4. Historical reconstruction from micromorphology: a case study from the Lleyn Peninsula, Wales

4.1 Introduction

Understanding the causes of microstructures (Chapters Two, Three) and recognising their spatial relationships allows us to reconstruct the environmental history of deposits. In this chapter the environmental history of a deposit at Criccieth, North Wales (*Figure 4.1*), is reconstructed in more detail than is possible using macroscale features. Such studies are all too rare, partly because of our ignorance as to the causes of microstructures, and partly because of a lack of confidence in microstructural homogeneity on a larger scale. Both views can be attributed to the youth of microstructural research. Such interpretations are, in fact, reasonable - if care is taken over their application. While it is essential that further studies are made of heterogeneity within small areas of outcropping glaciogenic sediments, it should be remembered that the same scale differences are encountered in other branches of geology.

The Quaternary deposits of the Lleyn peninsula, in North Wales, have been the source of much controversy. Past discussions centred on the number of terrestrial glaciations in the area (Saunders, 1968 vs. Boulton, 1977). However, present interest in the peninsula stems from an older debate; that between the supporters of terrestrial glaciations and glaciomarine floods. Eyles and McCabe (1989) have split workers by suggesting that the Irish Sea deposits are glaciomarine (*Figure 4.1*). This origin would add weight to the theory that the last major deglaciation ($\delta^{18}0$ Stage 2$\rightarrow$1) was so rapid because the edge of the major ice sheets were floated from their beds (Broecker and Denton, 1990). With this in mind, it has been realised the Lleyn may represent a perfect laboratory for glaciologists to determine the controls acting to produce major deglaciations.

Naturally, the two debates have become mixed for much of the peninsula. Many areas that were once interpreted as recording two glaciations have been reinterpreted as a lodgement sequence overlain by glaciomarine material (Eyles and McCabe, 1989). However, the debate has also become mixed on a more unconscious level. Traditionally the peninsula has been divided into two regions; the west/north, which was overridden once or more by Irish Sea ice, and the east/south, overridden once or more by Welsh ice from South Snowdonia (*Figure 4.1*). As the glaciomarine reinterpretation has focused on the Irish Sea deposits in Ireland, the same deposits have been studied on the Lleyn (Eyles and McCabe, 1989; M^cCarroll and Harris, 1992; B.G.R.G. Subglacial Working Group meeting, 1995). The east/south are still regarded as terrestrial, despite the fact that any marine transgression associated with the Irish Sea Ice is likely to have also affected the area only a matter of kilometres to the south west.

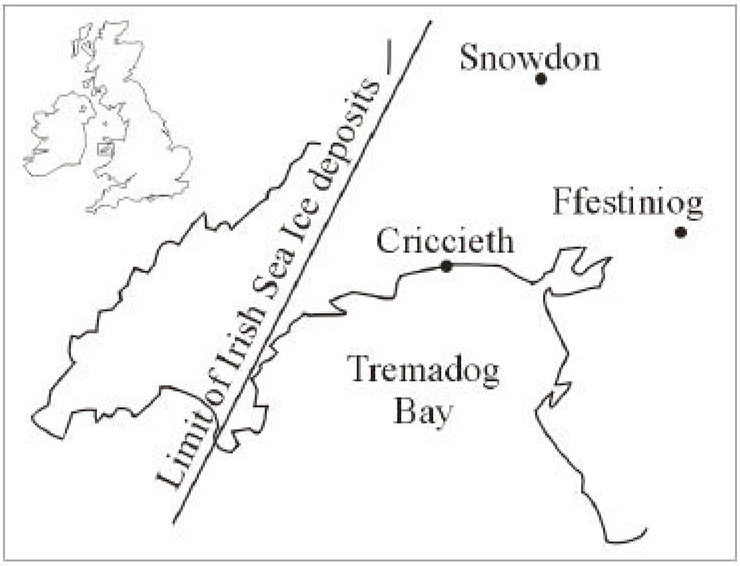

Figure 4.1 The Lleyn Peninsula, North Wales, showing the eastern limit of material deposited by Irish Sea ice in d^{18}O stage 2 (position within United Kingdom and Eire inset).

With this background in mind a site in the south west of the Lleyn was picked for an assessment of the use of micromorphology in distinguishing the environmental history of glaciogenic sediments, in particular a deposit which may have undergone a 'passive' reaction to the stress and hydrological changes it experienced (rather than affecting them). The mechanical response of such a sediment should be simpler to interpret in terms of the surrounding conditions than a sediment that has actively fed back to affect those conditions. Such more complex situations will be dealt with in future chapters.

The deposits around Criccieth on the south coast of the Lleyn have been the subject of discussion for almost a century. They have variously been described as representing one (Boulton, 1977), two (Fearnsides, 1910) and three (Saunders, 1968) terrestrial glaciations. This chapter first attempts to collate and correlate in one place the information on the macroscale sedimentology of the area; more specifically the sedimentology of the microstructural sample site. This information is then compared with a detailed outcrop and microscale study to determine the nature of the deposits. This study uses two techniques. Understanding the *processes* involved in the formation of the microstructures allows us to bracket the likely conditions in which the deposits formed. The *spatial relationships* of the microstructures then allow us to reconstruct the temporal progression through the suites of possible environments in a way that gives considerably more detailed information than previous macrostructural studies of the area.

4.2 The deposits and their relative chronology on the basis of outcrop scale sedimentology

The outcrop in question lies to the East of Criccieth on the South coast of the Lleyn Peninsula, between the town and the sea cliffs (SH507381, *Figure 4.2*) (for details of the surrounding areas see Saunders, 1968; Matley, 1936; Boulton, 1977). The deposit will be referred to here as the 'bay middle' deposit. The two dimensional form of the outcrop is stratigraphically and topographically similar to outcrops locally described by Boulton (1977) as drumlins buried by flow material (*Figure 4.3*). However, the internal structure of the deposit is unusual, and does not match the topographic inversion seen by Boulton.

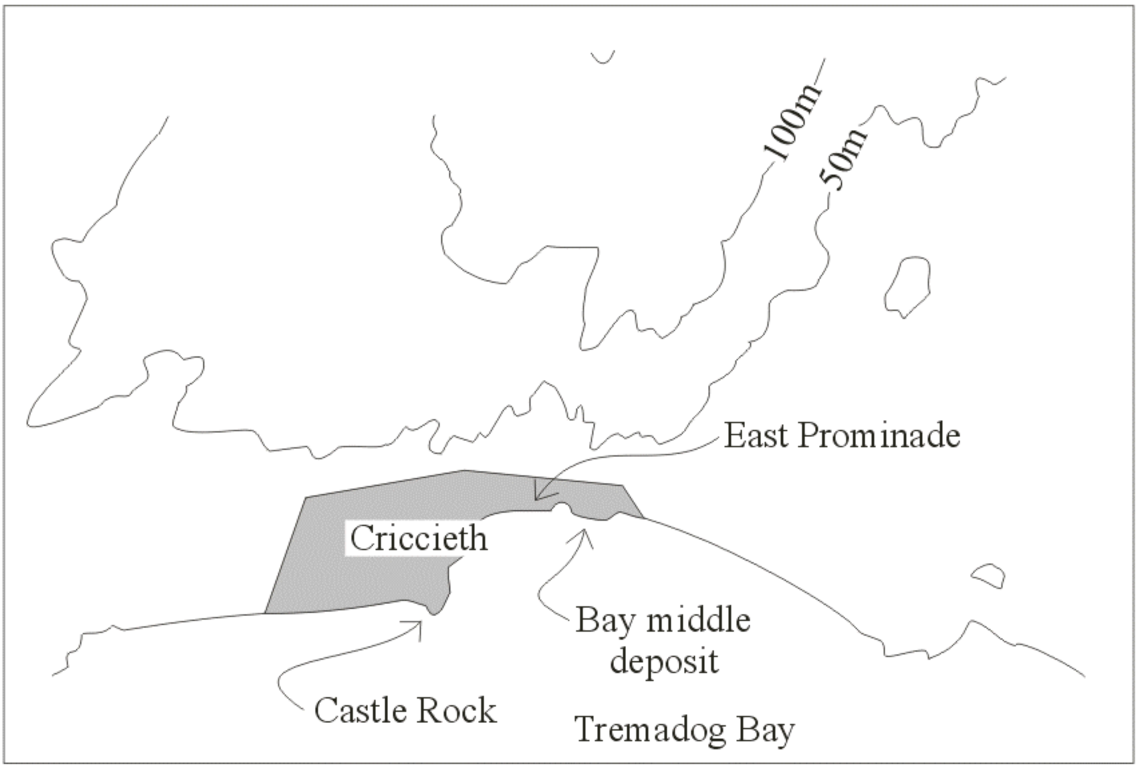

Figure 4.2 Locations around Criccieth, North Wales, showing the position of the 'bay middle' deposit examined in the text.

At present, the deposit is lobate, rising above the level of the surrounding bay. The broad upper surface gently slopes inland, joining the hill rising under the eastern outskirts of Criccieth (*Figure 4.2*). The three dimensional form is unknown below the surface. The two dimensional outcrop consisting of several lithofacies in an anticlinal form, at least in the case of the upper three lithofacies and the lower blue grey diamict (*Figure 4.3*). However, the general anticlinal form belies considerable complexity both within and between lithofacies, particularly between lithofacies D and E.

4.2.1 The sediments

Figure 4.3 shows the sedimentary character of the feature. A near complete cross section above sea level was available during fieldwork in 1993 and 1994.

The outcrop scale sedimentology is;

Lithofacies A: fine silt/sand layer with localised disturbance.

Lithofacies B: clast supported diamict of slate, which fills a frost wedge in lithofacies C and has an involuted boundary with lithofacies A.

Lithofacies C: massive matrix-supported but clast-rich diamict yellow in colour. Clast fabric is random (Grant, 1990).

Lithofacies D: massive matrix-supported but clast-rich light yellow diamict with an weak clast fabric (Grant, 1990).

Iron stained boundary

Lithofacies E: massive blue clay-rich matrix-supported diamict.

The same sequence is seen west of the Castle Rock (SH500377) in Criccieth and as far as Glanllynau (*Figure 4.2*). However, on the eastern side of Castle Rock the sequence is reduced to 25 m of lithofacies C/D, with no other visible beds (though bedrock cannot be seen). Houses are situated on the edge of this small outcrop so it is possible lithofacies A and B were removed before foundations were laid here, being both structurally unsound and horticulturally poor. Further towards the outcrop studied here, the sequence under the town's east promenade (*Figure 4.2*) was revealed by deep foundation placement in 1994. Though the material is certainly glacial, the deposition could be glacial, proglacial, or from the construction of the promenade;

Lithofacies X: dark grey clay without clasts (2m).

Sharp boundary with 2m boulder embedded between the clay and diamict.

Blue dark grey massive matrix supported diamict (2m).

Gravely yellow clast rich, though possibly matrix supported, diamict (2m +).

It was impossible to sample the sediments therefore a visual comparison only can be used. This suggests that the section revealed lithofacies E and D/C, but that they were inverted, and that lithofacies X is astratigraphic and anthropogenic. Stratigraphic inversion is seen elsewhere in the sequence (below). It should be noted that the surface of the blue diamict thus represents an erosional boundary and could not be expected to contain the features associated with boulders in Chapter Five.

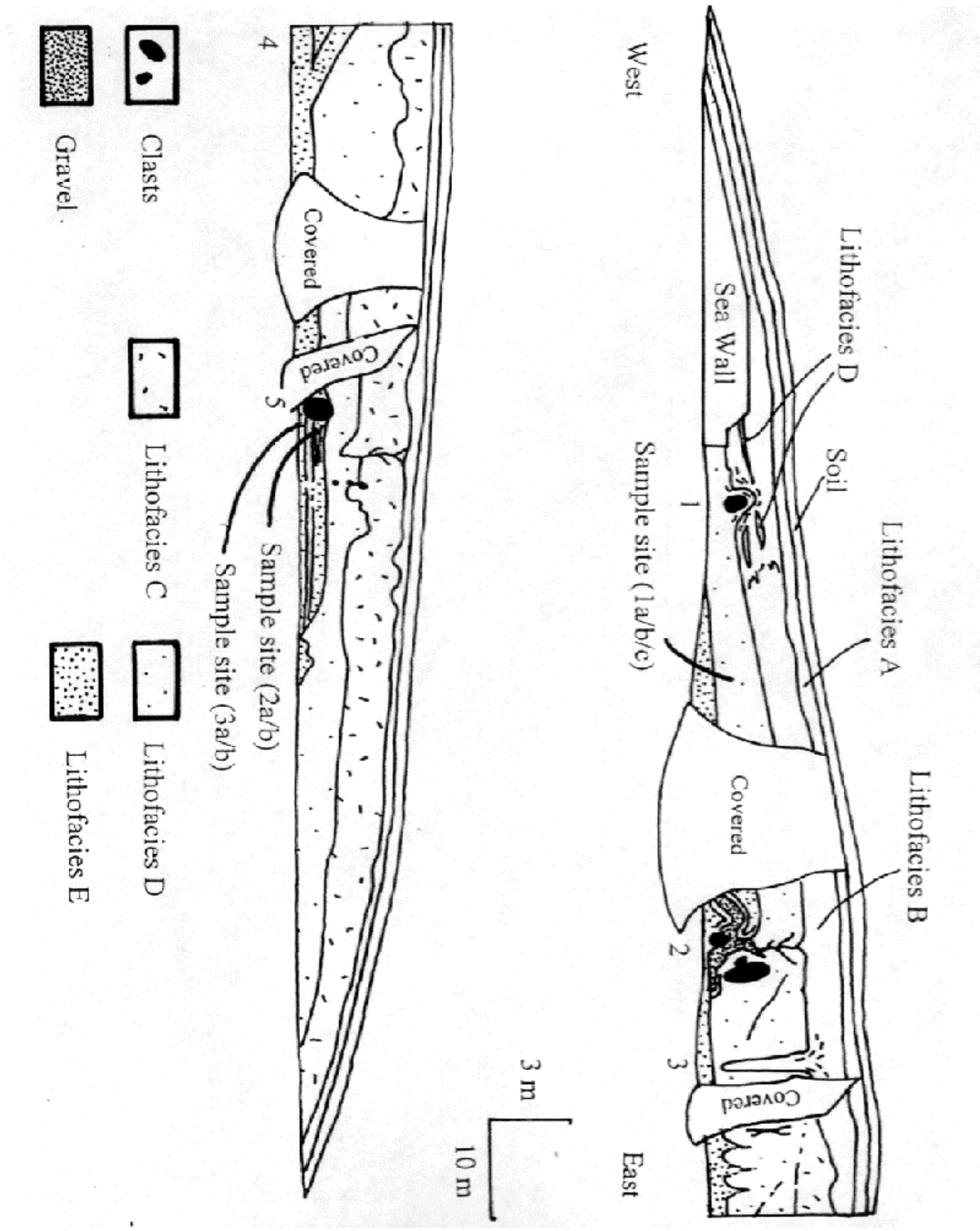

Figure 4.3 Outcrop profile for the 'bay middle' deposit at Criccieth, North Wales.

4.2.2 Previous interpretations

The area has been studied and interpreted by other authors. However, the variation in descriptive techniques means it is difficult to reconcile the 'bay middle' sequence with any of the accounts. Saunders' (1968) sequence describes similar sediments, but with additional stratigraphic layers. Grant's (1990) sequence has a similar stratigraphy, but differs in sediment description, despite using the same scheme (Eyles *et al.*, 1983).

The specific location described by Saunders at Afon Wen is now covered, however, 300m to the east the laminated outwash sands and gravels he describes *can* be seen. These coarse deposits can be correlated with Grant's laminated silts and gravels further east at Glanllynau. The correlation is only tentative, and should be contrasted with Matley's (1936) claim that both areas are included in a 50 ft (13.9 m) terrace. Matley suggests the terrace is formed from gravels *above* glacial sediments, making the correlation of the gravels untenable. Matley's claim is, however, based on the continuity of this landform rather than stratigraphy. If the correlation outlined above *is* accepted the regional stratigraphy given in

Table 4.1 is gained.

The sedimentological conditions described by Boulton (1977) are considerably more complex, but the complexity is wholly local.

Afon Wen Saunders	**Glanllynau Grant**	**Criccieth Grant (probably East of Castle Rock)**	**Criccieth Saunders (probably West of Castle Rock)**	***Figure 4.3***
Peat + Gyttja			soil	soil
				lithofacies A: fine silt / sand
	Dcm			lithofacies B: + Dcm slates
		erosion surface		frost wedge forms
upper gravely till	Dcm	Dcm	upper gravely till	lithofacies C: Dmm - yellow clast rich random diamict
				lithofacies D: Dmm - clast rich light yellow diamict
gravel + sands	gravel + silt			
weathering horizon + frost wedges		erosion surface	weathering horizon	Fe staining + deformation structures
blue grey slatey till	Dmm	Dmm	blue grey slatey till	lithofacies E: Dmm - blue grey diamict
			head	lithofacies F: unfound
			soliflucted till	lithofacies G: unfound
			head	lithofacies H: unfound

Table 4.1 Regional correlation of sediments described in different studies carried out in the Southern Lleyn Peninsula.

Table 4.1 can be shown to give a regional stratigraphy that is in line with Boulton's three-dimensional mapping whatever ultimate interpretation is applied to it. It seems likely that the sequence observed by Grant and the 'bay middle' deposits are one and the same. As bedrock is not visible in the middle of the bay, nor is likely to have been in the past, it seems reasonable to suppose Saunders' exposure was to the west of Criccieth where a similar sequence to the bay middle deposits exists. Here there are no bedrock outcrops, but vegetated inactive cliffs may be obscuring the section. Fearnsides (1910) records the sequence on both sides of Castle Rock as boulder clay resting on angular unworn talus with "a scree-like stratification", under which is a wavecut platform a few feet above the present tide. This description matches Saunders' sequence. Both sides of Castle Rock are now covered with sea defences.

Lithofacies	**Possible environments**	**Reasoning and caveats**
A	Periglacial loess	A micromorphological study would probably not confirm this, the less permeable materials below having encouraged subsurface flow illuviation and particle reorientation. These processes will have removed delicate aeolian structures.
B	Periglacial solifluction material	Evidence of mass movements and small (~1m) stream deposition. Fills frost wedge (3; Fig. 4.3) without slumping structures and the material involuted at surface. The material is draped over, rather than around the large clast at '1' (Fig. 4.3) suggesting mass movement deposition rather than the deposition of individual clasts in a fluvial environment. West of Castle Rock lithofacies B contains boulders and occasional sand lenses (~1m length) suggesting a highly active environment of streams and mass movements, a hypothesis in line with Boulton's (1977) reconstruction of the area further west at Glanllynau.
C	Periglacial cryoturbation of lithofacies B and D.	Present only where B is absent and D is reduced. Cryoturbated fabric with a high angular slate content. Frost wedge at 3 (Fig. 4.3) suggests depth for periglacial action. West of Castle Rock the boundary with E has clast concentration suggesting fluidization of D or a fluvial event.
E	Glaciogenic sediment flow (Boulton, 1977; Grant, 1990) or Lodgement till (Saunders, 1968), or flows under lake / marine conditions (Matley, 1936).	Clast orientation eigenvectors cover the first two possibilities (Grant, 1990). See text for further discussion.
F	Subglacial till (Grant, 1990; this chapter, Chapter Five)	It seems unlikely given the exposure of the site that this formed under a pre-Dimlington stadial (δ^{18}OStage 2). See text for further discussion.

Table 4.2 Potential environments represented by the Southern Lleyn sediments

Given this correlation, Table 4.2 is an outline of the possible environment each lithofacies represents.

Interpretative clashes involving the sediments revolve around both the environments and history they represent. These arguments are compared below.

Lithofacies D : yellow, clast rich, matrix supported, massive diamict

Lithofacies D has a weak southerly dipping fabric, with eigenvectors suggesting glaciogenic sediment flow, deformed or undeformed lodgement till (Grant 1990). Grant suggests that the material is a series of flow deposits formed on top of margin-parallel buried ice ridges, in line with Boulton (1977). Saunders (1968) suggests a lodgement till, and provides evidence that for some of the area covered by lithofacies D, glacial retreat was active rather than by stagnation as suggested by Boulton (1977). The layer is continuous over much of the south eastern Lleyn, with a fabric which sweeps from north-south at Glanllynau to a 080-260° fabric at Afon Wen (Saunders, 1968) (*Figure 4.4*). To fit the Boulton/Grant model, the deposit at Afon Wen would have to infer a change in the orientation of stranded ice ridges to 080-260°. If the ridges reflect the orientation of the ice margin, as Boulton suggests, this change in orientation may indicate a late-glacial piedmont glacier spreading into Tremadog Bay during deglaciation.

An alternative explanation is a lobe of material flowing from the high ground to the north of Criccieth. Matley's (1936) stratigraphy is impossible to relate to any local sequence, but he suggests all the material above a basal boulder clay (lithofacies E) was deposited in an ice-marginal freshwater lake during the last deglaciation. Such an interpretation must also include the glaciomarine option. Such deep water origins could plausibly explain the deformed internal nature of the sediments (through slumping) and the regular surface expression of the deposits. Whatever the explanation, it must also account for the claim by Saunders that the layer exists at Crugan 10 kms further west than Afon Wen.

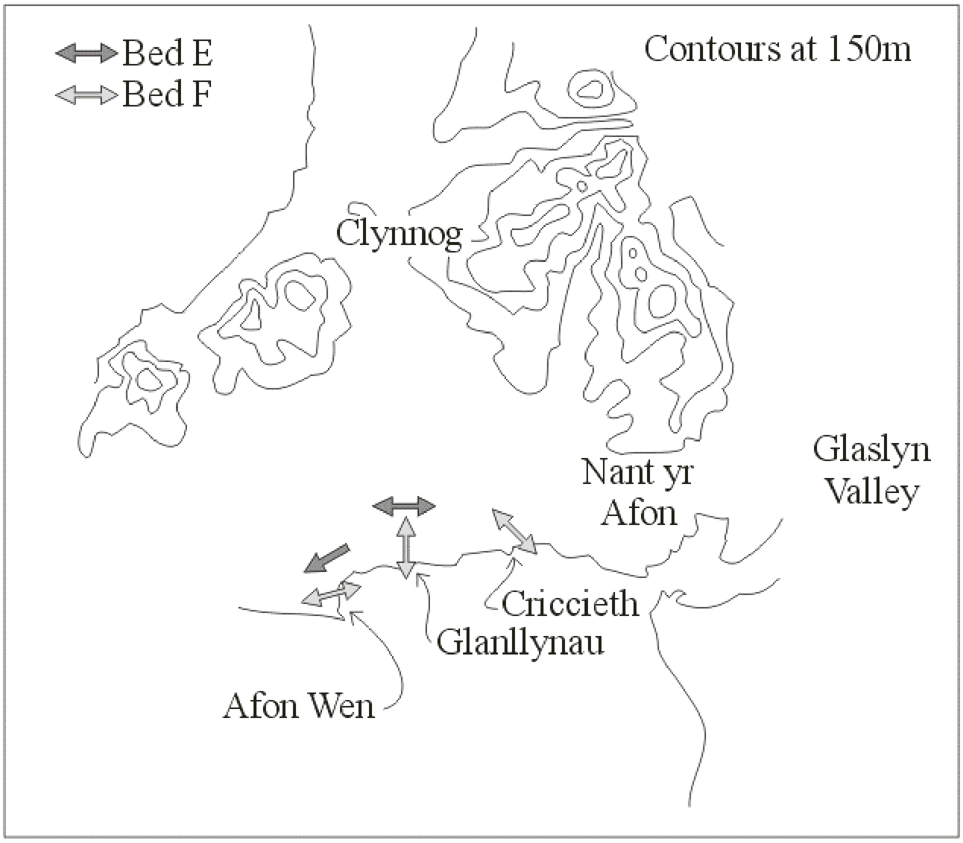

Figure 4.4 Eastern Lleyn Peninsula showing direction of pebble fabrics in lithofacies D and E described by Saunders, 1968, Boulton 1977, and Grant, 1990.

The deposits' identification as a subglacial deposit formed in a glaciation after that depositing lithofacies E (Saunders, 1968) relies on two lines of evidence. Firstly, the presence of frost wedges in the sequence (lost beneath 'Butlin's') at Afon Wen (Saunders 1968) and Glanllynau (D. Evans, *pers.comm.*, 1995). These features are said to represent a significant time period between the two diamicts D and E. However, in contrast to Saunders' claim this period does not have to be a full interglacial. In addition, the frost wedges at Glanllynau are similar in form to a possible fold feature that will be discussed below. The second line of evidence for an interglacial is a proposed iron stained 'weathering' layer at the top of the lower diamict (Saunders 1968). It will be shown in the micromorphological study below that such layers could also have formed either subglacially or in a short periglacial period. The 'outwash' gravels and sands/silts in the sequence provide no useful information in this context. They are on the southern margin of the deposition area associated with a col to the far north in Clynnog (SH450480, *Figure 4.4*). Ice must have abutted the northern hills at the time the sands were deposited in the ice-free South. Such a situation is in line with the glaciomarine theory, in which ice retreats north-south in the Irish Sea, however, casts little light on the nature of the lithofacies D.

Lithofacies E: stiff blue-grey matrix supported, massive diamict

At Criccieth, this diamict is at least *partially* a glacitectonite derived from laminated muds (D.Evans, *pers,.comm*., 1997). It has generally been recorded as massive, however, very fresh, storm erroded, sections are needed to see any laminations (D.Evans, *pers,.comm*., 1997). The diamict has a varying clast orientation along the coast from NNW-SSE east of Criccieth to E-W at Glanllynau to movement from the NE in Afon Wen (Saunders, 1968; Boulton 1977; Grant, 1990) (*Figure 4.4*). All the fabrics measured in the literature are more strongly clustered than in the higher diamict. The regional orientation change could be reconciled with the traditional picture of ice moving out of the Ffestiniog Vale and splaying into Tremadog Bay (*Figure 4.1*) by considering ice movement onto the coast at Criccieth, and its deflection along the present coastal plain at Glanllynau and Afon Wen by the topography immediately inland. Alternatively, Fearnsides (1910) suggested the material was deposited by western ice that had passed over the Lleyn and was forced inland from Tremadog Bay. This position should be respected given the author's extensive knowledge of the area's geology, however, it seems more likely that the northern material was reworked from glaciofluvial deposits. Boulton (1977) has also suggested ice flowing from the north. Both views are repudiated by Fearnsides' own work which suggests a considerable ice thickness in the Glaslyn Valley and over Nant yr Afon valley (SH550400, *Figure 4.4*). Striations and erratics suggest the ice moved down the Glaslyn Valley from Snowdon (*Figure 4.1*), and stopped ice moving from the north at Criccieth.

The diamict contains heavily weathered erratics which Saunders (1968) took as evidence for the deposit including glacial material older than itself. Such a boulder is seen at point 5 on Figure 4.3. Here weathering is continuous across striations, suggesting weathering occurred after the glaciation associated with the deposit. The hypothesis that the deposit itself is older than the last glaciation seems unlikely in such an exposed area, though the sediments could have been protected from the Late Devensian ice by the gravel deposits of Matley (1936). This would make his terrace surface of Ipswichian (δ^{18}O Stage 5) age.

In conclusion, it is impossible to gain any satisfactory origin for the deposits from the macroscale sedimentology, the literature, or the implications of the information contained within it. Thus, in the next section outcrop and microscale structural evidence is presented with the aim of elucidating this controversial area.

4.3 The macrostructure

4.3.1 Folding

Description

At point '2' on Figure 4.3 lithofacies E overlies lithofacies D, either as a sheared off block or a nappe (see *Figure 4.5* and *Figure 4.6*). In section the feature appears to originate to the north west. After, or as a part of this deformation, the lithofacies have been folded into an open parallel form (*Figure 4.5*). Neither compressional event is represented elsewhere in the Southern peninsula, with the possible exception of under the East Promenade at Criccieth (see above).

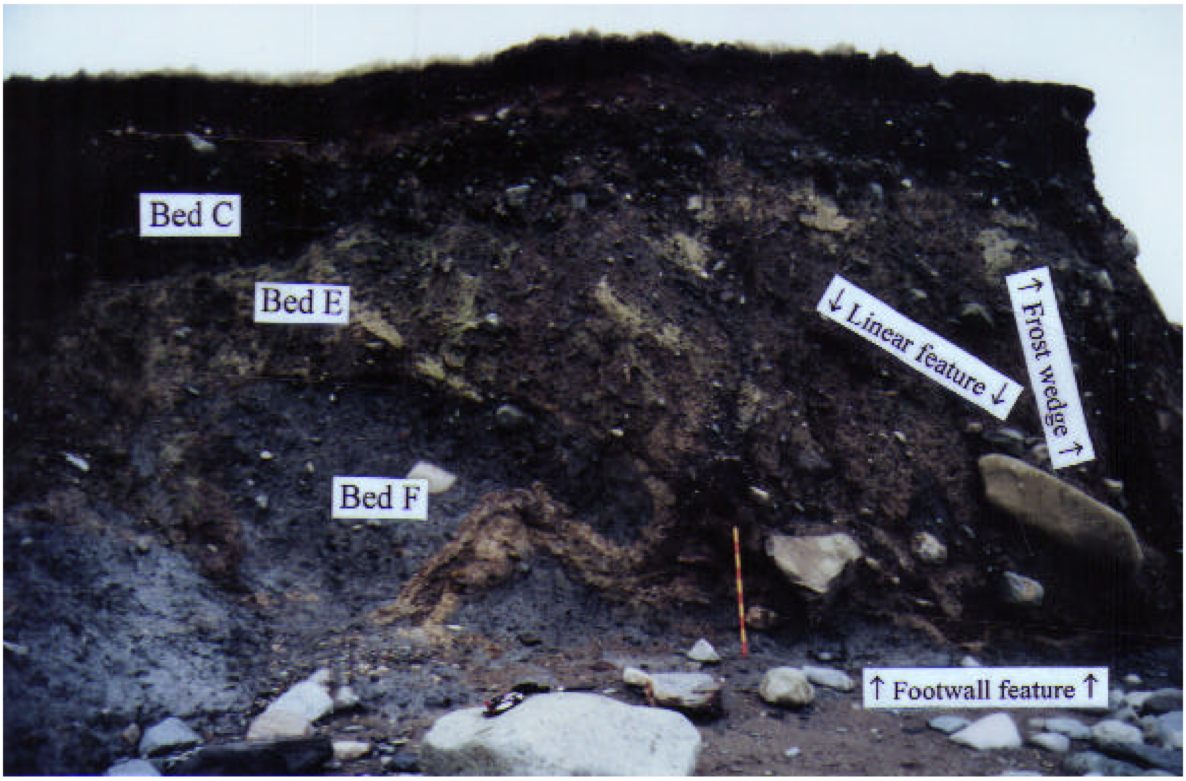

Figure 4.5 Features in the Criccieth 'Bay middle' deposit. Note what appears to be a recumbent fold of blue diamict (lithofacies E) in the centre of the picture. The centre of the fold is filled with darker clastic material in a light envelope. Similar material can be seen in a smaller structure just above lithofacies E to the right of the photograph. A dark frost wedge extends through the sequence in the far right of the picture.

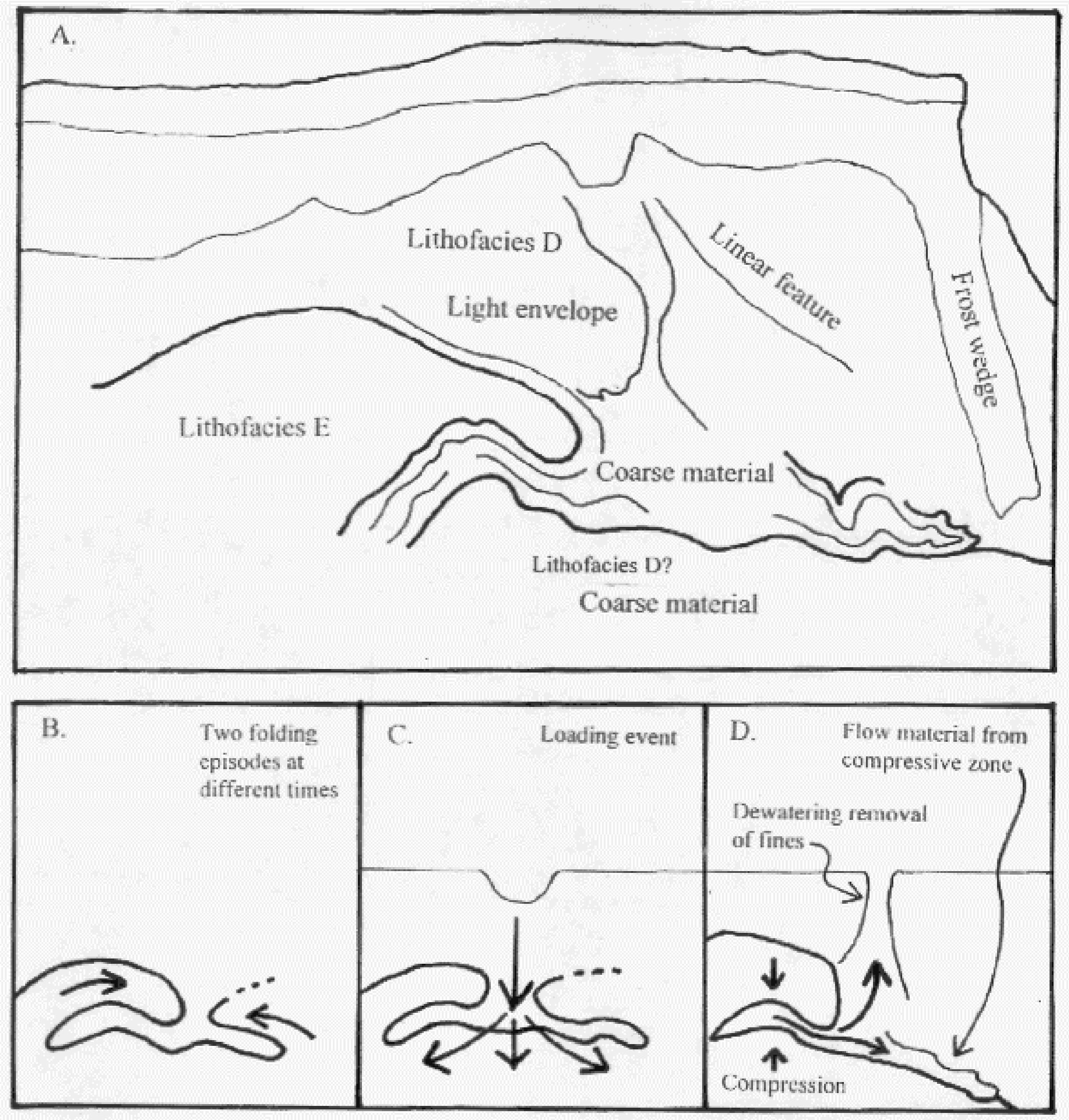

Figure 4.6 a) The main features of the 'fold' structure. Possible explanations: b) two folding episodes, c) loading, d) slump complex.

The 'fold' is unusual, in that the fold interior, which one would expect to be filled by lithofacies D, is composed of iron stained clastic material surrounded by an envelope of light material around 15 cm thick. This clastic layer spreads up out of the fold, through lithofacies D, thinning and arboressing until the boundary with the overlying slate lithofacies B (though this example has proved hard to photograph, an equivalent is shown in *Figure 4.7*). A second strange feature of this 'fold' suite is the small fold-like structure lying on the surface of the footwall of lithofacies E. The nose of this faces south east (in outcrop) and it has a similar internal sedimentology to that of the main fold.

Figure 4.7 Part of an arborescent clast concentration in lithofacies D.

Interpretation

The combination of clastic material and light envelope matches descriptions of frost-wedges elsewhere (Saunders, 1968). However, this interpretation cannot account for the absence of the light layer elsewhere in the section. Nor can it account for the extension of the clastic material up through lithofacies D. The frost-wedge interpretation of these features is also in doubt at present (D.Evans, *pers.comm.*, 1997).

The structural suite could be a double fold, though the change in stress direction necessary to form the small footwall ‘fold’ would demand explanation. Equally, the whole suite of structures could represent a cross section through a loading structure, with the clastic material moving into lithofacies E in two directions while it was weak. However, neither explanation satisfactorily accounts for the arborescent structure of the clastic material in lithofacies D. A more complete explanation interprets the major fold as having supplied dewatering fluid during the folding strain. This fluid dewatered upwards to form an arborescent dewatering channel. Some fines were probably removed from this channel during the deformation, while the remainder were removed more recently by water percolating through this porous zone.

Under this interpretation the clastic material left in the fold interior represents a fluid-supplying gravel bed within lithofacies D (which explains the localised deformation), or material from either lithofacies with the fines washed out. The smaller ‘fold’ is interpreted as clastic material that has flowed out of the larger fold and down the sloping footwall of lithofacies E. The consistencies of the materials involved demands that the light layer around the clastic fold interiors is a postdeformational weathering 'rind' around the highly permeable clastic material. The envelope cannot be translocated fines as the clastic material flowing to form the second ‘fold’ would have sunk through such material.

The consistencies of the materials also demand that the feature formed under gravity. lithofacies E must have been hard enough to fold rather than move more pervasively. lithofacies D must have been weak enough to allow material to move out of the fold interior and down the footwall (ie. probably extremely saturated and easily fluidized). However, if the strain was caused by lithofacies D overriding lithofacies E, lithofacies D must also have been strong enough to maintain the stress necessary to cause the fold. The stress problem becomes redundant if the original nappe/sheared block formed under gravity as a slope deposit, overriding the clastic material. The most obvious situation these conditions could occur in is a deep-water environment. It seems unlikely that such a feature could be produced under the force of the proglacial flows proposed by Boulton (1977) to account for lithofacies D.

The simplest explanation for this complex feature is therefore a fold episode associated with a landslip and weathering. It is interesting to note, as a further complication, that there may be a boundary in the yellow diamict dipping at ~45° in the same direction as the fold, starting just east of the top of the arborescent structure (we are not able to gain a chronology as the two do not interfere). The boundary is marked by large boulders, or possibly suggested by their coincidental positioning. Exploited boundaries *are* seen in lithofacies D to the west of Criccieth castle. These dip in 3D towards the beach at 40° (south) and may be related to Grant's weak lithofacies D southerly fabric. Note, also, that Grant's NNW-SSE fabric for lithofacies E matches (is explained by?) the fold direction. The fold thus contradicts the suspected ice flow east of Criccieth for lithofacies E from Glaslyn Valley, but it does not contradict the regional flow of lithofacies D, suggesting it is post-glacial.

4.3.2 Contacts between lithofacies.

Description

At area '4' on Figure 4.3 lithofacies E appears to rise and merge with lithofacies D in a ramp of matrix supported material which has a recent landslide base as its upper surface and has been undercut at its base to reveal lithofacies E.

The boundary between lithofacies C and lithofacies D varies considerably around area '5' on Figure 4.3. There is an unusual step in the boundary down to the East. Along this step runs a vertical anastomosing pebble fabric similar to that attributed to dewatering with respect to the fold above (*Figure 4.7*). The fabric leaves the stepped boundary and continues up to, and fans out at, the base of lithofacies B. Downwards, the fabric splays at the base of the step where it meets lithofacies E.

Interpretation

Difficulty in mapping due to landslips make an accurate assessment of Area '4' on Figure 4.3 difficult, they particually obscure the boundary between the ramp and lithofacies E. It is possible the ramp material is lithofacies D after weathering.

Area '5' on Figure 4.3 appears to confirm the periglacial mixing hypothesis for the origin of lithofacies C (note the depth of post-depositional frost wedge at '3'). The inclination would be to attribute the variations of the boundary to buried ice melt following Boulton (1977) and Grant (1990). However, the fabric may be associated with the consolidation dewatering of coarse material deposited at the top of lithofacies E below this step. This coarse material is further described in Chapter Five.

In conclusion, the deposits are very complex on a small spatial, and probably temporal, scale. Many of the section's structures have never been recognised in other deposits, or have been recognised but misinterpreted or passed over. It seems likely that more detailed structural and sediment mapping will reveal the solution to a number of the problems posed above. However, the most promising technique available, which has never been used in the area, is the micromorphological study of the features and sediments. As this remit of this thesis is micromorphology, it is to this technique we now turn.

4.4 The micromorphology of lithofacies D and E

4.4.1 Sampling and methods

A hand-sample was taken from lithofacies D (location *Figure 4.3*). All sample material in this thesis was taken after between 50 to 100 cm of material was removed from the outcrops in question to limit recent damage. The sample was of a fine, yellow, silt with no visible structure. The sample was sectioned orthogonally to gain two orientated thin sections. The poor thickness of one sample led to a second thin section being cut despite the adequate quality of the former section for fabric analysis. Thus three thin sections were examined to see if they could cast any light on the controversial nature lithofacies D. One section is orientated north west to south east (section 1a) and two are orientated north east to south west (sections 1b and 1c). There were no clasts larger than the final thin sections within 20 cm of the sample site. Thus, it might be suggested that any clast effects on the thin sections would be characteristic of the whole sediment. Any local effects from small clasts would grade across the thin sections. Such gradients were not found and the samples are therefore regarded as representative.

A hand-sample was also taken from lithofacies E (location *Figure 4.3*). The sample was of blue-grey clay silt, with no visible structure, and sectioned orthogonally to gain two orientated thin sections. One section is orientated east-west (section 2a) and the other north-south (section 2b). While these samples were taken to prove a prediction outlined about a specific feature in lithofacies E discussed in Chapter Five, they reflect on the general sedimentology of this lithofacies too, and are discussed in this context in this chapter.

All the thin sections in this thesis were prepared by T.Ridgeway, in the Institute of Earth Studies, University of Wales, Aberystwyth, with (limited) assistance from the author. A close approximation to the preparation process used has been given by Awadallah (1991). The production of slides follows six stages.

1) The hand-specimens are trimmed down to rectangular prisms with sides of ~2 cm with a sharp knife attempting to minimise disturbance by avoiding stressing larger clasts and pulling material away from the prism's faces, rather than 'slicing' (in this case this work was undertaken by the author).
2) The material is placed into containers that extend above their tops, which are marked with the sample orientations determined in the field. These are then covered with epoxy based resin ('Epo-thin', supplied by Buehler Ltd, University of Warwick Science Park, Coventry, is recommended, but the resin used in this thesis varied), and placed in a vacuum oven at ~30°C. This oven draws air out of the samples, which become impregnated with the resin. This resin then cures over the course of a day.
3) The samples are cut down to the approximate size of a microscopy slide and the top 2 to 3 mm of one side of the sediment trimmed off using a oil lubricated cutting wheel (water based systems as used in hard rock sectioning are unsuitable for use with resin impregnated samples).
4) The trimmed face of the slide is examined, reimpregnated if necessary (ie. if there are patches that have not taken up resin), retrimmed if necessary, and polished on a diamond paper polishing wheel. This face is then stuck to a microscopy slide with epoxy resin and clamped while it cures at room temperature to ensure temperature changes do not crack the glass.
5) The sample is then trimmed down to ~ 2 mm thick with a cutting wheel and hand ground to 1 to 2 grains thickness on oiled diamond paper of increasingly fine grains. During this process the slide is continually checked.
6) Finally, a cover slide is stuck to the slide with epoxy resin, again clamped at room temperature.

Preparation-induced features of the thin sections include;

a) resin discoloration;

b) sample cracking;

c) the removal of grains during coarse trimming (which may then spin locally within the sample causing damage);

d) air bubbles;

e) trimming disturbance prior to impregnation.

All are rare, with the exception of (e), which is seen around the edge of samples. All are also easily recognised and discounted.

The samples in this thesis were examined using a petrographic microscope (Olympus B201), unpolarized, plain polarized, and cross-polarized light and cross-polarized light with a ‘tint’ or ‘$^1/_4$ wavelength’ plate. The latter splits the mixed wavelength light that passes out of most minerals under cross-polarised conditions such that finer colour distinctions can be made, that is, slides appear to be highly coloured, rather than the more typical grey-scale. These ‘birefingence colours’ allow mineral identification and assessment of grain alignments. Grains orientated in a single fabric direction all change colour at the same time as the slide is rotated within the polarized light. Once such an area has been located, the grain orientation can be assessed by examining the individual grains at a higher magnification.

The synchronous colour change of such aligned areas allows us to recognise simple patterns of alignment within sediments. Plainly, our ability to recognise patterns will be partly determined by our previous experience (in a cultural rather than an individual sense). A review of the problems of pattern recognition is beyond the remit of this thesis, and the reader is recommended Bruce and Green (1990) for a full review. Lengths and population numbers in this thesis are determined by 100 random point counts where possible. In the cases where several slides were taken from one site, the slides were described ‘blind’, that is, without knowledge of their position within the sequence, though additional measurements were made after a hypothesis was put forward involving the sediments if necessary.

4.4.2 Description (lithofacies D)

Section 1a (see *Figure 4.3* for sample site) has a strong omnisepic fabric with an apparent dip 45° down to the north west (*Figure 4.8*). This fabric fills all the spaces between other fabrics, and areas of stronger fabric within it are split and shifted by later shear events. The fabric is therefore presumed to precede all other fabrics seen in the material. The event forming this fabric is denoted as the Primary Fabric Event. There is a strong and discrete shear fabric developed with an apparent dip orthogonal to the primary fabric, in which the fabric has reoriented so that mineral grains are approximately vertical (Shear Event One) (*Figure 4.8*). This fabric suggests sinistral displacement and this interpretation is backed up by the movement of the slight heterogeneities in the primary fabric. These shears are further displaced by discrete linear zones of strong primary fabric alignment (Shear Event Two) suggesting later dextral shear in the primary fabric direction.

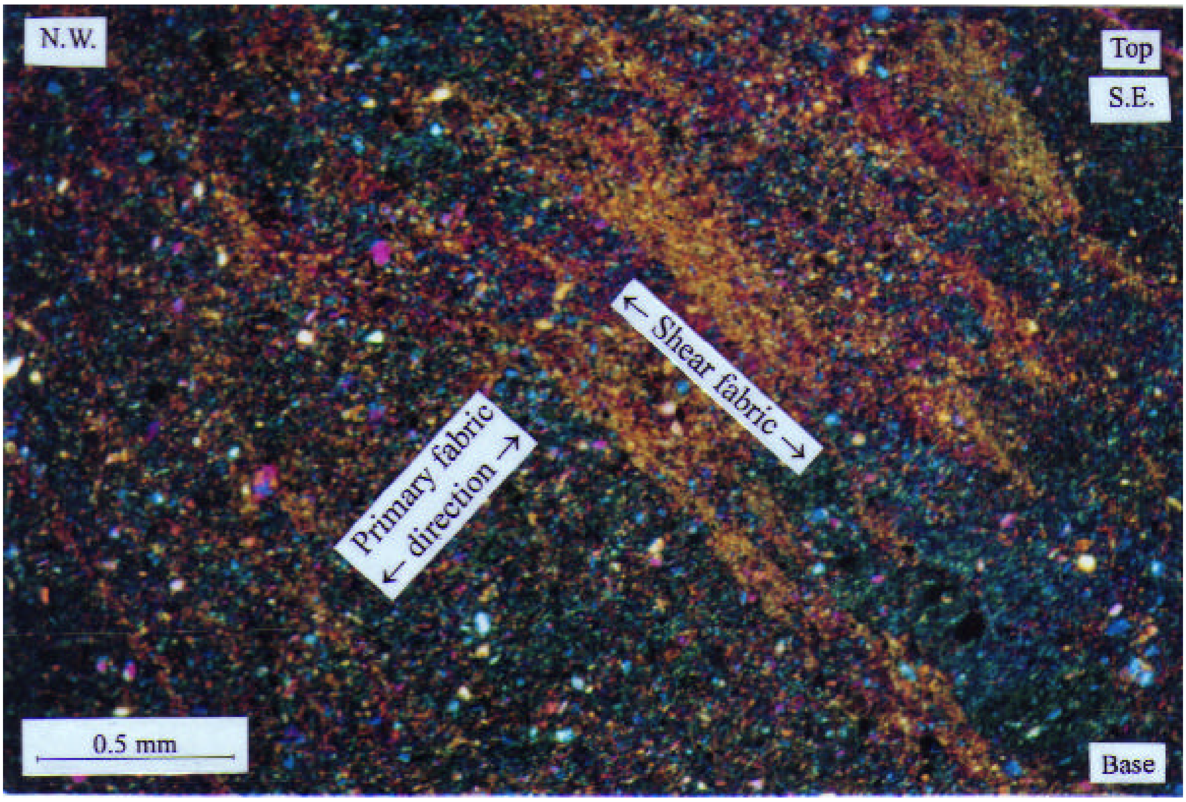

Figure 4.8 Tinted polarized micrograph of section 1a (vertical section from north-west to south east) showing strong north-west dipping primary fabric (blue-green) and a shear fabric dipping south-east (yellow).

Iron staining is present in Section 1a. This is not unusual in Quaternary thin sections which will have suffered some pedogenesis (Chapter Two). However, as shall be shown, in this sample staining is of chronological significance. In section 1a, the staining shows an intensity gradient building up to a boundary, below which there is no staining. This pattern is as expected, iron being deposited along very mild fluid restricting layers or at the limit of travel by capillary action or under a pressure gradient. However, the boundary often has gaps, after which the boundary gradient is reversed to below the boundary (*Figure 4.9*). Figure 4.10a shows the boundary orientations across the slide.

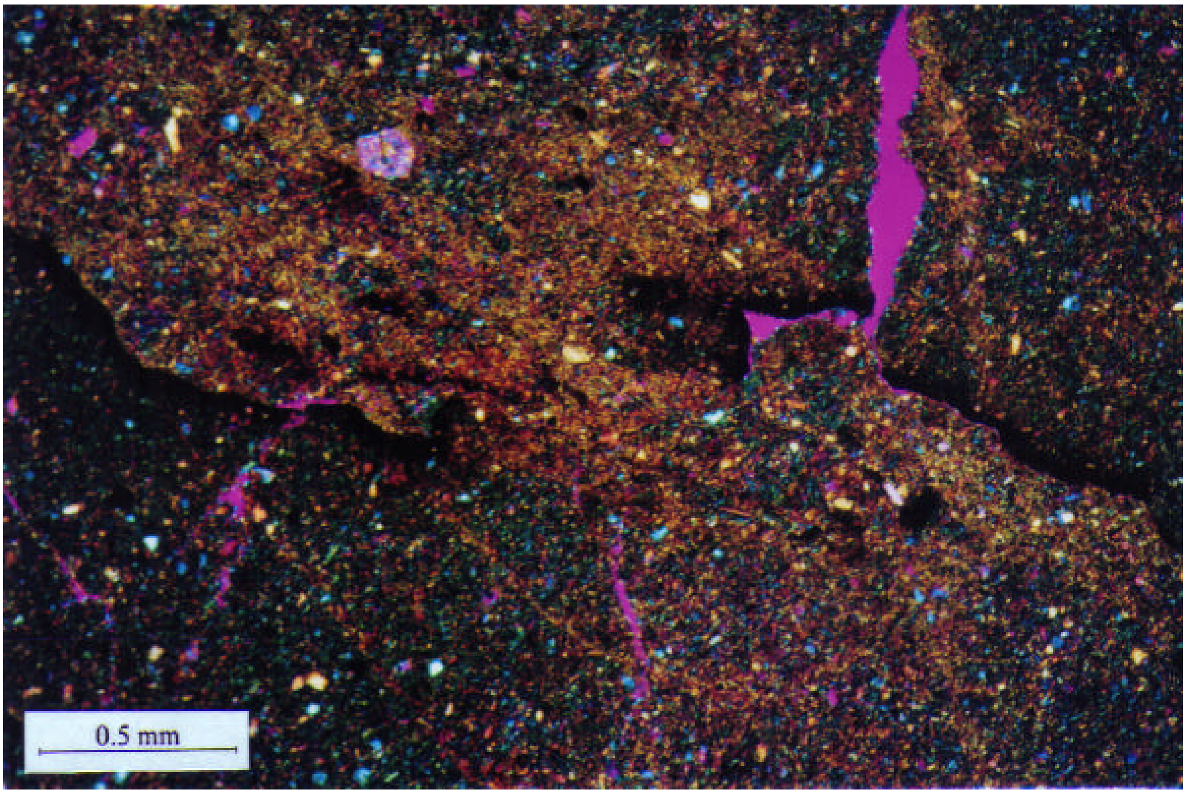

Figure 4.9 Tinted polarized micrograph showing part of the iron stained boundary (brown-black) in section 1a (vertical section from north-west to south east).

Sections 1b and 1c (see *Figure 4.3* for sample site) are broadly similar to each other, as would be expected. The upper sixty percent of the slides are formed of blocks with a single direction internal fabric or random fabric material. These blocks are separated by shears in numerous directions. The lower forty percent of the slides consist of areas below a strong iron stained boundary (*Figure 4.11*) which have strong single direction fabrics with an apparent dip 45° south west. These areas are cut by two shear zone sets (*Figure 4.13*). It is presumed the primary fabric formed in the same Primary Fabric Event as that seen in Section 1a.

The first shear zones have an apparent dip orthogonal to the primary fabric with sinistral *and* dextral displacement. The second shears displace these shears dextrally and are orientated horizontally. Internally, the first shears have grains aligned along the zone, the second have an apparently random internal fabric. It is assumed that the first shears are those formed in Shear Event One and the second those formed in Shear Event Two. There is no evidence of the second shears being truncated by the first, however, there is a variation in the displacements of the first shears along one of the second shears. This variation may suggest Shear Events One and Two were simultaneous, though it may be due to different levels of movement along/ductile accommodation around the shear. The fact that the Event One shears with less displacement along Event Two Shears were formed more vertically suggests a rotation of the primary stress direction with time. This may be a result of a change in the load application direction under strain along the Event Two shears. Alternatively, the rotation may be a result of a change in the fluid conditions. If the shears were formed synchronously this increase in angle might represent drying conditions (Chapter Three).

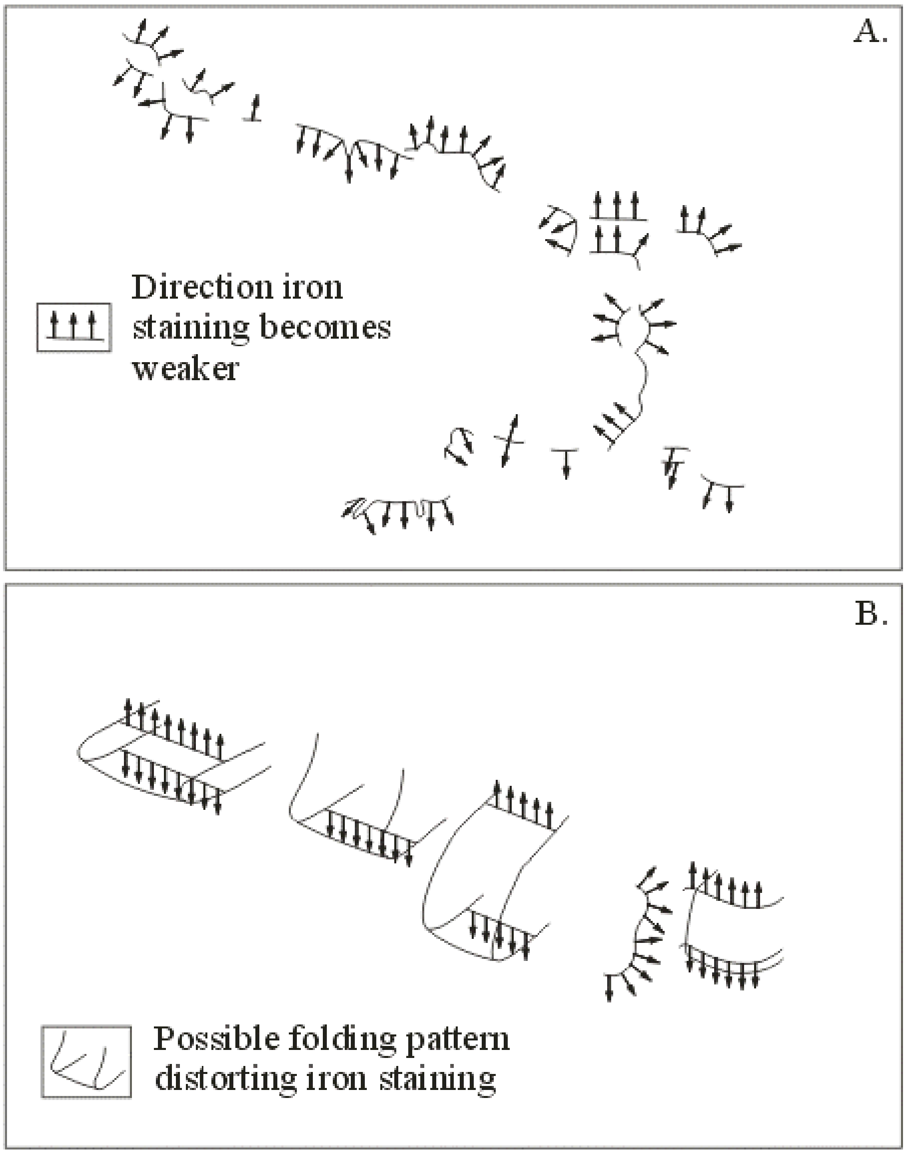

Figure 4.10 a) The Iron staining in section 1a (vertical section from north-west to south east). b) Diagrammatic representation of the possible folding responsible.

Iron staining is found bounding the blocks on at least one side, rather than being inside the blocks. This positioning indicates the staining strengthened the material prior to block formation (*Figure 4.14*). In places dewatering deformation can be seen to have occurred (*Figure 4.15*) after or during block emplacement. Dewatering is also seen at the boundary between the upper and lower areas (*Figure 4.11*). Shears from Shear Event One can be seen crossing the dewatering areas indicating that dewatering occurred before this event. Some of the blocks in the upper area contain shear zones of both Shear Events dictating that the blocks were moved after these events. There are, therefore, traces of *two* dewatering periods.

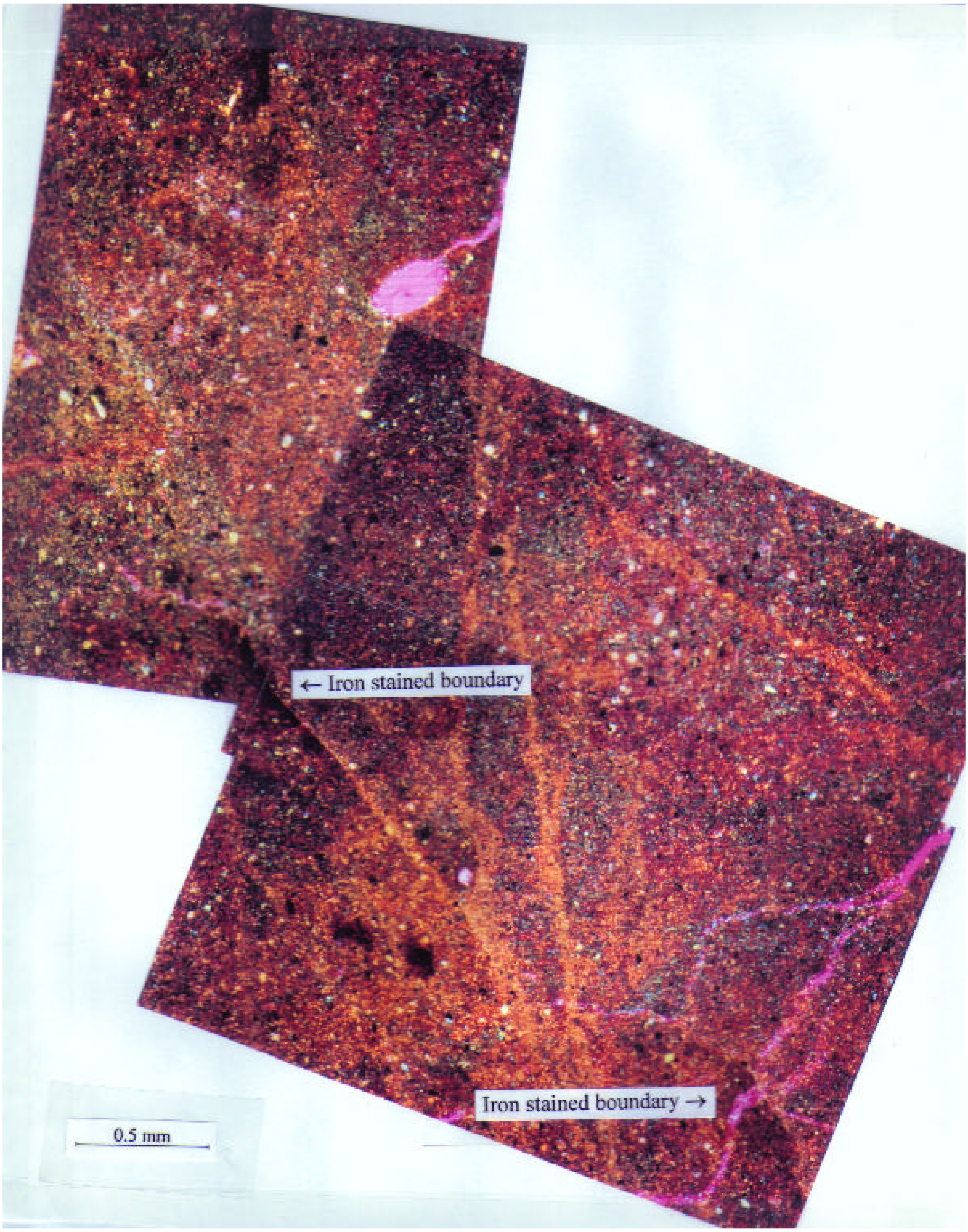

Figure 4.11 Tinted polarized micrograph showing the boundary between the two areas of Sections 1b/c (vertical sections from north east to south west). Above the boundary the material is formed from rotated blocks, each with its own primary fabric direction. Below the boundary the material has a single primary fabric.

4.4.3 Description (lithofacies E)

Sections 2a and b have similar micromorphologies. Each is formed from clays and silts with conformable silt sized material layers of various lengths up to 5 mm, and various widths up to 0.4 mm (*Figure 4.12*). These layers are truncated and rotated by shear bands in a wide variety of orientations. The shears have a high strain morphology (*Figure 4.12*, and Chapter Three) and where a previous fabric can be seen, the dislocation across the shear is often infinite. Both the layers and the matrix surrounding them have single internal fabric orientations between the sets of shears, through deformation occasionally has destroyed the fabric completely. This suggests an original primary fabric that has been deformed, though to no consistent final orientation (*Figure 4.12*).

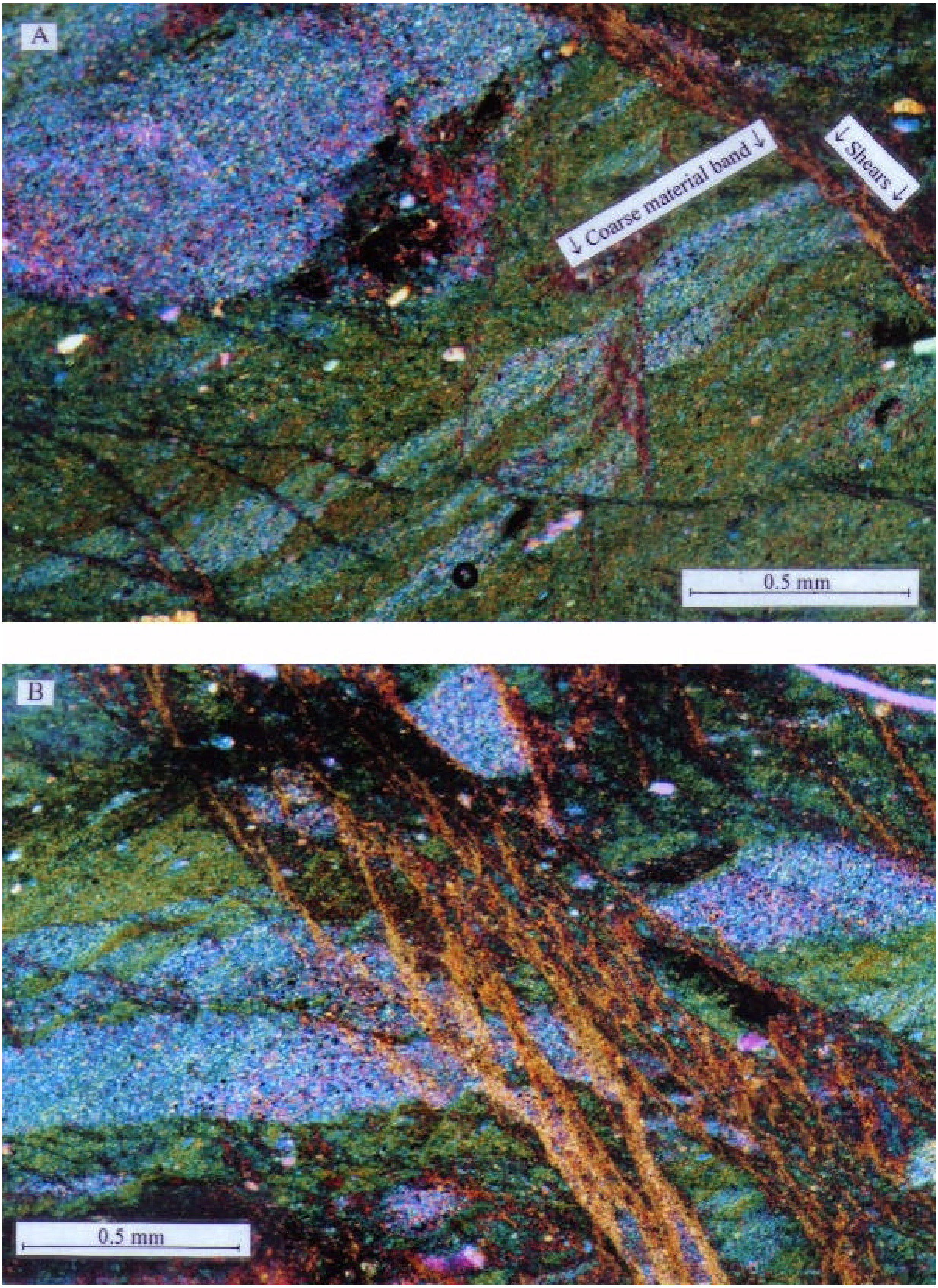

Figure 4.12a/b Sections from lithofacies E (sample 2a). Cross polarized light with tint plate. West-east vertical plane.

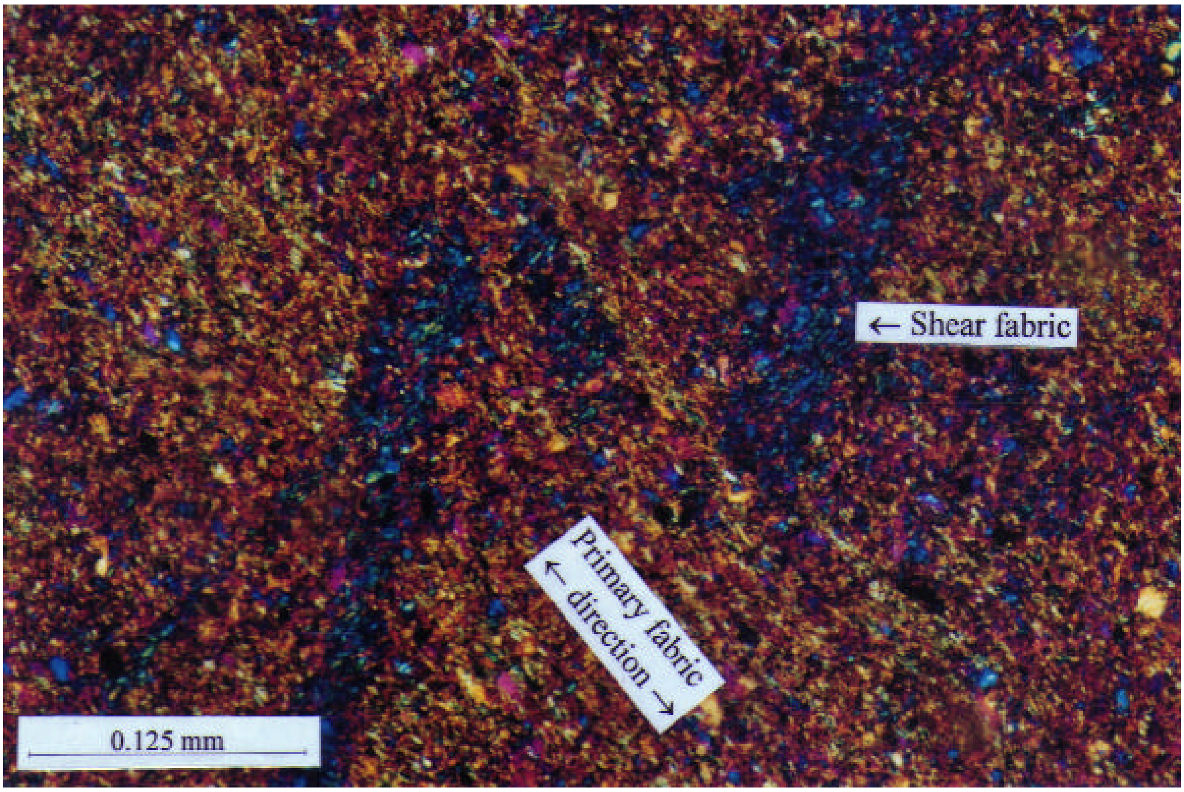

Figure 4.13 Tinted polarized micrograph showing shear fabrics in section 1b / c (vertical sections from north east to south west). Primary fabric (yellow) dips south west. Shears formed in Shear Event One (blue) dip north east, and are displaced by shears in the primary fabric direction (yellow as well).

4.4.4 Interpretation (lithofacies D)

The displacement across the shears formed in Shear Event One and Two may indicate they were the result of a single compressive deformation, or tensile conditions at a flow-nose (following Menzies and Maltman, 1992, sample M2). In this case the compressive stress would be approximately horizontal, and tectonic, rather than by vertical loading (as found by Menzies and Maltman). As such, the features could not be due to consolidation (Chapter Three). However, there is no evidence for the second shears being truncated by the shears of Shear Event One. Their simultaneous development is speculation based on the likely environments of formation. Two temporally disparate, opposing, stresses producing a single shear set each are less likely than a single compressive force. The features are unlikely to have formed under a simple shear geometry. The development of simple shear fabrics includes the development of secondary shears (thrust shears and conjugate Riedels) after the initial (Riedel) shears (Morgenstern and Tchalenko, 1967, see Chapter Three). However, the progressive development of the fabric on increasingly large scales during shear means the two sets of shears *are* truncated by each other in simple shear geometries. Thus, the fabric seen here is unlikely to represent a simple shear geometry. This leaves a pure shear geometry, or more complex strain conditions as possible. One possible explanation is that the movement on the first set of shears was eventually prevented on a larger scale than the thin sectioned area, and the second shear set activated to relieve stress. Such a sequence has been suggested for the larger scale back-thrusting of the Bride Moraine on the Isle of Man (G. Thomas, *pers.comm.*, 1996).

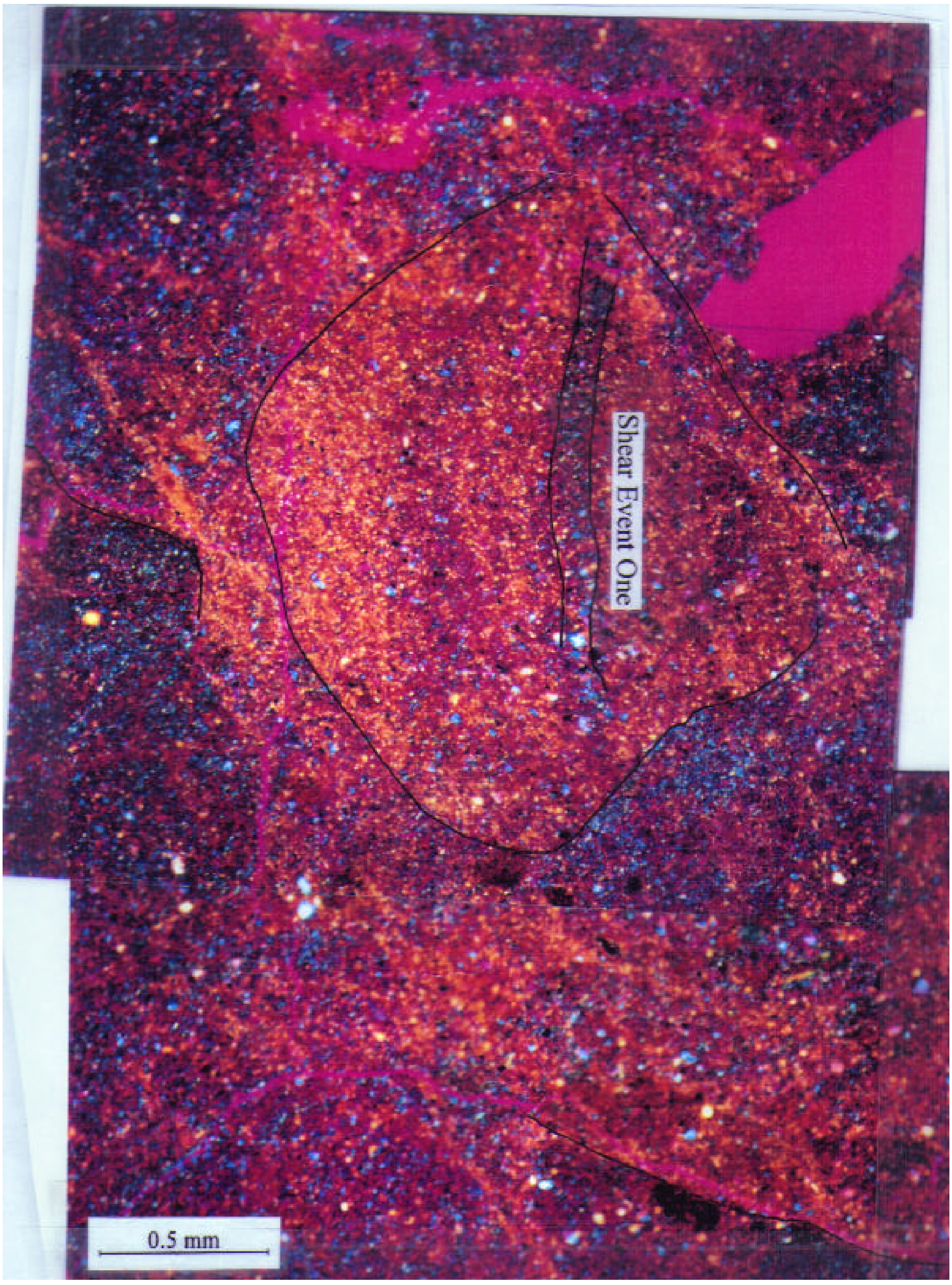

Figure 4.14 Tinted polarized micrograph showing an iron stained block in the upper part of section 1b (vertical section from north east to south west).

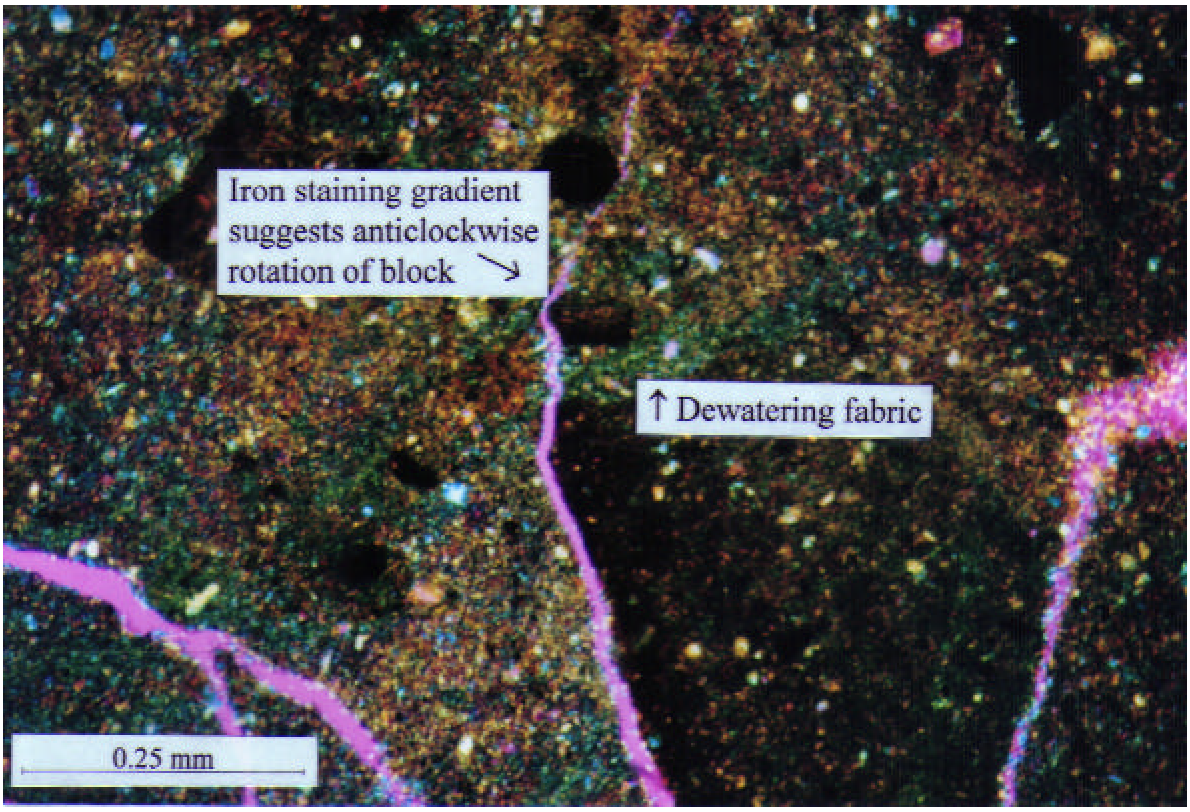

Figure 4.15 Tinted polarized micrograph showing a dewatering fabric destroying a block in section 1b (vertical section from north east to south west).

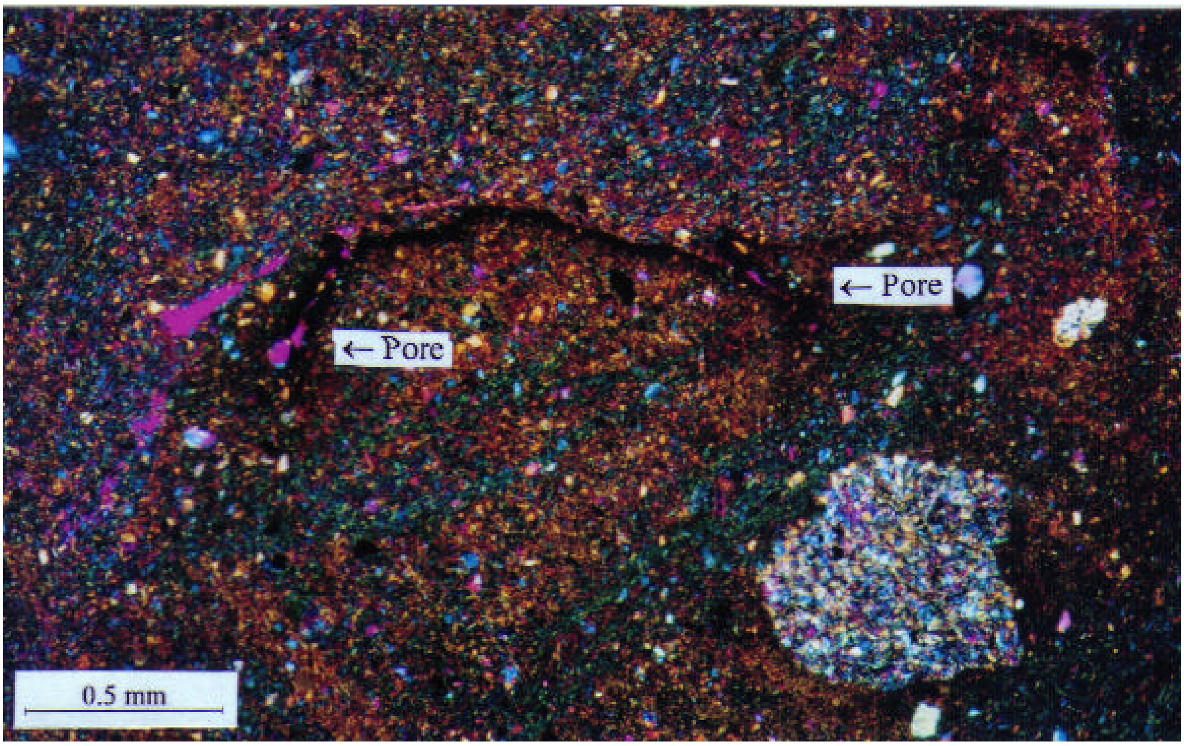

Figure 4.16 Tinted polarized micrograph showing iron staining around pores in section 1a (vertical section from north west to south east).

The complexity of the iron stained boundary in slide 1a. (*Figure 4.10a*) indicates one of two possibilities.

a) The water carrying the iron did not flow simply from top to bottom of the slide. Instead it moved by capillary action or under a fluid pressure gradient against gravity, such that staining occurred at flow barriers from both above and below. There is evidence for such heterogeneous movement in the form of iron staining around large pores (*Figure 4.16*). That these *are* pores and not sampling and preparation cracks is suggested by their location in the hardest part of the sediment; the iron stains. Deposition of iron from bulk through-flow is unlikely *after* an efficient pore system developed, therefore the throughflow would have to be earlier than the pores. There is no need to resort to subglacially pumped meltwater to explain the pressure gradient necessary for heterogeneous through-flow. If saturated sediments are slightly heterogeneous (as seen in the primary fabric) they are likely to develop heterogeneous fluid movement as they drain. The deposition of impervious iron layers would have led to the development of a pore system as they would allow the head to built up, however, it is equally possible the head build-up was externally induced. Pore systems rarely develop in iron-pans in soils, however, the potential head in thin soils is much smaller. The presence of the primary fabric and its lack of a consistent staining gradient direction suggests the heterogeneous flow was not due to ice growth in the material.

b) The boundaries were implaced and subsequently deformed as in Figure 4.10b.
The primary fabric inside the bound areas has been disturbed so that it is largely random, though horizontal bands of primary fabric broken up by shears (in the relative orientation of Event One shears) are found within this. The horizontal bands could be indicative of the folding of the sediment. If so, then this folding represents another deformational event (Fold Event One).

The randomness of the fabric fits either explanation as such randomness may constitute a flow barrier. The folding disruption may therefore have occurred prior to the iron emplacement.

4.4.5 Interpretation (lithofacies E)

The micromorphology of samples 2a/b is wholly consistent with the interpretation of the lithofacies as a glacitectonite of laminated sediments, made on the basis of ephemeral outcrop scale evidence (see above; D.Evans, *pers.comm*., 1997). Given the area over which lithofacies E is found it is likely that the original material was deposited in a marine or lacustrine situation. The fine lamination suggests the body of water was associated with an ice mass that had a water system that could transport coarse sediment into the proglacial environment (ie., a warm bedded ice mass). Any primary fabric is likely to have been formed subglacially, as deposition through water does not produce strong fabrics (Chapter Three). The well developed nature of the shears and the often completely reworked fabric of the matrix suggests considerable strain which points towards a subglacial origin for the deformation as well. We will see further evidence for the subglacial deformation of this material when we examine one particular feature that is present near the surface of lithofacies E (Chapter Five deals with this particular feature separately from this general discussion of the sedimentology of lithofacies E, largely to spare the reader a set of arguments unrelated to the general sedimentology, but also because the methodology for handling the evidence is very different).

4.5 Summary and Synthesis

To summarise the analysis given above a timeline may be constructed, thus,

Lithofacies E formed

a) Laminated sediments deposited in a lacustrine or marine situation from warm bedded ice.

b) Laminated sediments deformed subglacially.

Lithofacies D formed

c) Primary Fabric Event forms a fabric with a maximum true dip of 35° down to the west. This alignment is either due to compression orthogonal to the fabric (suggesting flow or subglacial consolidation under an overburden and pure shear stress) or pervasive shear (which may be subglacial). The development of such fabrics is examined in Chapter Seven.

d) The iron stains may have been deposited.

e) Fold Event One distorts the iron stain boundaries. The fold direction is complex.

f) The iron stains may have been deposited.

g) The sediment dewaters. This drying may explain the change from the pervasive deformation of (c), to the discrete shear of the two following events.

h) Shear Event One produces a shear plane with a maximum true dip 35° down to the east. Note that the ice in the area moved east to west.

i) Shear Event Two produces a shear plane with a maximum true dip 45° down to the north west. These shears may have developed late in Shear Event One, and therefore represent the Principle Displacement Zones (Chapter Three).

j) Blocks seen in the upper parts of sections 1b and 1c move. This movement appears to be by pervasive deformation, with the flow of material carrying the blocks. However, the large number of differently orientated shear zones in the upper area may suggest some movement by discrete shear. These shears may also have developed late in Shear Event Two; more vertical shears may have formed later in this event. These shears survived in the lower, 'unblocked', areas of 1b and 1c where they were protected from break-up by the iron boundary. The return to pervasive shear may imply a lower effective pressure than during the shear events.

k) The sediment dewaters.

There is no evidence in the sediments that any of the events from 'c' onwards took place subglacially, except the moderately high strains which must have been involved in 'c'. The timeline is by no means certain as some features seem to be formed diachronously. There are instances of Shear Event One shears stopping at dewatering fabrics. However, these tend to be small and this truncation may be attributed to the extra strain needed to orientate the more random fabric. More serious is the identification of dewatering fabrics which appear to have been formed after block emplacement. These fabrics may suggest either events (g) to (j) occurred simultaneously (which would explain the shears associated with the blocks) or that there was a second dewatering event (k). If the second is the true interpretation it would certainly match a lower effective pressure in event (j) associated with more pervasive movement (Chapter Three).

One of the most important inferences that can be drawn from the thin sections is the simple fact that the iron staining at the boundary between the upper and lower diamicts is not indicative of an interglacial or interstadial period, as some researchers have suggested. This timeline suggests that the iron staining occurred prior to the last deformation though possibly after the primary fabric formation. Thus, at the longest estimation, iron deposition occurred sometime between the start of the last glaciation and the end of periglacial activity (under cold climate conditions). There is no reason to suppose the iron staining at the boundary between the two diamicts is not from the same event, concentrated by the permeability change to the heavy, consolidated, clayey, lithofacies E.

Permeability change alone, however, is not a sufficient reason for the chemical precipitation of iron; there must be a chemical environment change. In soils and between lithofacies D and E, where water levels and material vary vertically, it is not hard to produce vertical chemical changes. However, subglacial or flow tills would be expected to be saturated throughout and it is hard to envision chemical changes vertically in lithofacies D.

Figure 4.17 gives the environments in which different iron minerals are stable (Baas-Becking *et al.*, 1960, Garrels and Christ, 1965). Iron is only commonly a solute in anoxic marine/lake sediments and in acidic peaty soils. Outside of these environments iron movement is rare. Ice thicknesses dictate that upland peats did not survive the glaciation of this area. The iron supply was, therefore, the sediment itself, or its source rock. This hypothesis matches the large amount of 'primary' iron minerals in the thin sections. This hypothesis is also backed up by the depth the sample was taken from. It is unlikely that washed-in iron would precipitate so widely throughout such a thick sediment if the precipitation was caused by the diamict's chemistry.

Thus, the most likely explanation for the iron staining is that the sediments were at some stage submerged under anoxic deep-water conditions. The sequence of events involved in the iron deposition will be dependant on the mineralogy of the precipitate. The colour in thin section suggests the precipitate is hematite, however, the yellow staining of the deposit on a larger scale may point to greater pyrite precipitation. Further evidence in favour of pyrite is given by Grant (1990), who suggests that there is little hematite in the sediments on the basis of magnetic studies.

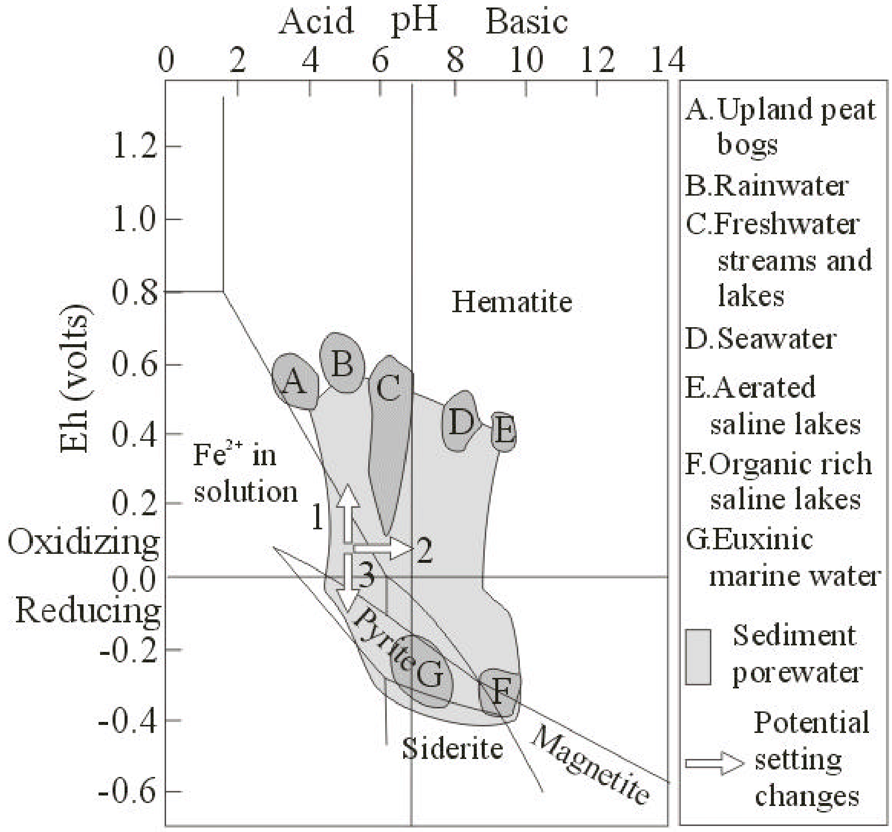

Figure 4.17 Different chemical conditions in natural environments (shaded with letters) and the iron minerals stable in them (lines and names). Arrows show the paths in pH and redox potential (Eh) space that possibly explain the presence of iron staining in lithofacies D. After Baas-Becking et al., 1960; Garrels and Christ, 1965; Tucker, 1991.

Figure 4.17 shows the three possible environmental changes that would have led to precipitation. Hematite could have been deposited in a change from anoxic to oxic water (Path 1) or from anoxic fresh water to anoxic saline water (Path 2). Pyrite could have been deposited in a change from oxic to anoxic marine conditions (Path 3). The redox potential of natural environments are chiefly controlled by bacterial action (Baas-Becking et al., 1960). It seems likely that the sediments were deposited in an environment too cold for rapid bacterial action on the scale of the precipitation seen here. It is possible that anoxic conditions could be produced chemically by non-seasonal capping of the deep water by ice or fesh water. However, the precipitation was probably induced by a change in pH. This limitation suggests Path 1 is most likely. The conflict between the most likely environment (hematite producing) and the likely mineralogy (pyrite) can only be resolved by a more detailed mineralogical examination.

Each path can be accommodated into the history given for the deposit. While we have no evidence that gives an absolute origin of lithofacies D, it is almost certainly ‘glaciogenic’ in the broadest sense of forming due to the presence of a glacier. What we *do* have evidence for in the sediment is its history *after* deposition. The sediment was deposited in a saturated state and deformed, the deformation being pervasive so as to remove the structures associated with deposition and form the primary fabric (event c). This deformation could have occurred subglacially, proglacially, or periglacially. Iron deposition occurred in the diamict at some point after this in a proglacial lacustrine / glaciomarine setting caused by the trapping of water against the hills to the North, or by isostatic depression in front of the ice, respectively. The throughflow was either heterogeneous or the iron stains were deformed in the same environment after iron deposition (f). Outcrop-scale folding may also have occurred in this environment. The sediment then dewatered as the external water level fell (g) and was subsequently deformed by shear (h,i) and pervasive movement (j). The shears are not suitably orientated for them to have been associated with consolidation, and the low strain recorded in the shears renders them unlikely to have been formed subglacially, as does the evidence for a previous deep water environment. The change from discrete to pervasive shear may have been due to a change in water phase (for example, the change from permafrost to solifluction in a periglacial area), between two environments, or in one, seasonally variable, environment. Alternatively it may have been associated with the extrusion of fluid from areas of discrete deformation. Such an extrusion was seen in the formation of outcrop scale folding, which may also be synchronous with the deformation seen here.

4.6 Conclusions

The micromorphological study above shows that the iron staining between lithofacies D and E was formed after the start of the last glacial period. This chronology removes one line of evidence that was used in the argument for two glaciations in the area. The identification of the 'fold' structure seen in outcrop as a deformational feature throws doubt on the similar 'frost-wedges' used as the other line of evidence in the argument.

The microstructural analysis suggests lithofacies E formed in glaciomarine or lacustrine conditions, and was then overridden and deformed. However, the evidence gives little information as to the absolute origin of lithofacies D. Boulton's (1977) evidence from Glanllynau indicates that lithofacies D was probably deposited proglacially from supraglacial meltout material. However, the microstructural study *does* allow us to see that much of the outcrop scale structural evidence is almost certainly postglacial in origin at Criccieth, and that lithofacies A to D cannot be described by 'broad brush' terms such as 'terrestrial' or 'glaciomarine' at this location, as they have been altered and remobilised in both a proglacial, and possibly a deep-water, environment.

That the sediment passed through a deep-water environment after initial deposition is suggested by its deformational and chemical character seen at the micro- and outcrop scales. These attributes give contradictory evidence for the size of such a water body. A *local* ice-marginal lake would explain the absence of structures seen in this deposit in material west of Castle rock, however the iron staining of lithofacies D is regional. This regional staining suggests the *structures* at Criccieth are limited to this location by local topography, and the absence of the ice-wasting conditions invoked by Boulton (1977) further along the coast. Following the period of chemical precipitation associated with a subaqueous environment, there was a period of disturbance. The presence of lithofacies C and a large frost wedge in sequence indicates a period of periglaciation, including considerable cryoturbation.

To conclude, lithofacies E formed through the deformation of laminated water-lain sediments. The microstructures in lithofacies D cannot give an absolute origin for the material, however, they do provide evidence for the postglacial history of the material (a summary of this history is given in *Figure 4.18*), and show that much of the remaining structural record of the sediments is postglacial.

This study has revealed considerably greater environmental detail than is possible using outcrop scale features through the use of sub-millimetre scale structures. Such details allow us to reconstruct the environmental history of the deposit with greater accuracy. The following chapter, in contrast, concentrates on a unique event, and aims at a more detailed reconstruction of the processes acting during the glacial formation of lithofacies E. This reconstruction allows us to accurately detail aspects of glacier dynamics.

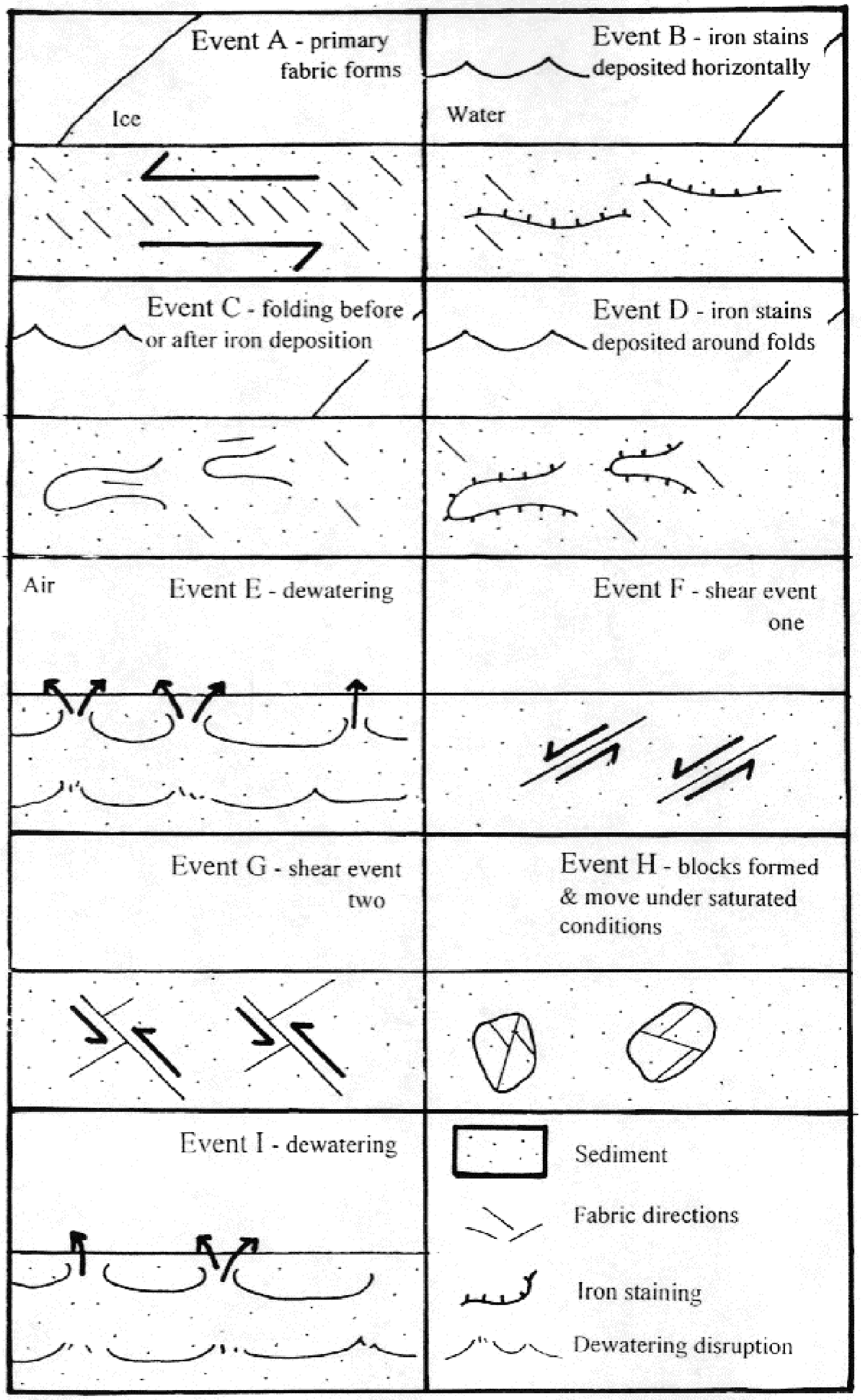

Figure 4.18 The postglacial history of the deposit at Criccieth.