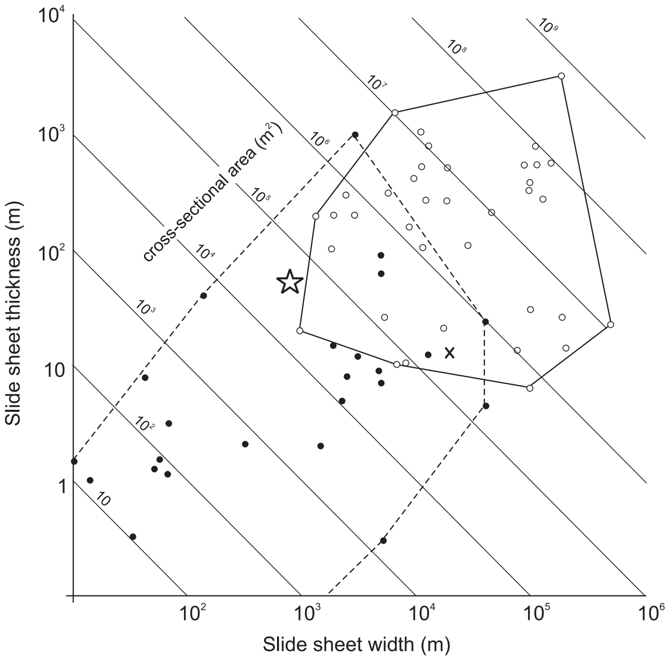

Figure 7. *Plot showing the dimensions of slide units in the geological record (solid circles) and from present day continental margins (open circles) (after Woodcock, 1979a). The F_0 slide is shown by the star.*

Discussion

Woodcock (1979a, p. 137) observed that "...the submarine slides now commonly revealed by seismic reflection profiling on present-day continental margins are, on average, several orders of magnitude larger than the slumps and slides inferred from the on-land ancient geological record". Woodcock (1979a) showed this diagrammatically by plotting slide sheet thickness against slide sheet width (Figure 7). This discrepancy was attributed to the fact that small-scale slides on present-day continental margins cannot by imaged by seismic reflection, and ancient examples of large slide units are being misinterpreted and attributed to some other tectonic mechanism. Typical dimensions of slides, slumps etc were included in Galloway (1998, table 1).

When the Lynton Formation slide unit is plotted on Woodcock's (1979a) graph (shown modified in Figure 7) it is clear that the unit plots near the overlap in fields of modern continental margin slides and ancient slides. Furthermore, the Lynton Formation plot is based on the minimum size of the slide due to the limited exposure. The five solid circles in Figure 7, representing ancient slides of greater dimensions are from Tertiary sites and described by Gregory (1969), Rupke (1976) and Mikulenko (1967). The solid circle at 'x' represents a slide described by Newell *et al.* (1953) from the Permian of North America. The major slumps investigated from modern settings (Pickering *et al.*, 1995; Galloway, 1998) are typically from deep-water (turbiditic), slope-edge or base of slope settings. However, the slide unit described here appears to have been formed in association with sediments deposited in a shelfal setting. This raises problems for such a large slide. At present there is no evidence for an adjacent break in slope. The nature of the pre-Lynton (Lower Devonian) sedimentary rocks is unknown. The nature of the underlying reflector 'x' (Miliorizos *et al.*, 2004, fig. 7) has been much discussed: whether tectonic, or purely sedimentary, and due to coarser-grained, delta front sediments.

In conclusion, the Lynton Formation slide sheet is one of the larger of such sheets recognised in the geological record. On-land exposures seldom allow the full dimension of a large slide to be proved, and it is the coastal outcrop and steep and high cliff that have helped in the recognition of this geologically old slide, although in a tectonically complex situation.

Acknowledgements

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