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Ductile and brittle styles of subglacial sediment deformation: An example from western Ireland

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ABSTRACT

In western Ireland, within a drumlin formed inside the margin of the late Pleistocene ice sheet, a range of different styles of ductile and brittle sediment deformation is observed within subglacial diamicton (till) and associated subglacial waterlain sediments. At Roonah Point, County Mayo, the structures associated with these different deformation styles include gravel clusters that have loaded subjacent sediments, glacitectonic shears, water escape structures, and clastic dikes. These structures are found for tens of metres laterally within the same diamicton units and the structures may cross-cut or be superimposed upon one another. Based on these properties and geometric relationships, the relative chronology and processes and patterns of subglacial deformation can be reconstructed, including an evaluation of subglacial conditions and pore water pressure regimes. This illustrates the relationship between glacitectonic forcing by ice–bed coupling, and the structural response within subglacial sediments to changing pore water pressure gradients.

1. Introduction

The processes that take place within subglacial sediments, as opposed to those that take place at the ice–bed interface, are not well understood. This is largely because the strain regime generated by overlying ice flow is difficult to measure from beneath modern glaciers or reconstruct from the geological record, and the ways in which strain can be manifested within subglacial sediments are strongly dependent on sediment size distribution, pore water content, clay content, and the degree and duration of strain events imposed by ice–bed coupling and glacitectonism (Hooyer et al., 2008). Several studies have examined the relationship between strain regimes and sediment deformation styles based on modelling or experimental (ring shear) data (Iverson et al., 1998; Hiemstra and Rijsdijk, 2003; Larsen et al., 2006; Altuhafi et al., 2009) but such studies are difficult to translate to three-dimensional field settings (Truffer and Harrison, 2006; Larsen et al., 2007). As a consequence, studies of sediment deformation in field settings have mainly used an inverse approach, qualitatively deducing aspects of the subglacial strain regime from mesoscale field observations (10^{-1}–10^{1} m-scale) (e.g., Rijsdijk et al., 1999; Piotrowski et al., 2004; Hiemstra et al., 2005, 2011; Roberts and Hart, 2005) or from micromorphological evidence (e.g., van der Meer, 1993; Phillips et al., 2007; van der Meer and Menzies, 2011; Menzies, 2012). The problem with both of these approaches, however, is that they have viewed the subglacial strain regime as a static entity, that is either constant over time or acts as a single event. More recently, studies have recognised that strain events are polyphase, and that several overprinted deformation structures on different scales may result (e.g., Lee and Phillips, 2008; Rijsdijk et al., 2010; Phillips et al., 2013a). This helps view strain–deformation relationships as emergent, time-linked, and with feedbacks through changes in subglacial sediment properties (including the development of macro- and microstructures, macro- and microshears, macro- and microfabrics, sediment brecciation).

Strain events within unconsolidated sediments can give rise to two end-member deformation styles which for convenience are herein termed ductile and brittle deformations (Table 1). *Ductile deformation* is defined as the non-uniform (or grain-by-grain) response of unlithified sediments to an applied stress or strain regime. A wide range of ductile deformation structures can be identified within glacigenic sediments on the mesoscale (field-scale) and microscale (e.g., van der Meer, 1993), and these are most easily identified where sediments are horizontally layered and where deformation has contorted these layers. For example, folding often results from an asymmetric strain regime applied to unlithified stratified sediments (Phillips et al., 2007). Deformation structures are less easily identified on the mesoscale when deformation affects sediments that are more homogeneous and unstratified, which is typical of glacigenic diamicton (Hart, 1995; Hindmarsh, 1997). Under these conditions, diagnostic structures may include relatively strong clast fabrics

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Table 1
The most common ductile and brittle mesoscale deformation structures described from glacial environments in the field, and their properties (from reference sources cited in this paper).

Deformation style and structures	Typical diagnostic deformation properties
Ductile	
Folds	Folded sediment layers from which fold height, width, wavelength, strike of the axial surface and dip direction/angle can be measured
Clast fabrics	Indicative of the strength of the principle stress tensor that can cause in situ clast rotation and thus a strong macroscale clast fabric
Deformed sand stringers	Sand stringers, usually deposited as a thin, flat lens at the ice–bed interface and between layers of diamicton, can be deformed above by loading of large clasts, or more commonly when the surrounding diamicton is squashed by large-scale subglacial deformation. As such, deformed sand stringers can act as a marker horizon for large scale subglacial deformation.
Clast loading from above	Density inversion can cause loading of large clasts onto subjacent softer sediments, leading to bending, contortion or deformation of these sediments around the external surface of the clast (seen especially when subjacent sediments are stratified)
Brittle	
Shear zones/décollements	Where a sediment body changes its geometry, most commonly by extension in the subglacial environment
Listric	Most commonly extensional at depth and compressional above, where the lowermost part of the curved décollement plane is rooted in a zone of weakness, often a subglacial thermal boundary within subglacial sediments beneath polythermal ice
Riedel	Commonly en echelon fractures developed during simple shear; may have both brittle and ductile deformational elements
Hydrofractures	Linear and usually long and thin, sometimes interconnecting structures formed when the value of the principal stress tensor is exceeded by pore water pressure within the material, resulting in very rapid (explosive) formation of fractures, directed outwards from the area of greatest confining pressure. Pore water migrates rapidly through these fractures and the pore water pressure within the material drops.
Water escape structures	Structures that are indicative of directed and concentrated pore water flow within a material. These structures may include (A) the transport and deposition of fine sediments along the margins of the fluids transport zone (i.e., laminated sediments aligned parallel to shear zone margins); (B) formation of a coarse gravel lag within the fluid transport zone as fine sediments are preferentially washed away; (C) where saturated subjacent sediments are loaded from above, pore water migrates upwards, often around the higher permeability margins of the load. This can result in 'fingers' of finer sediments (style A) or lags (style B) protruding upwards, forming a three-dimensional honeycomb-like effect. Water escape structures also commonly dissipate in style away from the area of the highest pore water pressure; i.e., the laminated infills (style A) become thinner, finer grained, and less linear in geometry.
Clastic dikes	Genetically associated with both hydrofracturing and water escape in fine grains subglacial diamicton, clastic dikes are large-scale (< several metres across) linear structures that are most commonly vertically aligned but may be oblique or even horizontally aligned. Clastic dikes usually have parallel and sharply defined margins and infills of clast supported to openwork granules to boulders. Matrix is usually absent. The gravels may be chaotically organised to planar stratified, parallel to dike walls. Based on infill type and sorting, several phases of clastic dike formation can often be identified.

(Carr and Rose, 2003), individual outsized clasts that have been rotated, thus disturbing surrounding finer-grained sediments (van der Meer, 1993), and bent or contorted intraformational sand stringers. Soft glacigenic diamicton can also be deformed by the passive loading from above by higher-density clasts (Rijsdijk, 2001; Weaver and Arnaud, 2011). This density inversion will persist until sediment density is uniform throughout or clasts cease to move, often strongly determined by grain–grain friction and ongoing sediment dewatering. Relatively low-strength diamicton can therefore be deformed easily (Hart, 1995; Table 1) and result in formation of ductile structures that are not linear in their geometry; i.e., these structures are bent, contorted or folded in three dimensions according to strain regime, sediment grain size and sorting, pore water content, and other factors (Hindmarsh, 1997). This complex geometry therefore distinguishes ductile deformation structures from linear, brittle structures, described below. Furthermore, sediment deformation by the non-uniform application of strain results in an increase in pore water pressure within the sediment body and the development of strain-induced pore water pressure gradients (Iverson et al., 1994; Truffer and Harrison, 2006). In turn, this can lead to the formation of water escape structures which are directed down this pore water pressure gradient (Phillips and Hughes, 2014).

Brittle deformation refers to the response of a homogeneous medium to applied strain, in which the entire medium responds in a uniform way (i.e., not on a grain-by-grain basis in the case of unconsolidated sediments), which is manifested by the formation of linear structures such as shears or faults through the medium (Caputo, 2005). These linear structures have an alignment (strike direction, dip angle and plane geometry) that corresponds to the stress field that is imposed upon the medium (described below) (Engelder, 1999; Katz et al., 2004; Simón et al., 2008). This means that these structures are to a much lesser extent influenced by the properties of the medium such as grain size and grain sorting than those produced by ductile deformation. Brittle deformation structures including faults, shears/décollements, and fracture fills such as clastic dikes are commonly described in the glacial literature (e.g., Burbidge et al., 1988; Dreimanis and Rappol, 1997; van der Meer et al., 1999, 2009; Le Heron and Etienne, 2005; Phillips et al., 2013b; Phillips and Hughes, 2014) (Table 1) but their physical mechanisms of formation in the glacial environment are poorly known either from laboratory or theoretical perspectives (Rathbun et al., 2008; Altuhafi et al., 2009; Rathbun and Marone, 2010; Tarplee et al., 2011). In the subglacial environment, especially near to the ice margin, extensional and/or compressional glacier regimes can lead to both normal and reverse faulting within subglacial sediments (Phillips et al., 2007, 2013b). As with ductile deformation structures, linear but non-horizontally-aligned faults and shears/décollement planes are best observed where they affect stratified sediments which allows the direction and amount of displacement to be measured accurately (e.g., Busby and Merritt, 1999; Evans and Wilson, 2007). Where these structures occur within homogeneous subglacial diamicton, the direction and displacement are less easily identified but often the presence of slickensides within the shear zone or along individual shear planes shows that relative movement has taken place, thus that these structures are shears and are not bedding planes or erosional surfaces. In addition, because the increase in sediment strain that causes shearing is often also associated with a coeval increase in pore water pressure (Truffer and Harrison, 2006; Phillips et al., 2007), evidence for fluid flow along the shear zone is commonly seen. This evidence can include the deposition of laminated, water-sorted fine sands and silts parallel to the shear planes; the development of clast supported or openwork gravels along the shear zone, caused by the transport of fine sediments away from this zone by migrating fluids; or fluidised or disturbed sediments at the down-ice terminus of the pre-existing shear zone, where highly-pressured migrating fluids are no longer constrained along the shear zone and are able to dissipate into the surrounding sediments (e.g., Kumpulainen, 1994; Dreimanis and Rappol, 1997; van der Meer et al., 1999, 2009; Denis et al., 2009), often forming a honeycomb-link structure (Rijsdijk et al., 1999). This process is different to the process of hydrofracturing, which is where pore water pressure build-up within a sediment pile is suddenly released by the formation of fractures within the sediment (Phillips et al., 2013b).