Subglacial deformation associated with a rigid bed environment, Aberdaron, north Wales.

JANE K. HART
Department of Geography, University of Southampton, Southampton, SO17 1BJ, UK, jhart@soton.ac.uk

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@ http://boris.qub.ac.uk/ggg

Abstract

At Aberdaron, north Wales, a complex sequence of homogeneous tills and fluvial sediments overlie a hard rock base. The lower diamicton association at the bottom of the sequence consists of deformed tills and lenses of stratified sediments. It is suggested that these represent deforming bed tills and subglacial fluvial units which have been deformed together by subglacial excavational deformation. The central part of the section is marked by undeformed fluvial sediments along an unconformity which has been folded in places into a series of antiforms. It is suggested that the fluvial sediments were deposited by subglacial fluvial processes, and these three forms represent: i) canal features associated with "steady state" deforming bed conditions and a braided channel network; ii) channel features and iii) R-channels associated with rigid bed conditions. It is further suggested that this fluvial event was followed by a drumlinising event associated with fast ice flow (subglacial deforming bed erosion).

Keywords: deforming bed till, subglacial channels, glaciation of Wales, drumlins, Devensian glaciation.

Introduction

The Weichselian glacial sediments along the coast of north Wales (Figure 1) have attracted a great deal of research in recent years. Eyles and McCabe (1989) suggested a glaciomarine origin for these deposits, while McCarroll (1991), McCarroll and Harris (1990, 1992) and Austin and McCarroll (1992) have elegantly shown how this site does not contain any *in situ* glaciomarine sediments, and have interpreted the sediments within a terrestrial rigid bed model. More recently, Hart (1995a) has suggested a terrestrial deforming bed origin for these sediments. This area was affected by both the Welsh ice sheet, which moved outwards from Snowdonia, and the Irish Sea ice sheet, which moved over the weak unconsolidated sediments at the bed of the Irish Sea.

Subglacial deforming bed conditions occur when a glacier moves over unconsolidated sediments, in which high pore water pressures are generated. This leads to a coupling between the ice sheet and the underlying sediment, which produces an increase in velocity of the glacier (Boulton and Jones 1979) and deformation in the underlying sediments (Hart and Boulton 1991a). There are a growing number of sites in Britain where deforming bed conditions have been inferred (Figure 1), however, most studies have concentrated on the unconsolidated lowlands, e.g. East Anglia (Hart *et al.* 1990, Hart and Boulton 1991a) or East Yorkshire (Boulton and Dobbie 1993; Eyles *et al*. 1994; Evans *et al.* 1995). Similarly in North America, research has been concentrated in areas composed of unconsolidated sediments, e.g. the Great

Lakes area (Boulton *et al.* 1985; Fisher *et al.* 1985; Beget 1986; Hicock *et al.* 1989; Alley 1991; Clark 1992). In contrast, in north Wales, the bedrock which is near the surface consists of rigid metamorphic and igneous rocks of Pre-Cambrian to Carboniferous age (except for a few isolated igneous intrusions). As a result of this, the landscape has a dramatic relief (over a 1000m in Snowdonia and up to 140m on the Lleyn Peninsula), and the coast line consists of a series of headlands and bays.

In this paper the glacial sediments at the site of Aberdaron, on the extreme western point of the Lleyn Peninsula (Grid Reference SH 173, 263) (Figure 1) are examined. This site is located within a bay almost 3 km long. The glacial sediments at this site were deposited by the

Figure 1 - Location of the site, with some examples of some of the reported UK and Ireland deforming bed sites (after Hart, 1995c).

Devensian/Weichselian Irish Sea ice sheet. Aberdarron is located approximately 10 km west of the zone of interaction between the two ice sheets which occurs in the Porth Neigwl area (SH 242 283 to SH 290, 256). The Aberdaron sediments are re-examined and the different styles of deposition and deformation compared with other similar sites.

Sedimentology of the Aberdaron section.

The coastal section at Aberdaron is shown in Figure 2 and mostly consists of grey fine-grained homogenous diamicton with lenses of stratified clays, silts, sands and gravels. Whittow and Ball (1970) suggested that there were two advances of the Irish sea ice sheet across Lleyn, a first from the NNW and a second from the NNE, separated by non-glacial conditions. However, McCarroll (1991) has shown that only one advance affected this area.

The section was analysed using sedimentological and structural investigations. Till fabric analysis was also carried out at many of the sites. At each site a minimum of 25 clasts with an axial ratio greater than 1.5:1 were sampled. The initialised eigenvalues were then calculated. These eigenvalues (S1, S2 and S3) summarise fabric strength along the three principal directions of clustering (after Mark 1973; Dowdeswell and Sharp 1986). A fabric with no preferred orientation (weak fabric) would have equal eigenvalues, whilst a strong fabric would have a high value in the direction of maximum clustering (S1) which is usually the direction of tectonic transport, and a low value in the direction of least clustering (S3).

McCarroll (1991) divided the sequence at Aberdaron into two sediment associations:

1. a *lower diamicton association* described as a crudely stratified diamicton containing contorted lenses of fine sand and silt, and interpreted as a melt-out till;
2. an *upper diamicton association* consisting of diamicton beds separated by sands and gravels, and interpreted as flows tills and braided stream deposits. This unit was not examined in this study (except at its base) because of problems of inaccessibility.

The general sequence described by McCarroll (1991), of a lower diamicton association with discontinuous stratified beds and an upper diamicton association with continuous beds, can be seen best in the central part of the section (240-600m - figure 2). Here the two diamicton associations are separated by an unconformity. It can be seen from figure 2 that the unconformity between the two diamicton associations is not subhorizontal, instead it is composed of a series of antiforms. The largest one is seen at site 9 where the unconformity is marked by a sandy clay bed, which contains normal faulting on the limbs of the antiform, with a throw of 12 cm with a strike of 14^{o} (tectonic direction of 134^{o}). In the east of the section there is a large periglacial slope deposit (head) built up against the pre-Dimlington sea cliff (Wig scree, McCarroll and Harris 1990).

This present study showed that the lower diamicton association consists of three different facies which are well illustrated at site 1 (250 m along the section in Figure 3).

Homogeneous Grey Diamicton - This is a fine grained diamicton found throughout the sequence, but mostly at the base. McCarroll and Harris (1990) describe that in both upper and lower diamictons the “dominant facies is a dense mud with scattered stones and broken shell fragments”. Austin and McCarroll (1994) show that these shells are not *in situ* but were picked up by the glacier as it crossed the bed of the Irish Sea. Two fabrics were taken in this unit at site 1 and 2. The results from the till fabrics are shown in Figure 4 and Table 1. These results

indicate a low fabric strength and a south westerly ice flow direction.

Grey Diamicton with ungraded laminations and deformed lenses - This is very similar to homogenous facies described above, but has a series of laminations and lenses within it. This facies is found at different levels within the sequence and at site 1 this occurs immediately above the homogeneous diamicton and above the distinct unconformity (it is also found in this location at site 3). There are a number of different styles of laminations and lenses within this facies:

Figure 3- Schematic diagram of Site 1 showing the top of the lower diamicton association and the base of the upper diamicton association, the unconformity the separates the two units, part of a channel shaped feature, and the different diamicton facies in the lower diamicton association.

a) ungraded thin (1- 10 cm) laminations of sand and/or silt within the grey diamicton (Figure 5a). In some places these are a melange of sand and clay (Figure 5b);

Table 1 - Eigenvalue results from Aberdaron and other related sites.

Site		**S1**	**S3**	**direction (°)**
This study	1	0.665	0.153	231
	2	0.667	0.086	208
	3a	0.504	0.135	178
	3b	0.574	0.034	159
	3c	0.48	0.163	188
	7a	0.733	0.072	331
	7b	0.733	0.039	331
	7c	0.655	0.069	257
McCarroll and Harris 1991 Aberdaron	LDA	0.585	0.077	NNE /SSW
		0.615	0.127	
		0.701	0.119	
		0.723	0.115	
		0.723	0.077	
		0.754	0.088	
	UDA	0.485	0.077	NW/SE & NE/SW
		0.508	0.077	
		0.585	0.177	
		0.585	0.157	
		0.615	0.127	
		0.615	0.107	
Lawson 1979, Melt-out till Matanuska Glacier, Alaska		0.747	0.018	
		0.778	0.029	
		0.781	0.058	
		0.837	0.048	
		0.840	0.021	
		0.850	0.034	
		0.853	0.037	
		0.884	0.029	
Hart 1995c, Debris-rich ice Matanuska Glacier, Alaska	1	0.634	0.143	
		0.591	0.056	
		0.807	0.076	
	2	0.649	0.024	
		0.633	0.023	
Hart and Waller 1996, Debris-rich ice Worthington Glacier, Alaska		0.730	0.043	
		0.552	0.52	
		0.591	0.031	

b) Lenses of stratified sediments where the internal structure was concordant with the external shape (Figure 5b and c). These are often surrounded by laminations which echo the external shape of the lens.

c) Lenses with internal deformation (i.e. internal bedding discordant with lens shape) (Figure 5d). At site 8, one of the larger sandy silt lenses has a deformed channel shape, but the internal bedding contains chevron folding.

d) Lens - shaped zones of differing lithology within the diamicton, e.g. site 4, where the diamicton is composed of many chaotically arranged clasts of silty sand (1 - 10 cm in diameter) associated with thin (1 cm thick) streaks of sand.

Within the lenses of stratified sediments, the material has behaved differently. The sandy clay layers have been deformed by brittle deformation (due to the cohesive properties of clay), whilst the silty-sand layers have deformed by ductile deformation. Also there is an interaction between the contrasting lithologies (i.e. sand and diamicton) with the formation of boudins which can be seen at site 5 (620m along the section).

The fabric associated with this facies was investigated at site 3 (285 m along the section) (Figure 6). The diamicton is clay rich at the base and contains a small (30 cm) isoclinal fold (fabric 3a) which has a strike of 88^{o} (tectonic direction 178^{o}). It becomes more sandy towards the top (fabric 3b). The unconformity is marked by a planar bed of gravel which is discussed in more detail below. Above the unconformity there is a further grey sand-rich homogeneous diamicton associated with a stratified lens of sandy-silt and ungraded lamination. This upper diamicton grades upwards into more homogeneous clay-rich diamicton (fabric 3c). The fabric strengths at these three locations are similarly very low and indicate a southerly ice flow direction.

Undeformed stratified sediments in planar and channel forms - In the western part of

Figure 4 - Fabric results from: a) this study; b) Aberdarron - McCarroll and Harris (1992); c) melt-out till from Matanuska Glacier, Alaska - Lawson (1979); d) debris-rich basal ice layer from Matanuska Glacier, Alaska - Hart (1995b) and e) debris-rich basal ice layer from Worthington Glacier, Alaska - Hart and Waller (1996). The thick dashed line marks the boundary between: lodgement tills and deforming bed tills with a thin deforming layer (below the line); from deforming bed tills with a thick deforming layer (above the line) (Hart, 1994).

Figure 5 - Schematic diagram to show the deformational styles within the grey diamicton: a) Ungraded thin (1-10 cm) laminations of sand and/or silt. b) Lenses of stratified sediments where the internal structure was concordant with the external shape with laminations which echo the external shape of the lens; c) Deformed lenses; d) Lenses with internal deformation (i.e. internal bedding discordant with lens shape).

the section, at the top of the lower diamicton association, there is a distinct boundary (unconformity), which is marked by a series of undeformed stratified features. These range from semi-planar beds of gravels seen at site 3 (Figure 6), through to inverted channel forms at site 6 (Figure 7), to large channel-shaped units (Figs. 2 and 8). The sediments within these units are stratified water-lain deposits, and range in grain-size from silty- clay to coarse gravel. Much of the stratified sediment along the unconformity consists of planar units of sand and/or gravel. However at site 3 (Figure 6) it can be seen that erosion has occurred in places at the top of the unit (located adjacent to a deformed stratified lens within the diamicton). At site 6 (Figure 7) there is a series of channels which appear inverted. These have a flat base and a concave downwards top, but appear unaffected by either erosion or deformation.

The largest features are the channels, which have very straight tops and appear unaffected by deformation. Some of these consist of upper channels eroded into lower channels. The channel at site 1 (Figure 3) has planar bedded sandy-silt at its base, which is overlain by chaotically bedded gravel, with a final upper unit of sand and gravel .

Interpretation of the diamicton

Homogeneous diamicton are very difficult to interpret because of the similarity of many glacial environments. However, at Aberdaron, there is a sufficiently large number of other features to aid interpretation. In particular the ungraded laminations and folds; and the deformed and undeformed lenses within the diamicton. These are very typical of subglacial deformation which occurs beneath the glacier within a saturated deforming layer with high pore water pressures. The ungraded laminations form due to the attenuation of folds within the deforming layer (Hart and Boulton 1991a; Hart and Roberts 1994), and the lenses result either from material being brought into the deforming layer from pre-glacial sediments (usually outwash sands formed during the advance) or from direct subglacial fluvial sedimentation (Hart 1990; Alley 1991; Hart and Roberts 1994; Clark and Walder 1994; Hart 1995a). Hart and Roberts (1994) have described the different

Figure 6 - Schematic diagram of Site 3 the top of the lower diamicton association and the base of the upper diamicton association and the unconformity that separates the two units. The lower diamicton association at this site is composed of grey homogeneous tills with stratified sand lenses and folded sand laminations. The diamicton is more clay-rich at the base (Dk) and sand-rich towards the top (Ds). The upper diamicton association is also composed of homogeneous grey diamicton with ungraded laminations and stratified lenses. The diamicton is sand-rich towards the base (Ds) and more clay-rich (Dk) towards the top. On the unconformity is a wide and thin (planar) bed of stratified sediments which shows evidence of erosion.

styles of deformation of stratified lenses within the deforming layer (regardless of origin). The features seen at Aberdaron included cigar-shaped lenses (Figure 5b and c) which are formed by the attenuation of larger lenses within the deforming layer, and striped lenses (Figure 5d) formed by the folding of the lenses followed by attenuation. The small, chaotically bedded clasts within a lens-like form in the diamicton (described at site 4) were probably part of a stratified lens in the process of being broken down and incorporated into the deforming layer. The chevron folds found in the stratified lenses at site 8 must represent transverse compression which accompanies longitudinal extension typical of subglacial deformation.

The fabric data is also very consistent with the interpretation of a deforming bed till. Hart (1994) has shown that high fabric strengths are usually associated with lodgement tills or tills with a thin deforming layer, whilst low fabric strengths are associated with deforming bed tills having a thick deforming layer. On figure 4 it can be seen that the results from Aberdaron plot in the area typical of the latter.

The diamicton immediately above the unconformity (base of the upper diamicton facies) is similar to the lower diamicton association in that it is a grey diamicton with ungraded laminations, deformed stratified lenses and low fabric strength (e.g. Site 3 - figure 6), but higher in the sequence the stratified layers become more laterally extensive and the intervening till could not be sampled. I suggest that the diamicton in the lower and base of the upper diamicton associations is a deforming bed till, and the stratified units along the unconformity are subglacial fluvial deposits. However, the origin of the middle and upper parts of the upper diamicton association could not be determined in this study.

At Aberdaron the base of the diamicton was not exposed in the central and western part of the sequence. Thus it is not known if an outwash sand underlies the sequence, which could have been incorporated into the diamicton (to form some of the lenses). However, the base of the diamicton is exposed in the eastern part of the sequence where it overlies the Wig Scree. The diamicton immediately above this scree was examined in detail (site 7) and the fabric is shown in Figure 4 and Table 1. The boundary between the diamicton and the scree is very indistinct, and the diamicton contains a great many angular clasts derived from the scree. Fabric 7a was taken 1m above the scree and has a similar orientation to the paleoslope of the scree (NE/SW) and a strong fabric strength. Fabric 7b was taken higher in the sequence, 10m above the scree where the diamicton was more sand-rich, with more far travelled clasts. This has a high strength fabric oriented NE/SW. The upper site 7c which is in the upper diamicton association of the sequence is 20m above the diamicton/scree boundary, is in a very sandy diamicton with thin ungraded sand laminations. This has a weaker fabric strength and is oriented SW/NE.

Figure 7 - Schematic diagram to show the inverted channels of gravel at site 6 overlying the unconformity.

t appears that at this site as the glacier first moved over the area, ice flowed down the paleoslope of the scree and incorporated clasts into the base of the diamicton. At this time either lodgement till or a thin deforming bed till was deposited. The scree could have facilitated good drainage, thus preventing the build up of pore water pressure, and reducing the chance of deforming bed conditions. Higher in the section, the ice begins to flow in the direction of regional flow and deforming bed conditions may have occurred.

In contrast to the conclusions discussed above, McCarroll (1991) has interpreted the lower diamicton association as a melt-out till, and the upper diamicton association as an association of supraglacial sediment gravity flows and braided stream deposits. McCarroll and Harris (1992) suggested that the fabrics in the lower diamicton association are strong, indicative of melt-out till, whilst those in the upper diamicton association are weaker, indicative of flow tills. Their fabric results are shown in Table 1 and Figure 4. It can be seen that the results for the lower diamicton association are very similar to those from this study, i.e. they are of low to medium fabric strength, and plot in area typical of deforming bed tills with a thick deforming layer. Studies on the fabric from modern day melt-out tills are very rare because they can not be sampled *in situ*. One of the few reported examples is from Lawson (1979) (Table 1 and Figure 4) whose eigenvalues from melt-out till at Matanuska Glacier, Alaska were far stronger than anything found within the Aberdaron sequence. However, melt-out till fabric will just reflect the orientation of particles in the debris-rich basal ice layer, and it has been suggested by Hart (1995c) that the debris-rich basal ice behaves in a very similar way to the subglacial deforming layer. Thus, in theory, the strength of melt-out till fabrics depends on the basal ice conditions prior to melt-out. This is indicated by the fabric results from debris-rich basal ice layer from Matanuska

Figuure 7 - Photograph showing one side of the large channel feature at Site 1.

Glacier (Hart 1995c) and Worthington Glacier (Hart and Waller 1996) which vary in fabric strength (Table 1 and Figure 4). Similarly, the suggestion by Harris and McCarroll (1992) that the weak fabric of the upper diamicton facies is indicative of flow tills may be unfounded, since the fabric strength of a sediment gravity flow deposit varies according to slope angle and water content (Hart and Roberts 1994). So fabric data alone can not be used to distinguish between different type of tills, but needs to be combined with other sedimentological evidence.

Figure 9 - Different cross-sectional styles of subglacial fluvial features: a) canal and (after Clark and Walder, 1994); b) R-channel (after Clark and Walder, 1994); c) tunnel-fill.

Other criterion to identify melt-out tills are also problematic. Piotrowski (1992) has argued for presence of symmetrical clast drapes, which were not observed at Aberdaron; whilst Haldorsen (1982) has argued that a deficiency of medium- to fine-grain silts is indicative of melt-out till. The problem with the latter, is that if processes are similar in the debris-rich basal ice layer and the deforming layer, then the grain-size of sediment in the two layers will be identical and the final diamicton grainsize will depend on the nature of the original subglacial material.

It is suggested instead, that all the data collected from the site (fabric, sedimentological and structural) needs to be interpreted as a whole, and that this evidence is more indicative of a subglacial deforming environment than any other.

The subglacial fluvial features

The channel features found within the lower diamicton association, e.g. site 1, most likely represent subglacial fluvial deposits. Such features have been recorded from Dinas Dinlle in north Wales (Hart 1995a), north east England (Eyles *et al.* 1982), east Yorkshire (Evans *et al*. 1995) and at a number of sites in North America (e.g. Brown *et al.* 1987; Johnson and Hansel 1990; Clark and Walder 1994). It has been proposed by Boulton and Hindmarsh (1987) that, at the base of an ice sheet flowing over an unconsolidated substrate, at low pore water pressures water will flow through the sediments and the sediments will deform, but at higher pore water pressures, water will tend to become concentrated and flow in pipes. In the first state the subglacial sediment will be behaving in a similar way to a sediment gravity flow, whilst in the later state fluvial behaviour will predominate.

Clark and Walder (1994) have recently argued, based on the theoretical analysis of Walder and Fowler (1994), that there are two types of subglacial drainage. Where glaciers rest over deforming beds the subglacial drainage network should consist of many wide, shallow braided channels along the ice sediment interface, however where the glaciers rest on a hard substrate, the subglacial drainage network would consist of a network of a few large tunnels, with higher flow velocities. Walder and Fowler (1994) termed these wide shallow channels as “canals”, which consist of streams cut into the subglacial sediment with a flat roof of ice (Figure 9a). In contrast, another style of tunnel (associated with a more rigid bed) will be in the shape of an R-channel where water cuts into the ice (Figure 9b). The nature of the subglacial fluvial sediment will depend on the hydraulic gradient (surface slope) and the rheological properties of the till. They suggest R-channels associated with a deforming bed will only exist where the ice-surface slope is high (usually in a valley glacier) or the diamicton is very coarse grained (and thus resistant to deformation).

Clark and Walder (1994) have also argued that traditional eskers (large scale, sinuous, steep- sided, morphological features) can not exist associated with deforming beds. However, there are numerous examples of these, both modern and Pleistocene, e.g. the eskers at Breidamerkurjökull, Iceland (Boulton 1979; Price 1969); the Blakenley esker in North Norfolk (Sparks and West 1964; Hart and Boulton 1991b); and the eskers of East Yorkshire (Catt 1977; Evans *et al.* 1995). Many of these eskers, in particular, the Blakenley esker are cut down into the underlying till, indicating that the subglacial tunnel was within both the ice and the till (Figure 9c) (tunnel-fill).

Figure 10 - Interpretation of the formation of the different types of subglacial fluvial features: a) planar beds/canal features; b) channel features; c) inverted channels/ R-channels.

At Aberdaron we have an unusual situation where there are three styles of subglacial fluvial sediments: a) the inverted channels, which could be interpreted as R - channels;

b) the planar beds, which could be interpreted as wide canals; c) the channel features, which are more similar to either the bottom half of a tunnel-fill or a very narrow canal. The R-channels are composed of gravel, the wide canals formed of sand and gravel, and the channels are composed of silty-sand to gravel. The latter are superimposed on top of one another. These three styles of subglacial fluvial feature also lie along one horizontal (although later deformed) plane.

Assuming that a subglacial braided river system can exist associated with a deforming bed, then these may have occurred throughout the deposition of the lower diamicton association. However, those formed prior to the unconformity event would have been deformed by subsequent subglacial deformation and so outcrop as lenses and not canal forms. As discussed above, Clark and Walder (1994) suggest that the shape of the subglacial fluvial feature depends on the discharge and the strength of the sediment. Since all the features formed at Aberdaron are within a similar sediment, then at this site the discharge was very important. Subglacial fluvial activity may have occurred specifically at this site because subglacial water could have been funnelled into the low-lying area of Aberdaron (which today forms a bay). At the time period marked by the unconformity, once a braided river system had formed, the flow would fluctuate between tunnels, leading to deposition in the canal once pressures dropped (Fig. 10a). Once a tunnel formed, till from the surrounding deforming layer could flow into the tunnel (Alley 1992). This till may be removed by the water in the tunnel and thus allow the tunnel to grow (Fig 10b). In theory, till may be deformed towards the tunnel, or a coarse gravel lag build up around tunnel (as observed at Dinas Dinlle, Hart, 1995a), but these feature was not observed at Aberdaron.

The large channels could be formed in one of two ways, they could either occur due to high discharge and the till flowing into the channel allowing the tunnel to grow (and erode the sides of the channel) or by erosion associated with a rigid bed. At Aberdaron, the latter is probably most likely because the channels are superimposed on to one another.

In order for the R-channels (inverted channels) to form, the bed needs to be rigid. This indicates that the water system found it easier to evacuate the ice rather than the sediment. In order for the bed to become rigid, it must have drained, for this to have occurred there are a number of scenarios:

1. The most obvious explanation, is that the glacier retreated, and Aberdaron was in a more marginal position. It is unlikely that the glacier completely retreated (and the till surface was exposed) because there is no continuous fluvial sedimentation at the unconformity.
2. The bed strength increases because of local changes in the subglacial conditions, which would increase effective pressure, e.g. draining of the subglacial aquifer, reduction in basal shear stress, change in lithology of subglacial sediments.

Thus, it is suggested that at Aberdaron, the R-channels and large channels form associated with relatively rigid bed conditions, whilst the canal features form associated with “steady state” deforming bed fluvial conditions. Large channels in other locations (which do not show evidence of superimposition) may be indicative of higher discharge associated with the deforming bed. In this way there is an interrelationship between R-channels, canals and channels depending on discharge and sediment strength.

Comparison of the style of subglacial deformation at Aberdaron with other sites

The interpretation at this site is that subglacial deforming bed conditions existed throughout the deposition of the sequence, but that there were different styles of deformation. Hart *et al.* (1990) and Hart (1995a) have suggested that if there is net accumulation beneath the glacier then deposition will occur; if the deforming layer moves downwards through the sequence there will be excavational deformation and previous deformational events will be redeformed, but if the deforming layer moves up through the sequence there will constructional deformation and previous deformational events are preserved. However, if there is net removal of sediment there will be erosion, this may not be visible within the sequence unless there is some obstruction to flow, in which case drumlins will form.

Towards the base of the sequence (lower diamicton association) there is evidence of excavational deformation, where old subglacial fluvial sediments have been deformed. Between the upper and lower diamicton associations, there is a further deformational episode that deformed the lower diamicton association into open folds. I suggest that these features could be drumlins seen in cross-section. Such features have also been observed at the site of Melabakkar-Ásbakkar, Iceland (Ingólfsson 1987; Hart and Roberts 1994) and Happisburgh, UK (Lunkka, 1988). If these were drumlins then they would be concentric drumlins, i.e. the form of the interior is similar to that of the exterior (Slater 1929; Muller 1974). It has been postulated by Hart (in press) that these form due to longitudinal extension associated with subglacial deformation and represent large-scale boudinage. Drumlinisation has also been suggested at other sites in north Wales, e.g. Dinas Dinlle, Lleiniog, Beaumaris (Hart 1995a) formed in association with ice sheet coalescence.

As discussed above, it was suggested that drumlins form during a period of subglacial net erosion; it has been suggested by Hart (1995a) that this erosion occurs when there is either an increase in velocity or decrease in sediment supply. Drumlins often occur associated with ice sheet coalescence because: a) these are often associated with convergent ice flow (which could have been ice streams), in which there is an increase of velocity; and/or b) there may be a reduction in subglacial sediment supply upglacier where the ice sheets have joined and a saddle formed, under which basal shear stresses are very low and thus cannot deform/move the underlying sediment. Aberdaron is close to the zone of coalescence and so this may be an important factor in drumlin formation This drumlinisation follows an event which strengthened the bed (retreat of the glacier or local drainage of the bed). The drumlinisation event at Aberdaron may reflect an episode of fast ice flow (extra fast deforming bed conditions), as observed today at Jakobshavn Isbrae (Echelmeyer and Harrison (1990) or Ice Stream B (Alley *et al.*, 1986), as opposed to “steady state” deforming bed conditions.

After the drumlin event, subglacial deforming bed deposition occurred (with the deposition of the basal part of the upper diamicton association). Since the form of the drumlin was preserved this implies that constructional deformation occurred at first. This latter style of deformation is typically found at the glacier margin, and so this subglacial deposition may mark the final retreat stage. However the origin of the sediments towards the top of sequence is not known and may represent supraglacial sedimentation as suggested by McCarroll (1991).

Thus, at Aberdaron there are a number of main subglacial deformational styles/events: i) probable lodgement over the rigid bed rock as the glacier first advanced over the sequence; ii) once a till built up then subglacial excavational deformation with periods of subglacial fluvial activity formed the lower diamicton association; iii) a major drainage event; iv) a return to deforming bed conditions with an erosional episode associated with drumlinisation; and v) constructional subglacial deformation.

Conclusion

Thus, at this site, which was found in a hard bed rock environment, there was a thick (greater than 10m) deposit of deforming bed till. At the base of the sequence there was a deforming bed till with subglacial fluvial units which were probably formed *in situ* by subglacial fluvial sedimentation (lower diamicton association). These units were deformed and indicated that subglacial excavational deformation had occurred. Through the centre of the section runs an unconformity which is marked in many places by stratified sediments, which are in channel forms, planar forms (canal) or an inverted channel forms (R-channel). It is suggested that the canals represent “steady state” subglacial deforming bed fluvial activity, whilst the channels and R-channels reflect a more rigid bed. The change from deforming to rigid bed conditions could either reflect a glacier retreat, or local drainage of the bed.

The fluvial surface and the lower diamicton association has been deformed into anticlines which may reflect drumlinisation. These form due to subglacial deforming bed erosion, and may reflect an increase in ice sheet velocity. After this, subglacial deforming bed depositional conditions returned and a series of deforming bed tills and subglacial fluvial units were deposited (upper diamicton association) associated with constructional deformation. This latter event probably occurred during retreat.

Thus, the site at Aberdaron, resting on a hard rock bed, has a complex deforming bed till and fluvial sediment sequence which reflect different deformational styles. This style of deformation is quite unusual, and the different styles of deformation are only preserved due to the final episode of constructional deformation. It is proposed that “steady state” conditions existed at Aberdaron throughout most of the glaciation, but that there was one “fast ice” event where velocities may have increased and drumlins formed.

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Figure 2. Schematic cliff section (adapted from McCarroll and Harris, 1990).

Table 1 - Eigenvalue results from Aberdaron and other related sites.

Site		**S1**	**S3**	**direction (°)**
This study	1	0.665	0.153	231
	2	0.667	0.086	208
	3a	0.504	0.135	178
	3b	0.574	0.034	159
	3c	0.48	0.163	188
	7a	0.733	0.072	331
	7b	0.733	0.039	331
	7c	0.655	0.069	257
McCarroll and Harris 1991 Aberdaron	LDA	0.585	0.077	NNE /SSW
		0.615	0.127	
		0.701	0.119	
		0.723	0.115	
		0.723	0.077	
		0.754	0.088	
	UDA	0.485	0.077	NW/SE & NE/SW
		0.508	0.077	
		0.585	0.177	
		0.585	0.157	
		0.615	0.127	
		0.615	0.107	
Lawson 1979, Melt-out till Matanuska Glacier, Alaska		0.747	0.018	
		0.778	0.029	
		0.781	0.058	
		0.837	0.048	
		0.840	0.021	
		0.850	0.034	
		0.853	0.037	
		0.884	0.029	
Hart 1995c, Debris-rich ice Matanuska Glacier, Alaska	1	0.634	0.143	
		0.591	0.056	
		0.807	0.076	
	2	0.649	0.024	
		0.633	0.023	
Hart and Waller 1996, Debris-rich ice Worthington		0.730	0.043	
		0.552	0.52	
		0.591	0.031	

Glacier, Alaska				