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Timing and sense of shear in the Padstow Confrontation Zone, north Cornwall.

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Much of the recent debate regarding transport directions during the development of major folds and thrusts in north Cornwall has relied upon the establishment of structural facing and its interpretation. Determination of the of D1-north and D1-south structures at key localities e.g. Gravel Caverns, cannot by themselves lead to unequivocal solutions and misunderstandings of the significance of these relationships is widespread.

New evidence has been obtained by using sense of shear criteria in coastal sections along the Greenaways between Polzeath and Trebetherick Point. The earliest slaty cleavage (S1-south) is disrupted by steep faults marked by intense quartz veining. Later recumbent folding of these veins and cleavage fabric is accompanied by intense (S1north) cleavage development and a consistent southwards directed sense of transport. These structures are subsequently overprinted by a suite of (D2) structures which mark the effects of renewed northwards transport.

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Introduction

The existence of the Padstow Facing Confrontation as a zone separating areas of opposed D1 transport (Roberts and Sanderson 1971) has recently been the subject of much discussion (e.g. Selwood and Thomas 1988; Andrews et al. 1988; Seago and Chapman 1988). All the protagonists agree that some element of structural confrontation is necessary to explain the field relationships at such localities as Gravel Caverns (SW 931798). There is a consensus that models involving backthrusting most satisfactorily explain the confrontation but the timing of events and the extent of the backthrusting are given very different emphasis. Andrews et al. (1988) and Seago and Chapman (1988) argue that backthrusting produced regional scale, south-facing structures which exert major stratigraphical control, whilst Selwood and Thomas (1988) suggest that any Facing Confrontation is a local phenomenon. In this paper we document evidence for the timing of events using shear criteria, and use this to argue for a major episode of southwards directed backthrusting.

To the north of the Confrontation Zone the earliest deformation (D1-north) formed decimetric to kilometric scale recumbent south-facing folds (F1-north) with a penetrative axial-planar (S1 -north) slaty cleavage (Sanderson and Dearman 1973). Facing and vergence on these folds and the associated cleavage show that the rocks immediately north of Pentire Point are situated on the right way up limb of a regional scale D1-north fold (Andrews et al. 1988 fig. 6), the inverted limb of which is exposed between Pentire Point and Hayle Bay. The Gravel Caverns locality lies within the inverted limb.

South of the Confrontation Zone the earliest deformation (D1south) formed decimetric to kilometric scale recumbent northfacing folds (F1-south) with a penetrative axial-planar slaty (S1south) cleavage (Gauss 1973). Within the zone of confrontation the use of shear sense indicators in the complexly deformed Upper Devonian purple and green slates, exposed between Polzeath and Trebetherick Point (Fig. 1, the Greenaways), provides new evidence by which the relative ages of recumbent folding can be established.

The use of Kinematic indicators

Kinematic indicators are defined as geological structures that convey information about the deformation history of a given rock at a given scale (Cobbold and Gapais 1987). Of the many types of indicator available (see Choukroune et al. 1987 for a recent review) two are of particular interest. These are:

1) asymmetric augen structures;
2) vein geometries.

Asymmetric augen structures (Fig. 2a) are commonly formed when large resistant grains are contained within a more ductile fine-grained matrix. Foliation planes are asymmetrically distributed around the porphyroclasts and the grains have tails of finer grained recrystallised material of the same composition as the porphyroclast.

The behaviour of a vein during progressive simple shear will depend upon its orientation in relation to the finite strain ellipse (Fig. 2b). Veins that are near parallel to the stretching direction will be extended by thinning and boudinage, whereas veins that are nearly perpendicular to the stretching direction will shorten by thickening and folding. As deformation progresses some veins rotate into the stretching field, whilst at the same time the boundary between the stretching and folding fields migrates into the folding field. This results in some veins, which had previously been folded, being unfolded and boudinaged.

Interpretation of the Gravel Caverns locality

Selwood and Thomas (1988) have recently presented a reappraisal of the Confrontation Zone model based on their observations at the Gravel Caverns locality. Here, the Gravel Caverns Conglomerate Formation consists of poorly sorted conglomerates with an argillaceous matrix interbedded with grey slate. The conglomerate beds have yielded goniatites of mid

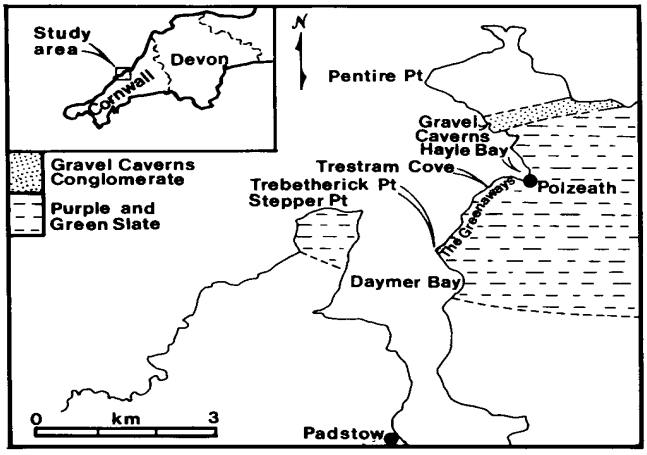

Figure 1. Sketch map of the Camel Estuary showing locations discussed.

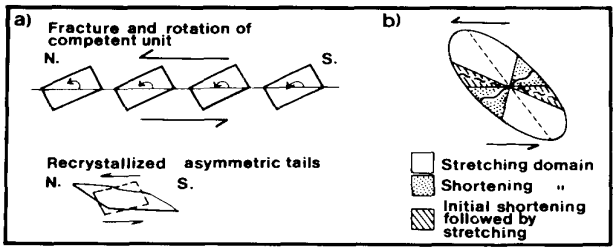

Figure 2. Shear criteria used to determine the transport direction associated with individual events. a) Formation of asymmetric augen structures. b) Variation in vein behaviour with orientation during simple shear (after Ramsay 1967).

age (House 1963). Scouring at the margins of the conglomerates indicates southwards younging. Since these beds dip gently northwards the formation is inverted.

The structural relationships at Gravel Caverns are summarised in Fig. 3a. A decimetric scale north-verging fold pair refolds an early slaty cleavage, and a closely spaced axial-planar cleavage dips southwards. The field relationships are undisputed (compare Selwood and Thomas 1988 with Andrews et al. 1988 or Roberts and Sanderson 1971).

The interpretation of field relationships at this locality is equivocal. Roberts and Sanderson (1971) argue, on the basis of cleavage orientation, that the second cleavage at Gravel Caverns is the southerly expression of the first cleavage developed to the north of the Confrontation Zone (S1-north). Consequently the earlier folded cleavage is equivalent to the first cleavage developed to the south (S1-south). This implies that the Gravel Caverns locality was initially on the right-way-up limb of an early north-facing fold (F1-south) and was inverted as a result of subsequent southwards transport associated with the formation of south-facing Fl-north folds (Fig. 3b). Clearly in this interpretation northwards transport is followed by southwards transport.

Another equally plausible interpretation is that the folded cleavage is that which is regionally developed to the north of the Confrontation Zone. This would also place Gravel Caverns on the inverted limb of a major Fl-north closure. In this case the spaced cleavage is axial-planar to a superimposed northerly verging parasitic fold related to D1-south (Fig. 3c). This interpretation would require initial southwards transport followed by northwards transport.

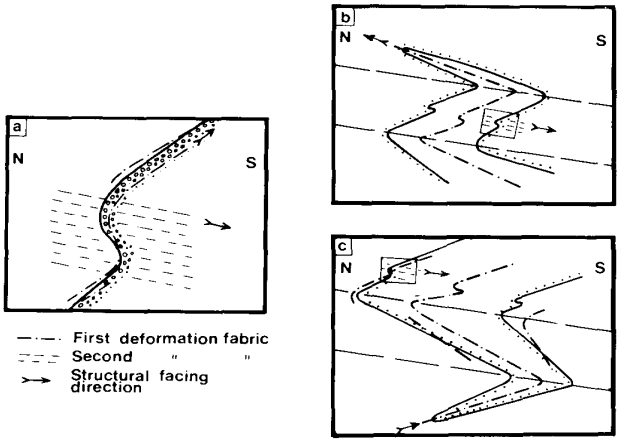

Figure 3. The Gravel Caverns locality. a) The field relationships at Gravel Caverns. b) Interpretation proposed by Roberts and Sanderson (1971). c) An alternative interpretation in which a south-facing first-fold is deformed by a northwards directed superimposed shear. The relationships in a) are predicted on the limbs of both b) and c).

We urge caution in interpreting the regional structure from the evidence at one locality, and use evidence from a broader perspective to decide whether the Facing Confrontation comprises northwards transport overprinted by southwards transport, or vice versa.

Field evidence from the Greenaways

Kinematic indicators in the rocks exposed on the Greenaways (Fig. 1) in the heart of the Confrontation Zone, can be used to establish the relative ages of northwards and southwards transport.

A metric scale recumbent, northwards-closing fold (Fig. 4) is exposed in the sea stack in the middle of Trestram Cove (SW 932789). There is an associated axial-planar slaty cleavage developed that dips gently southwards. Where this cleavage intersects with more sandy layers of bedding, the layers are rotated and develop asymmetric tails (Fig. 5a). Careful examination of these structures shows that northwards shearing is indicated by asymmetric tails within both limbs of the main fold. The hinge of the fold is disrupted by a number of brittle fractures that displace bedding and cleavage southwards. These are in turn crenulated by a fine but locally intense southwards dipping cleavage, indicative of renewed northwards shear (Fig. 4). In this locality early northwards transport was followed successively by southwards, and then northwards transport.

Some 200m to the south in an unnamed beach at SW 932800, gently northwards dipping bedding and a slaty cleavage are cut by a near-vertical fault marked by a narrow zone of intense quartz-veining (Fig. 5b). The fault displaces the bedding, which cannot be matched across it, although it does not juxtapose markedly different lithologies. Bedding and cleavage have been folded and the fault plane rotated and shortened by a subsequent episode of ductile deformation. Small quartz veins that dip moderately northwards are stretched and boudinaged (Fig. 5c). The overall geometry of the vein system indicates southwards shear. A later cleavage that dips gently southwards is axial planar to north-verging microfolds of the earlier cleavage. It is concluded that at this locality southwards shear was preceded by an early event (here of undefined shear sense) and followed by northwards transport.

At Trebetherick Point (SW 925779) the sequence comprises 10 to 15cm-thick purple silty beds alternating with 5 to 15cm-thick finer-grained green slates. These display an early cleavage lying sub-parallel to the gently north-dipping bedding. In the coarser purple beds this is overprinted by a steeply north-dipping cleavage, whilst in the green slate a very strong steeply southdipping cleavage is developed (Fig. 5d). These are differing attitudes of the same cleavage which results from bed-parallel northwards transport along the less-competent green layers (Fig. 6), rotating the cleavage so that it is folded into chevron style angular folds.

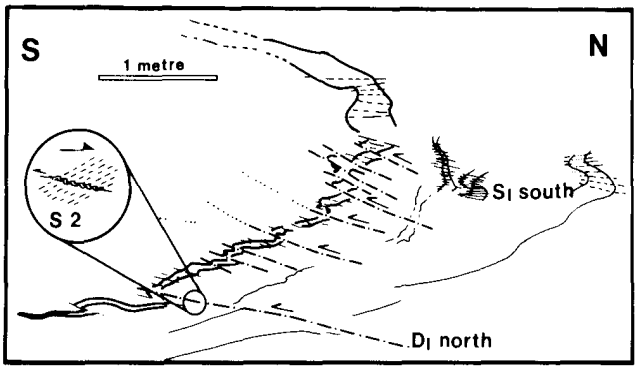

Figure 4. D1-south fold in Trestram Cove with axial planar S1-south cleavage cut by brittle D1-north structures which are crenulated by S2 (redrawn from photograph).

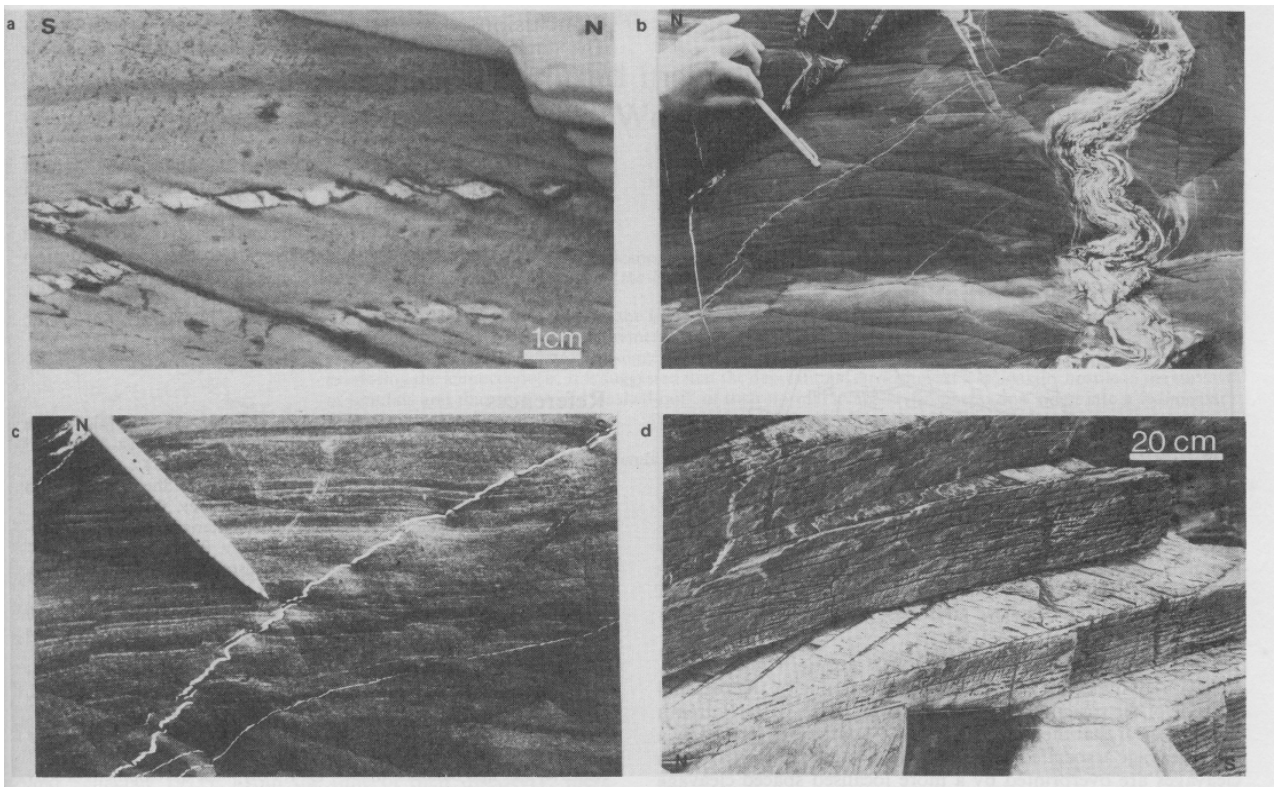

Figure 5. a) Asymmetric augen developed on the limbs of the main F1-south fold at Trestram Cove indicating northwards directed shear. b) Folded quartz veined fault and associated quartz veins on the beach at SW 932800. These folds are produced by south directed shear during D1-north. c) Closeup of small vein which has undergone compression and folding but is now becoming unfolded and boudinaged. d) Alternating purple and green slates at Trebetherick Point showing two cleavages. The earlier S1-south cleavage is bed parallel and is overprinted by a second spaced cleavage (S1-north) which dips northwards in the purple slate and southwards in the green slates. The spaced cleavage has been reoriented by renewed bed-parallel northwards shearing (D2) in the less competent green slates (see Fig. 6).

At each of these localities it is possible to define three deformation phases, of which the first is related to northwards transport, the second to southwards transport and the third to renewed northwards transport.

Discussion

These sections show that the earliest (north-facing) folds are accompanied by an axial-planar slaty cleavage and high angle detachments marked by intense quartz veining. These are formed by northwards shearing, and relate to the north-facing folds documented south of the Confrontation Zone. Later recumbent folding is accompanied by the development of a locally intense second cleavage, and a consistent southwards directed sense of transport. This is associated with the southwards thrusting and early south-facing folds present for many kilometres north of this area (Sanderson and Dearman 1973). In the terminology of Andrews *et al*. (1988) the earliest deformation is D1-south with its associated S1-south cleavage, and the subsequent event is D1-north with its associated S1-north cleavage. The nature and intensity of S1-north is partly controlled by the orientation and strength of the earlier S1-south. The third deformation phase is the expression of later northwards thrusting that is responsible for the formation of the High Strain Zone to the north (Andrews *et al.* 1988). This event simply overprints the earlier formed Facing Confrontation and is the "F3" of Roberts and Sanderson (1971). Hobson and Sanderson (1983, table 6.3), note that this is the regional "F2" phase developed north and south of the Confrontation Zone.

The observed relative ages of shear are predicted by the models of Andrews *et al.* (1988) and Seago and Chapman (1988), which differ little in concept from the model proposed by Selwood and Thomas (1988).

Selwood and Thomas (1988) describe what they say is a new deformation event. The ‘new’ folds that they describe however clearly have the earliest deformed cleavage axial planar to them. This means that they are part of the S1-south cleavage-forming deformation originally recognised by Roberts and Sanderson (1971).

Elsewhere, in the slates of the Gravel Caverns Conglomerate Formation centimetric scale disharmonic folds are noted. These are crosscut by all the cleavages and consequently display variable facing. However the restriction of these folds to this formation, which is clearly representative of an unstable environment, indicates their likely syn-sedimentary origin.

Selwood and Thomas (1988) suggest that they have recognised, for the first time, confrontation of facing in D1. Whilst it is clear that there is indeed such confrontation, this is the same conclusion as that of Roberts and Sanderson (1971), and it follows that D1 is not coeval across the Camel Estuary. Our evidence using shear criteria confirms the diachronous nature of the earliest cleavages across the Estuary.

The Selwood and Thomas (1988, fig. 6) model argues for inversion of the Trevone Sedimentary Basin in the Viséan with the development of northward-, upward- and southward facing folds. In this scenario the only Facing Confrontation to develop during D 1 is on the southern side of the Trevone Basin. They argue that the emplacement of the Tredorn and Boscastle Nappes (D2), by gravity sliding on a foreland dipping ‘shear zone’, over the Trevone Basin caused tectonic interleaving of north and south facing structures on the basin's northern

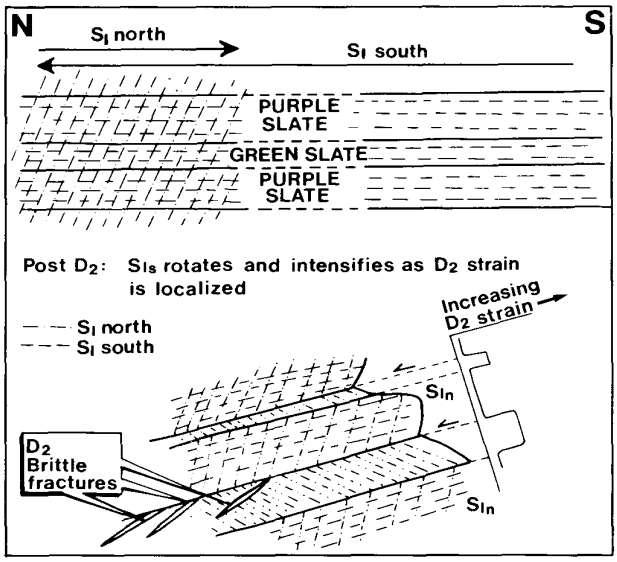

Figure 6. Schematic diagram of the evolution of the structures at Trebetherick Point. S1-north has been rotated by localisation of D2 shearing along the finer grained green beds (compare with Figure 5d).

south facing structures on the basin's northern margin (i.e. Polzeath). This is not consistent with the timing or the regional attitude of the structures (Shackleton et al. 1982). In the Polzeath area it is clear that the early cleavage (S1-south) is deformed by a later cleavage associated with southwards shear (S1-north). Both cleavages are overprinted by a more localised spaced cleavage (S2). This dips consistently southwards, not northwards as the Selwood and Thomas model requires.

The continuity of D2 structures (sensu Andrews et al. 1988) across the Camel Estuary, overprinting the earlier folds and cleavages formed during development of the Facing Confrontation, implies that the Facing Confrontation is involved in D2 thrust transport and is allochthonous, not an imbrication of allochthon and parautochthon as implied by the Selwood and Thomas model. The regional disposition of the structures requires that the Trevone Basin must have originated to the south of the source area of the Boscastle and Tredorn Nappes.

Selwood and Thomas (1988) conclude that the present distribution of strata in north Cornwall is largely the result of thrusting rather than folding on a regional scale. Whilst it is clear that in the High Strain Zone north of the Padstow Confrontation thrusts dissect and repeat the strata, the presence of large areas of flat-lying inverted rocks inland both north and south of the Confrontation Zone (Seago and Chapman 1988; Selwood et al. 1985) must indicate that fold nappes exert strong control on the stratigraphic distribution in the area.

We would summarise the sequence of events within the Padstow Facing Confrontation as follows:

1) northwards transport affecting the sediments of the Trevone Basin formed large recumbent north-facing folds with an axialplanar S1-south cleavage;

2) southwards transport forming large recumbent south-facing folds with an axial-planar cleavage probably resulted from backthrusting. This deformation overprints the earlier northwards propagating structures;

3) the regional D2 phase of folding and cleavage accompanied renewed northwards thrust propagation and thrust stacking of the recumbently folded Middle and Upper Devonian rocks.

Conclusions

The timing of events in the formation of the Padstow Confrontation Zone can be summarised as follows:

1) the earliest (north-facing) folds, with an associated axialplanar slaty cleavage and high angle detachments, are formed by northwards transport (D1-south);

2) later recumbent folding is accompanied by the development of a second cleavage, and a consistent southwards directed sense of transport (D1-north);

3) the third deformation phase is the expression of later regional northwards thrusting, which overprinted the Confrontation Zone (D2), and carried it northwards in a thrust sheet.

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