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Eye and sheath folds in turbidite convolute lamination: Aberystwyth Grits Group, Wales

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ABSTRACT

Eye and sheath folds are described from the turbidites of the Aberystwyth Group, in the Silurian of west Wales. They have been studied at outcrop and on high resolution optical scans of cut surfaces. The folds are not tectonic in origin. They occur as part of the convolute-laminated interval of each sand-mud turbidite bed. The thickness of this interval is most commonly between 20 and 100 mm. Lamination patterns confirm previous interpretations that convolute lamination nucleated on ripples and grew during continued sedimentation of the bed. The folds amplified vertically and were sheared horizontally by continuing turbidity flow, but only to average values of about $\gamma = 1$. The strongly curvilinear fold hinges are due not to high shear strains, but to nucleation on sinuous or linguoid ripples. The Aberystwyth Group structures provide a warning that not all eye folds in sedimentary or metasedimentary rocks should be interpreted as sections through high shear strain sheath folds.

1. Introduction

Sheath folds, those in which hinge lines curve more than 90° within their axial planes (Ramsay and Huber, 1987), have been described from a wide range of tectonic environments, such as mid-crustal shear zones, slump sheets, sub-glacial sediment, salt diapirs and ignimbrites (Alsop et al., 2007). Since the experimental work of Cobbold and Quinquis (1980), sheath folds have mostly been interpreted as the product of high shear strain. Such non-coaxial deformation amplifies the curvature of hinge lines initiated early in the deformation history by rotating fold segments that are oblique to the shear direction. Two-dimensional sections through sheath folds show closed loops called eye folds, the detailed geometry of which can be used to discriminate between simple-shear and general-shear strain regimes (Alsop and Holdsworth, 2006).

In this paper, eye folds and sheath folds are reported from a distinct deformational environment: convolute lamination within turbidite beds. The 2D and as far as possible, 3D geometries of convolute lamination are documented from the Aberystwyth Grits Group of west-central Wales. From this case study, it is deduced that eye folds in convolute lamination are cross sections through sheath folds, but of a type that do not require high shear strains to form. In the Aberystwyth Group, their geometry is probably due instead to nucleation on the already strongly curvilinear crests of sinuous or linguoid ripples in the underlying division of the graded turbidite. These structures flag a warning to the universal interpretation of high shear strain from eye and sheath folds in sedimentary and metasedimentary rocks.

2. Geological context of the Aberystwyth Group convolute lamination

The Aberystwyth Grits Group crops out in west-central Wales, and is particularly well exposed in coastal cliffs over the 45 km from south of New Quay to Borth (Fig. 1). The group is early Silurian (Llandovery) in age and part of a late Ordovician to late Silurian marine sedimentary sequence, the Powys Supergroup, deposited in the Welsh Basin after its volcanic phase during earlier Ordovician time (review by Howells, 2007). During Llandovery time, the Welsh Basin was transtensional, and underlain by upper crustal tilt blocks bounded by major NE-striking normal faults (review by Cherns et al., 2006).

The Aberystwyth Group is a turbidite system thought to have ponded in the downthrown hanging wall of one such fault, the Bronnant Fault (Fig. 1). Terrigenous clastic material was fed into this fault-bounded sub-basin mainly from the southwest, and transported northeastward along its axis by mass flows, predominantly

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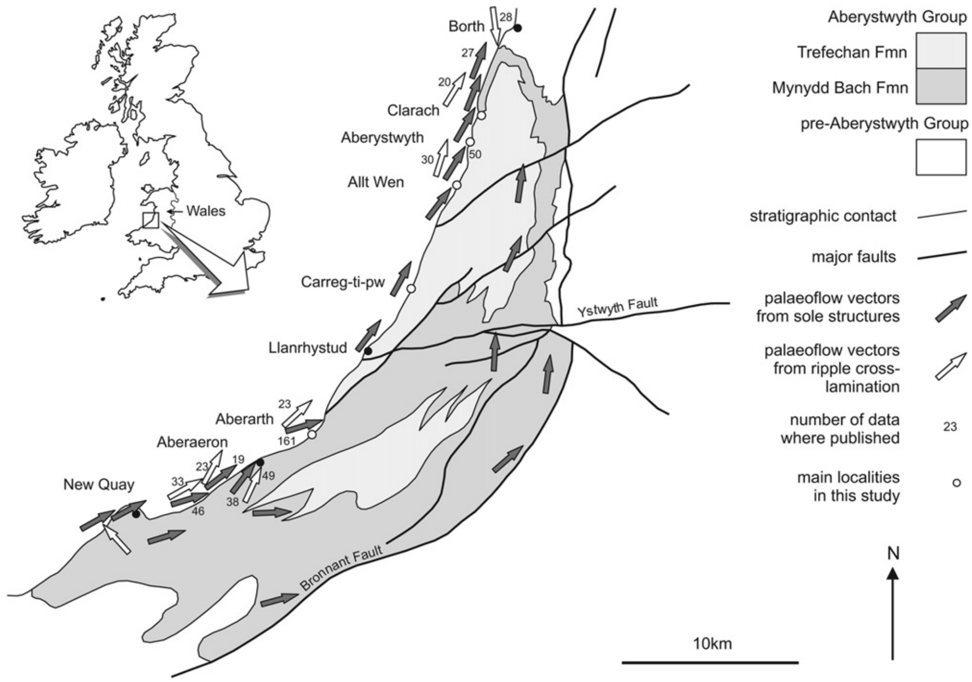

Fig. 1. Geological map of the Aberystwyth Grits Group outcrop in Wales (inset), showing dominant palaeoflow directions and the main localities (open circles) sampled in this study. Map from Davies et al. (1997) and palaeocurrents from Wood and Smith (1958), plus Borth cross-lamination data from McCann and Pickering (1989) and New Quay cross-lamination from Anketell and Lovell (1976).

turbidity currents (Davies et al., 1997). The average grain size and bed thickness in the system decrease both northeastward down the sub-basin and stratigraphically upwards, from the coarser Mynydd Bach Formation to the finer Trefechan Formation (Fig. 1).

The Aberystwyth Group was one of the first examples of ancient turbidites to be recognised (Kuenen, 1953), and the detailed study by Wood and Smith (1958) established the group as a benchmark for turbidite studies. Notable amongst subsequent work is the proximality analysis by Lovell (1970), remapping and revision of Aberystwyth Group stratigraphy by the British Geological Survey (Cave and Hains, 1986; Davies et al., 1997) and the interpretation of co-genetic debrites and turbidites by Talling et al. (2004).

Of particular relevance to the present study are palaeocurrent data (Fig. 1), mostly collected by Wood and Smith (1958), then augmented in the coastal sections by Anketell and Lovell (1976), Smith and Anketell (1992) and McCann and Pickering (1989), and inland by Davies et al. (1997). Over most of the outcrop, erosional flutes and grooves and depositional cross-lamination indicate turbidity flow towards the northeast quadrant, more easterly at the proximal end of the system and more northerly at the distal end. At the southern end of the outcrop, southwest of New Quay (Fig. 1), cross-lamination indicates northwesterly flow, transverse to that deduced from the sole structures (Anketell and Lovell, 1976). At the northern end of the outcrop, just south of Borth, cross-lamination indicates southwesterly flow, opposite to that further south (McCann and Pickering, 1989). None of our observations come from these anomalous sections.

Convolute lamination – folding of the lamination within one depositional bed – in the Aberystwyth Grits was reported by Jones (1938) and Challinor (1949), and studied by Rich (1950), even before the structure was named by Kuenen (1953) as 'convolute bedding', and before these rocks were recognised as turbidites. Rich (1950) interpreted the deformation as post-depositional, driven by downslope sliding of a thick package of beds down a basin slope. By contrast, Kuenen (1953) used the evidence of intra-bed truncations of the convolute laminae to prove that folding occurred during the deposition of each bed. He deduced that the folding occurred in fluidised sediment as continuing deposition inhibited water escape. He also documented the close geometric relationship of the convolutions to ripple cross-lamination, with folds tending to overturn down current. He thought that the folds nucleated on the ripples, and then amplified by a combination of lateral current shear and a vertical pressure differential between the crests and troughs of the structure. This perceptive interpretation is close to the one followed in the present paper, except that we suggest that the vertical deformation component was due to buoyancy forces generated within the liquefied sediment, as proposed by Allen (1977).

Here we are primarily concerned with the geometry of convolute lamination. Its detailed mechanism of formation is beyond the scope of the present paper.

3. Scale and setting of convolute-laminated units

A representative lithological log through part of the upper unit of the Aberystwyth Group – the Trefechan Formation – shows a sequence of graded beds ranging in thickness from about 20 to 150 mm (Fig. 2). Most beds grade up gradually from fine sandstone to an interval of interlaminated silt and mud, then pass up rapidly or abruptly into mudstone. Mud or mudstone in these descriptions comprises admixed silt and clay grades. More distal parts of the Trefechan Formation additionally contain thin beds grading from siltstone to mudstone, and contain a high proportion of mudstone overall. The lower unit of the Aberystwyth Group – the Mynydd Bach Formation – additionally contains thick beds, up to 1 m thick, comprising medium to fine sandstone grading up into a thin mudstone top.

Convolute lamination occurs primarily in the interlaminated silt and mud interval, although the underlying fine sand and overlying mud may both be involved in the folds. Convolute lamination is typically absent in very thin sand/siltstone beds (10–30 mm; e.g. beds 2, 5, 7, 8; Fig. 2). It can occur in sand/siltstone beds that are thin (30–100 mm; e.g. beds 3 and 9), medium (100–300 mm; e.g.

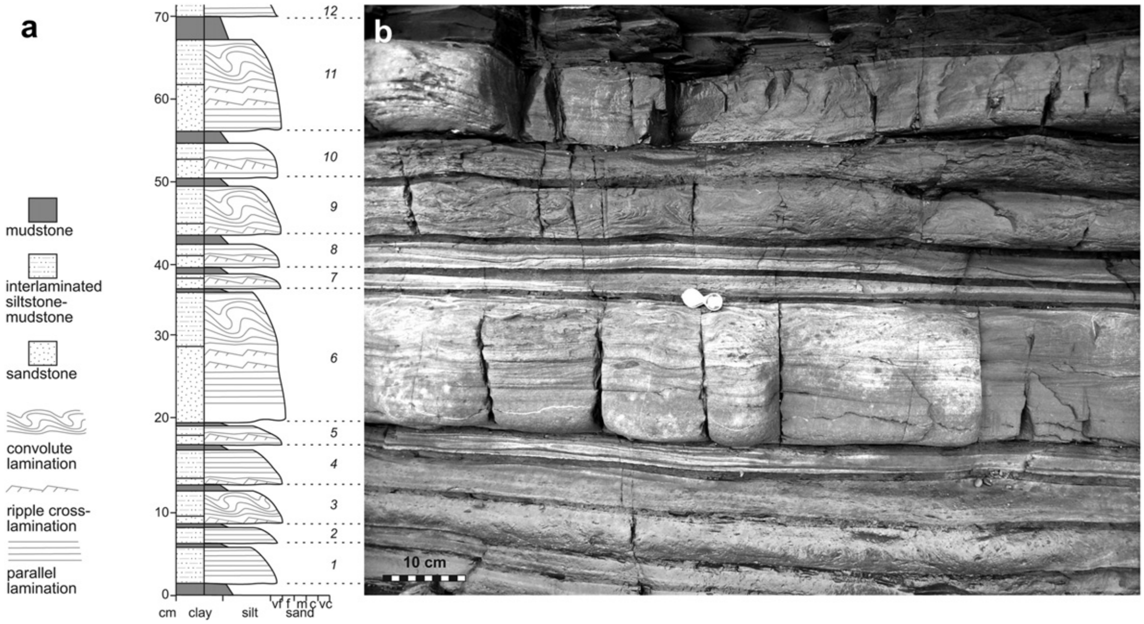

Fig. 2. (a) Lithological log of a representative section of the Trefechan Formation (b) at Allt Wen (SN 576 797), showing four typical beds that host convolute lamination.

beds 6 and 11) or, in other sections, thick-bedded (>300 mm). However, importantly, the thickness of the convoluted interval itself is always between 20 and 150 mm and is typically between 30 and 100 mm (Fig. 3). This small range of convolute interval thickness probably reflects a narrow window of critical rheological conditions in the depositing bed, controlled by a balance of grain size, sediment permeability and sedimentation rate.

The size of convolutions is important as a guide to the scale on which convolute lamination eye and sheath folds might be expected in metasedimentary rocks. Convolute lamination exists on both slightly smaller and larger scales in other turbidite sequences, reflecting a different balance of variables. It also forms in other environments, such as storm-dominated shelves (Collinson et al., 2006). Our conclusions in this paper should only be applied to turbidite convolute lamination, as its mode of formation in other environments may be different.

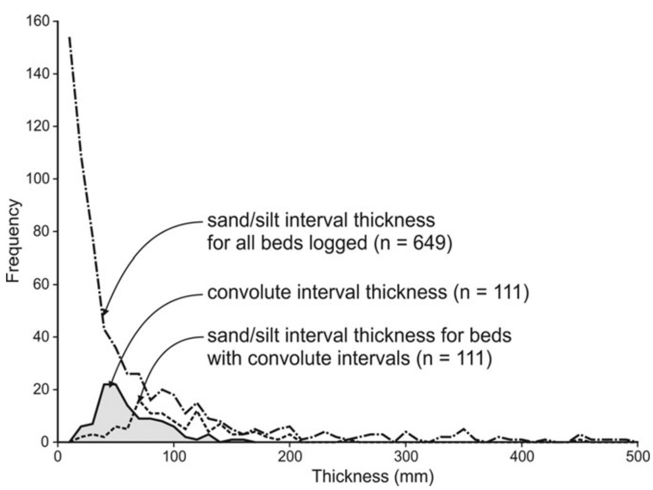

Fig. 3. Thickness frequency plot for a) the sand/silt intervals in all logged beds, b) the sand/silt intervals in beds with convolute lamination, and c) the convolute-laminated intervals themselves. Data come from logged sections at Aberarth, Carreg-ti-pw, Allt Wen, Aberystwyth and Clarach (see Fig. 1 for location).

4. Convolute lamination geometry viewed normal to palaeoflow

Field observations were all referenced to the local palaeoflow direction, using the data of Wood and Smith (1958) verified by direct observations. A typical convolute-laminated bed, viewed normal to the palaeoflow (Fig. 4), shows the following features from base to top:

- a sharp bed base overlain by a ripple cross-laminated fine sand,
- a convoluted unit involving the top of the cross-laminated sand and an overlying lithology of interlaminated silt and mud,
- convolutions amplifying rapidly upwards to a maximum in the centre of the folded interval, then decaying rapidly to flat parallel silt-mud laminae near the bed top,
- double-hinged convolutions weakly overturned down current,
- a rapidly graded or sharp contact with a mud top to the convoluted bed.

The convoluted interval involves only one set of folds, with amplitudes scaled to the thickness of the interval. The antiformal crests tend to be about three quarters of the width of the synformal troughs (Fig. 5a). Folds within one bed are consistently either symmetrical or asymmetrical. Those that are asymmetrical are overturned down-flow by an average of about 40° (Fig. 5b), presumably by current shear during ongoing deposition of the bed. The average shear strain is therefore about tan 40° = 0.84, and lower if compaction effects could be assessed. This value is much lower than the values of 10 or more normally ascribed to sheath folds (e.g. Cobbold and Quinquis, 1980).

Where the crests and troughs of ripple bedforms are visible at the top of the cross-laminated sand, they are typically in phase with the crests and troughs of the overlying convolutions (Fig. 6). Such observations are the basis for Kuenen's (1953) deduction that the convolutions nucleated on the ripple forms, and grew vertically and laterally during sedimentation by some combination of flow pressure and shear.

Field observations have been augmented by cutting, polishing and optically scanning selected sand/siltstone beds (Fig. 7). The

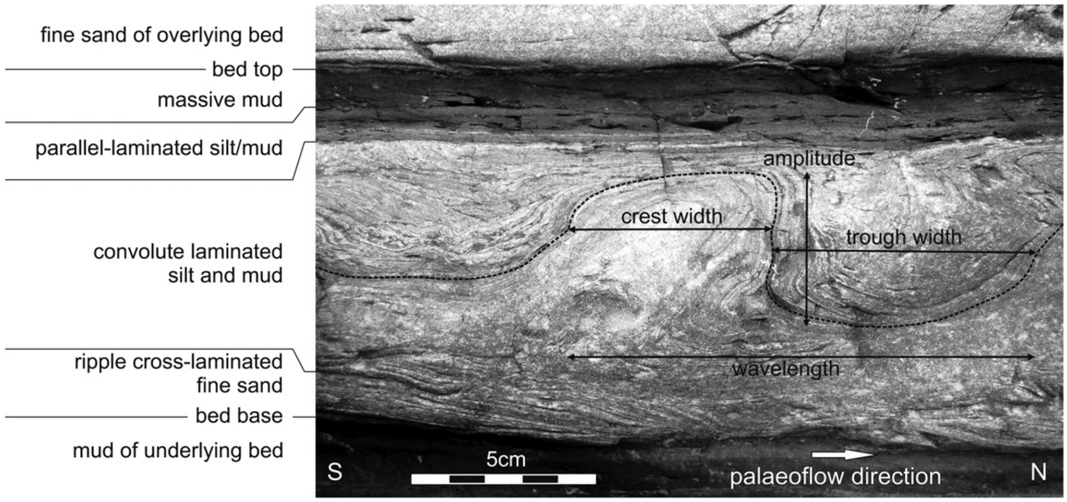

Fig. 4. A typical bed with convolute lamination, viewed perpendicular to the palaeoflow direction. (Allt Wen, SN 576 797).

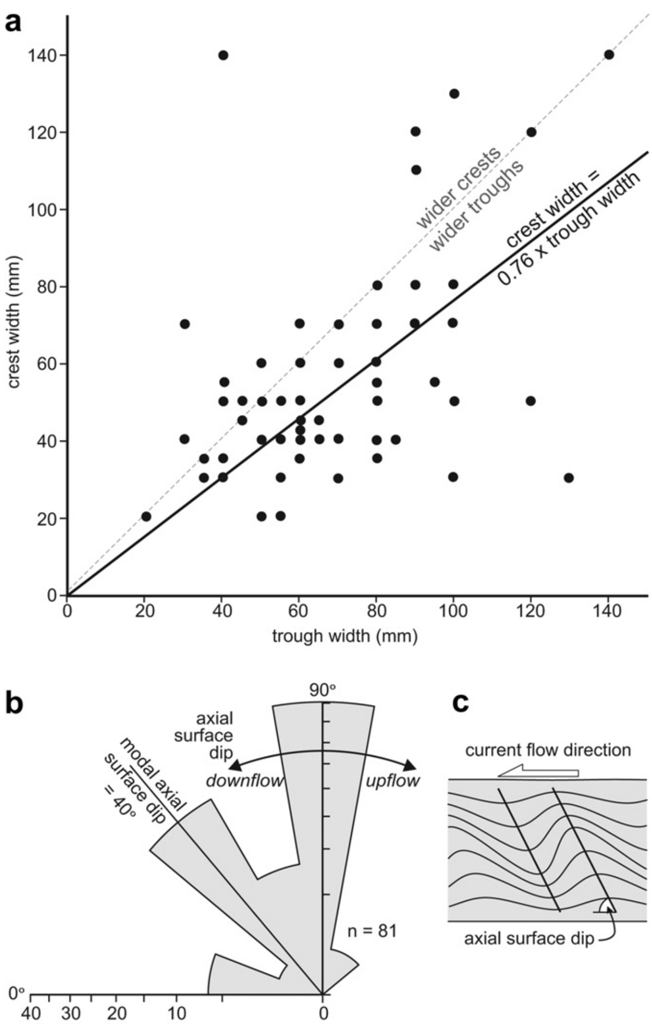

Fig. 5. a) Width of convolution troughs plotted against the width of their crests. Data from Aberarth, Carreg-ti-pw, Aberystwyth and Clarach, but predominantly from Allt Wen. b) The dip, with respect to gross bedding, of the convolution axial planes for 81 structures from the same localities, with sign conventions defined in (c).

geometrical features seen in the field are picked out in detail. In the typical example figured, viewed normal to palaeoflow, two of the anticlines and their three related synclines are overturned down current, as indicated by the basal cross-lamination. However the right-hand anticline is double hinged, one hinge overturned down current and the other up current. The core of this up current facing anticline comprises increasingly upturned cross-laminae suggesting buoyant rise of the sand as envisaged by Allen (1977). Packets of cross-laminations in the lee of the convolutions demonstrate that deposition and deformation were synchronous. Deformation coincided mainly with deposition of interlaminated silt (light) and mud (dark), and waned rapidly as the mud top began to be deposited.

In the context of this paper, the critical observation on convolute lamination viewed normal to current flow is that the laminae do not form closed loop geometries. This contrasts with convolute lamination viewed parallel to palaeoflow.

5. Convolute lamination geometry viewed down palaeoflow

Viewed down-flow, turbidite beds show the same vertical graded structure as when viewed normal to palaeoflow (Fig. 8a, b, c). However, closed loop patterns are sometimes present in the convolute-laminated interval. These form elliptical eye folds, with

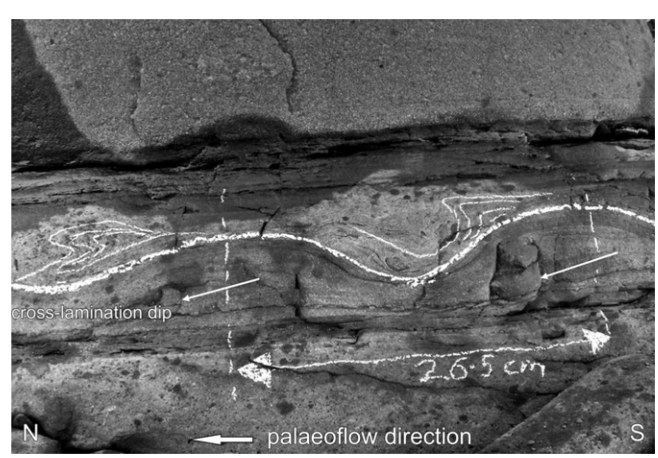

Fig. 6. Convolute lamination nucleated on underlying ripples. (Aberarth, SN 484 644). Ripple form and convolute lamination outlined in chalk.

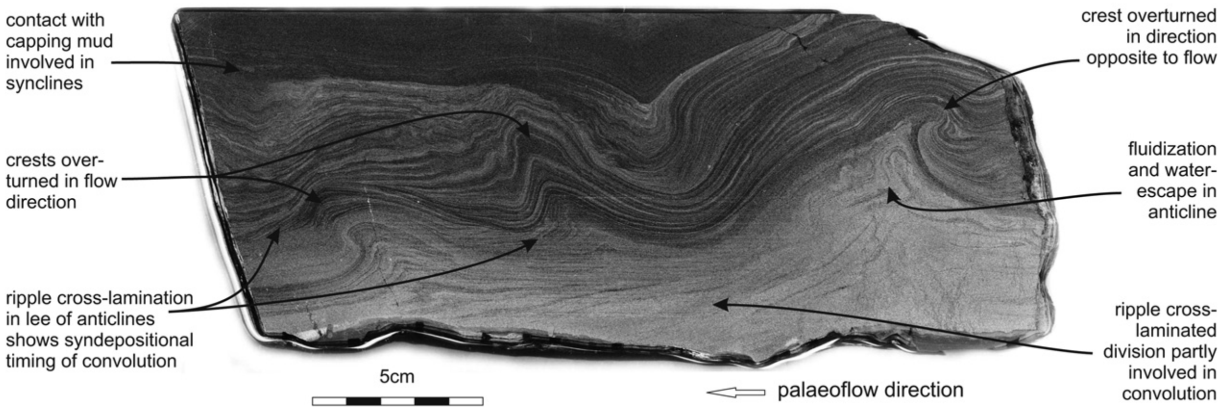

Fig. 7. Optical scan of a polished slab through a graded fine sandstone-mudstone bed cut parallel to local palaeoflow (from Allt Wen (SN 576 797)).

their short axes perpendicular to bedding. The first open laminae rimming the eyes typically have mushroom geometries, the mushroom stalks connecting to gently dipping laminae near the top or bottom of the beds (Fig. 8b). Cut, polished and scanned sections (Fig. 9) reveal more geometrical detail. Where the younging direction of the laminae can deduced by tracing the lamination sequence to the top or bottom of the bed, folds can be either anticlinal, with laminae younging away from the core, or synclinal, with laminae younging into the core. An important observation in down-flow views is that the cross-laminae tend to face in opposing directions in different parts of the bed. This geometry implies that the host ripples are sinuous or linguoid rather than straight-crested. An example of this opposed facing happens to occur in the upper right part of the figured sample (Fig. 9) but, in the field, commonly occurs low in the bed also.

Alsop et al. (2007) used various plots of eye fold parameters to compare sheath folds from a range of different natural environments: metamorphic rocks, salt, slump sheets, glaciotectonic settings, ignimbrites and analogue models. Comparable data from eye folds in this study plot firmly within the data field from eye folds more generally (Fig. 10). There is therefore nothing in the geometry of eye folds from turbidite convolute lamination that would distinguish them from eye folds formed in other environments.

6. Convolute lamination geometry in 3D

The three-dimensional geometry connected with eye folds has been deduced in several ways. One approach has been to cut orthogonal sections through convolute laminae and to construct perspective views into the combined grid of sections. An example of this approach (Fig. 11) shows how an eye fold in one view is associated with a tight fold in the perpendicular view. The combined geometry must locally have the tubular shape of a sheath fold.

A second, lower resolution, approach has been to link exposed plan views through a series of convolute folds to their appearance in cross section (Fig. 12). The plan view pattern is one of domes and basins reflecting undulating or discontinuous crests to the convolutions. Although crest-line culminations lie imperfectly along lines perpendicular to palaeoflow, the geometry is more compatible with nucleation on sinuous or linguoid ripples than straight-crested ripples.

7. Synthesis and interpretation

The geometrical study of the Aberystwyth Group convolute lamination has shown that eye folds are present when the structure is viewed parallel to the turbidite palaeoflow direction. These eye folds have proved to be cross sections through folds with curved hinge lines. Viewed normal to palaeoflow, these folds are mostly moderately overturned down-flow, though a minority overturn up current. The convolution anticlines are seen to nucleate on the crests of underlying ripples, which form the contact between the basal sand, and the overlying interlaminated silt and mud interval. Convolution synclines nucleate on ripple troughs. The three-dimensional form of the ripples is difficult to diagnose. However, opposing cross-lamination directions in down-flow views imply that at least some of the bedforms were sinuous or probably linguoid rather than straight-crested. Plan views of eroded convolutions support the interpretation that convolution crests and troughs (and their associated subjacent ripples) are highly non-cylindrical.

The geometrical parameters of the convolution eye folds show that they have shapes within the same range as eye folds in other deformational environments. Most of the wide range of eye fold examples in the literature (Alsop et al., 2007) are interpreted as cross sections through sheath folds. Sheath folds are, in turn, interpreted as the product of high shear strains amplifying the curvature of originally more rectilinear fold hinges. The eye folds associated with convolute lamination might be regarded as just one more addition to this range of examples, albeit from a novel deformational environment. However, they have a special importance. The evidence strongly suggests that the associated sheath folds are not the product of high shear strains. Instead, the curvilinear hinges of the folds result mainly from nucleation on the strongly curvilinear crests and troughs of sinuous and linguoid ripples.

An idealised view of this formation kinematics is shown in Fig. 13. Convolute anticlines are shown as nucleated on ripple crests with linguoid geometries whilst convolute synclines nucleate in the less well defined ripple troughs. The anticlines and, to a lesser extent, the synclines tend to migrate down-flow through time, as sediment accumulates in the lee sides of the convolutions, only to be further folded. Flow-parallel sections show this down current hinge migration in folds without any closed loop patterns (Fig. 7). However, any cross-flow section will show eye folds as soon as the lee side limb of the convolute folds starts to overturn, potentially at only modest shear strains (Figs. 8 and 9). On this model, anticlinal sheath folds tend to develop from the crest of each linguoid ripple, whereas synclinal sheath folds develop preferentially between the tails of the ripples. Crest-line culminations tend to line up transverse to flow, as seen in the field (Fig. 12).

8. Wider relevance of eye and sheath folds in convolute lamination

Convolute lamination is a very common structure in turbidites (Collinson et al., 2006). Turbidites are the predominant component

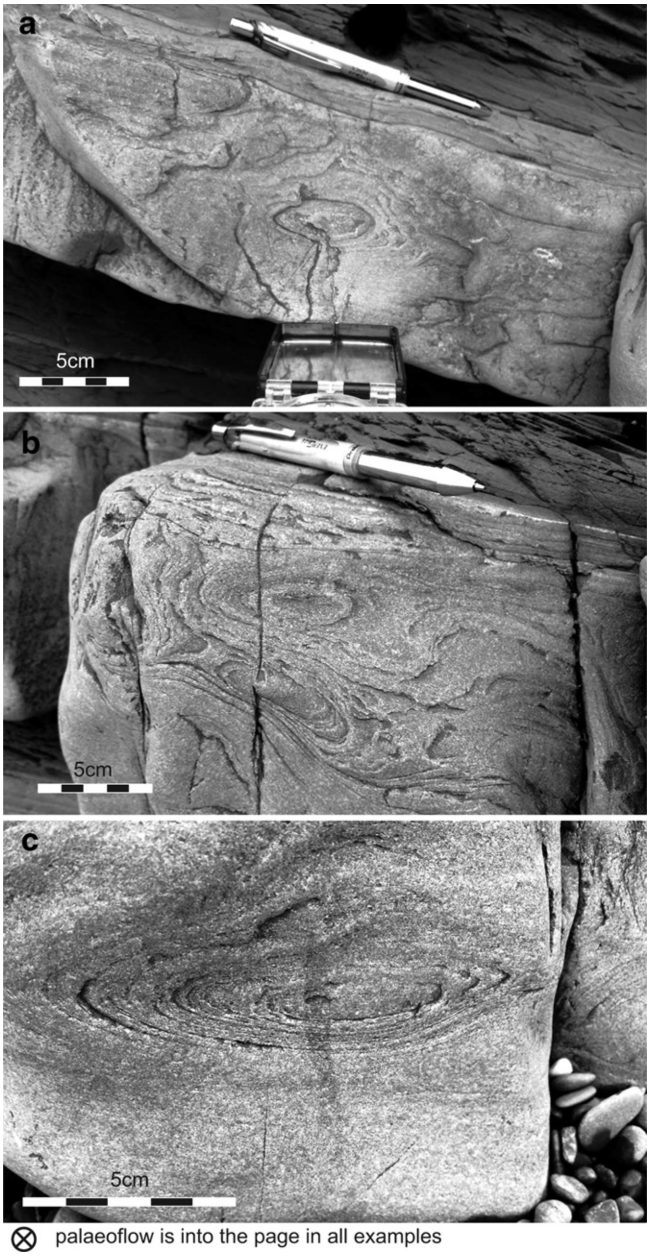

Fig. 8. Field photographs of eye folds from Aberystwyth (SN 583 827) all taken looking down palaeoflow, to the north-northeast.

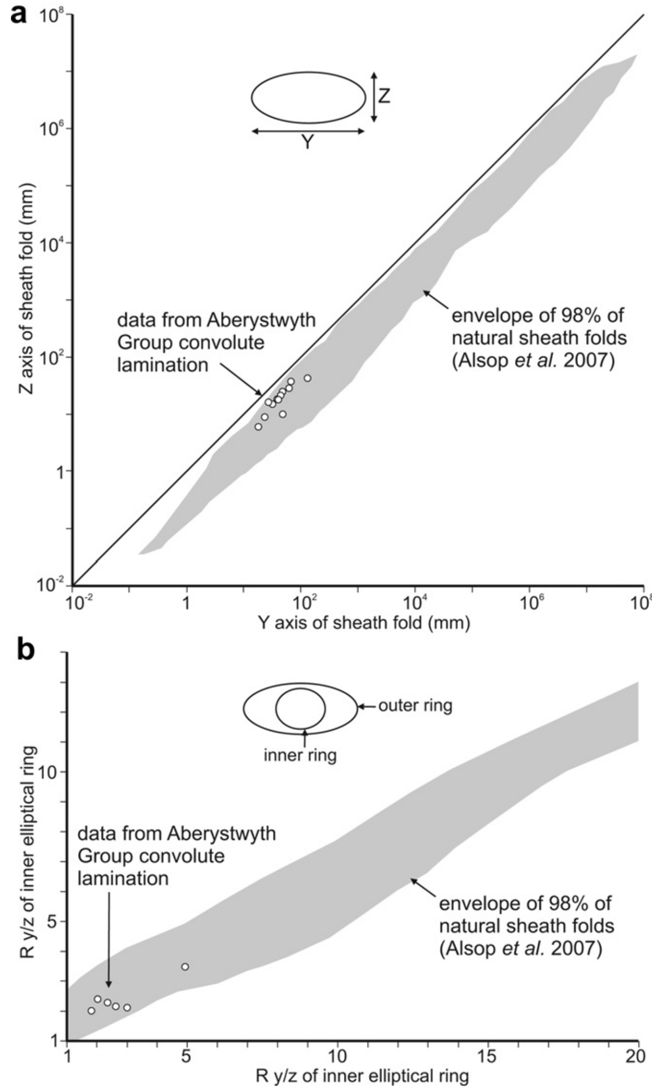

Fig. 10. Positions of Aberystwyth Group convolute lamination eye folds on two plots used by Alsop et al. (2007): a) length of the vertical axis (Z) plotted against the length of the horizontal axis (Y), b) the ratio Y/Z of the outer elliptical ring plotted against the ratio Y/Z of the inner elliptical ring. Toned area shows the scatter of 98% of Alsop et al's data.

of deep-water basinal sequences, which in turn form a significant proportion of the deformed rocks in old orogenic belts. The prevalence of eye and sheath folds in the typical turbidite convolute lamination of the Aberystwyth Grits Group therefore implies that such structures should be common in metasedimentary terranes.

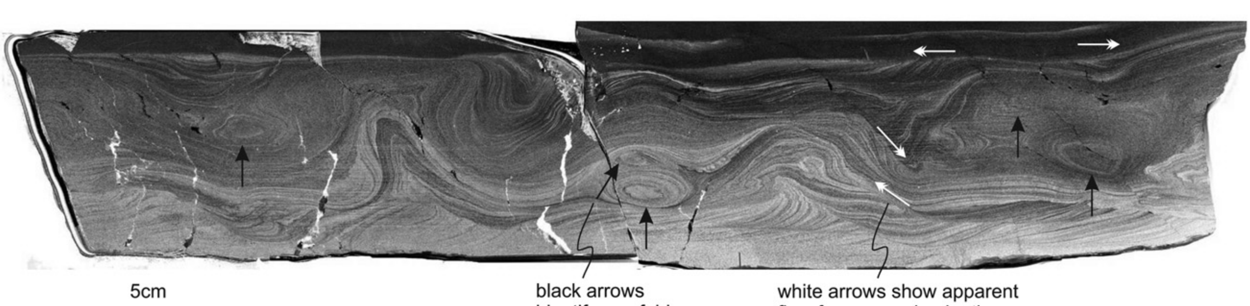

Fig. 9. Optical scan of a polished slab through a graded fine sandstone-mudstone bed cut perpendicular to local palaeoflow (from Allt Wen (SN 576 797)).

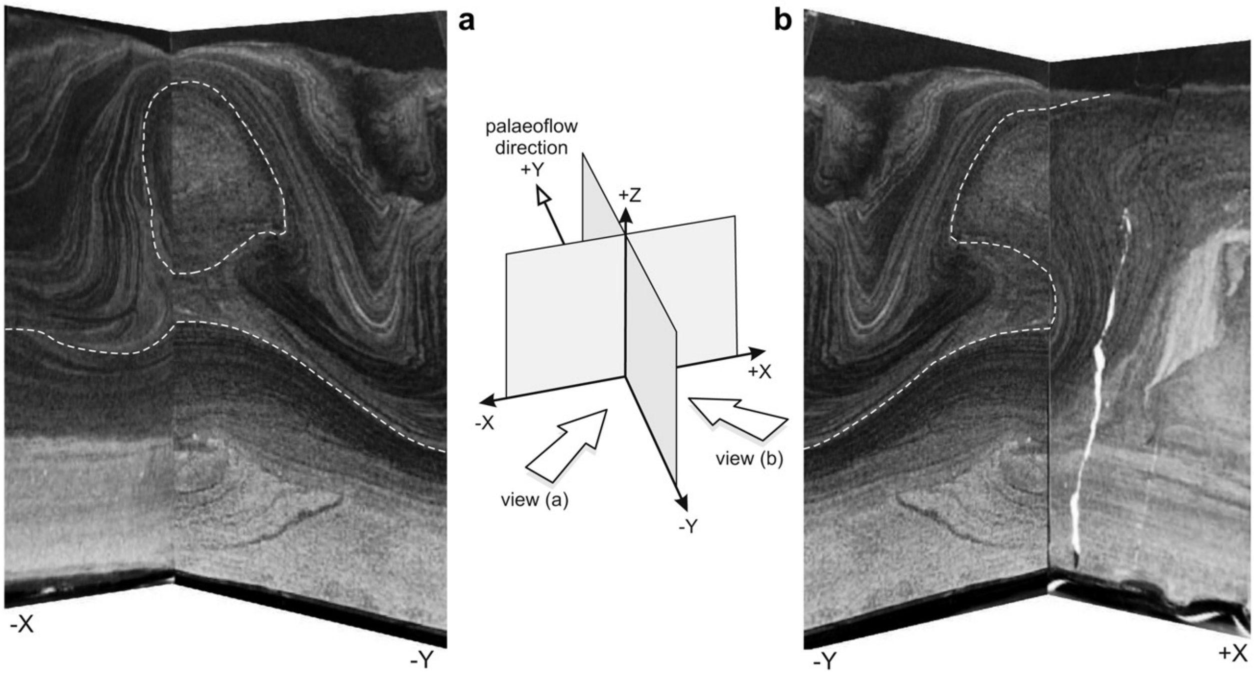

Fig. 11. Oblique views of two orthogonal optical scans through convolute lamination showing a linked eye and sheath fold. The view in a) is roughly normal to that in b). Reference axes are labelled on each view, where +Y is the down-flow direction (from Allt Wen (SN 576 797)).

The risk therefore exists that convolute lamination eye folds might be misinterpreted as the product of high shear strains, when the structures actually record nucleation of convolute lamination on sinuous or linguoid ripples.

In low-grade metamorphic settings, convolute lamination should be easily recognised as such. Indeed, the Aberystwyth Group has itself been folded, weakly cleaved and metamorphosed, if only to anchizone grade (Roberts et al., 1996; Davies et al., 1997) during the Acadian event (Woodcock and Soper, 2006). However, in higher-grade settings the syn-sedimentary origin of convolute lamination is more difficult to diagnose. Care should be exercised in metasediments wherever some or all of the following conditions apply:

- psammites and pelites are interbedded on scales of centimetres to tens of centimetres in laterally continuous units,
- alternating sharp and graded contacts between psammitic and pelitic units suggest original graded beds,
- eye folds are present within the psammites or psammite/pelite transition but not within the pelites,
- eye folds have their longest axis parallel to the psammite/pelite compositional banding,
- eye folds are in the range 20–100 mm in their shortest dimension.

In these circumstances, the possibility should be considered that eye folds do not indicate sheath folds formed by high shear strains. The alignment of sheath folds parallel or perpendicular to tectonic strike may be no confirmation of a tectonic origin. Turbidity currents commonly flow preferentially parallel or normal to basin margins, themselves tectonically controlled. The sheath folds in the Aberystwyth Group have their axes aligned with the palaeoflow,

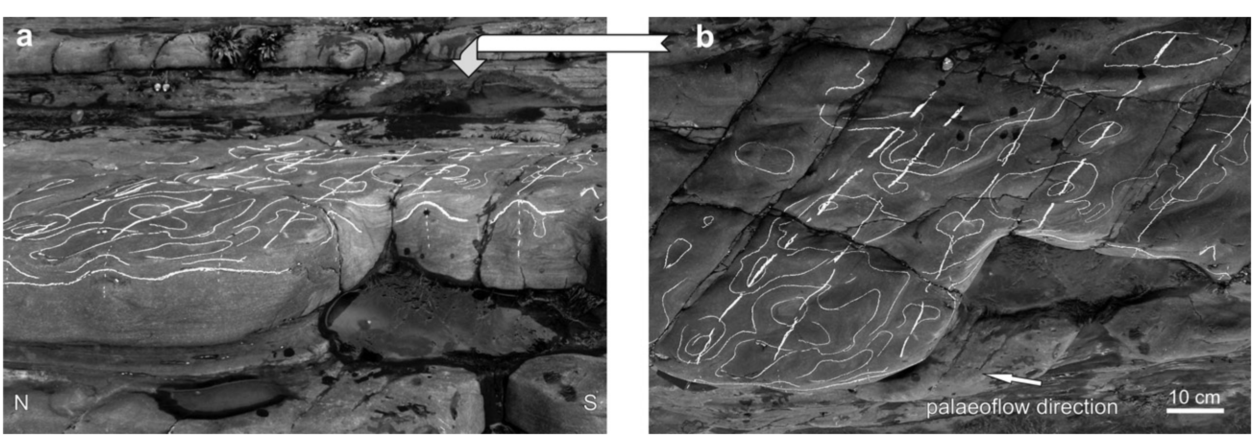

Fig. 12. Oblique (a) and vertical (b) views of a convolute-laminated bed, with some laminations outlined in chalk. In both cases, fold crest points line up (dashed chalk lines) roughly perpendicular to palaeoflow. (from Allt Wen (SN 576 797)).

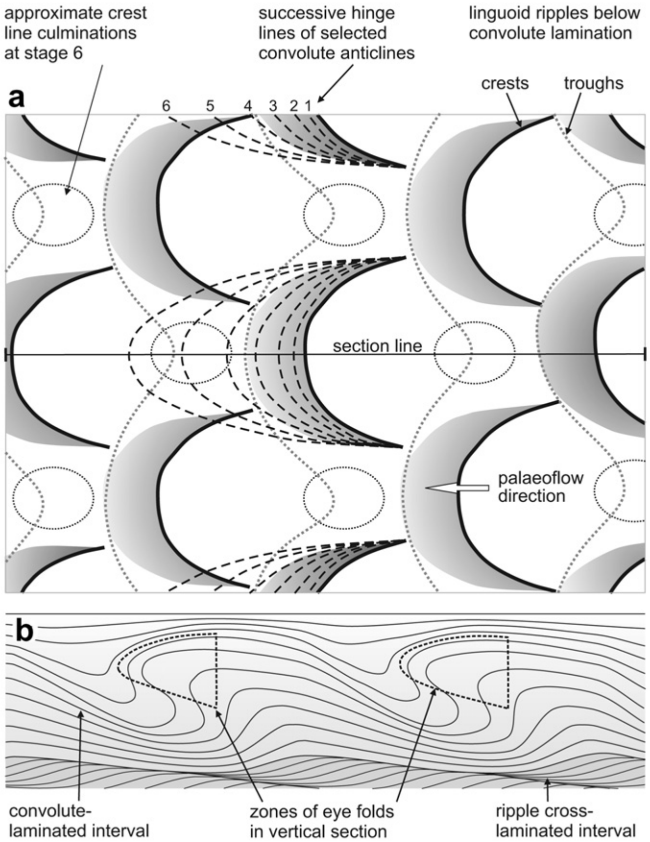

Fig. 13. Cartoon plan (a) and vertical section (b) showing how folds nucleated on linguoid ripples will give both synclinal and anticlinal sheath and eye folds, and lines of crest-line culminations.

which was parallel to fault-bounded basin margins. These faults in turn influenced the orientation of the later Acadian cleavage.

9. Conclusions

The geometrical study of the convolute lamination in the Aberystwyth Group turbidites has shown that:

- Convolute lamination occurs in intervals with a thickness mostly between 20 and 100 mm.
- Eye folds are present in convolute lamination viewed parallel to the turbidite palaeoflow direction.
- The eye folds are sections through non-cylindrical convolute folds that, generally but not ubiquitously, overturn down-flow.
- The convolutions formed during and not after deposition of the bed and have a down current asymmetry due to current shear.
- The average shear strains involved are less than 1.0, lower than generally necessary to generate sheath and eye folds.
- The sheath geometries result instead from nucleation of convolution hinges on already sinuous or linguoid current ripples in the underlying part of the turbidite bed.
- Caution is needed in diagnosing high shear strains from eye folds that might have formed within thinly to thickly bedded turbidite sequences, represented in metasedimentary rocks by psammites and pelites interbedded on scales from tens to hundreds of millimetres

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