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New insights into the deformation of a Middle Pleistocene glaciotectonised sequence in Norfolk, England through magnetic and structural analysis

Edward J. Fleming [a,b,*], Carl T.E. Stevenson [a], Michael S. Petronis [c]

[a] School of Geography, Earth and Environmental sciences, University of Birmingham, B15 2TT, UK
[b] Department of Arctic Geology, The University Centre in Svalbard (UNIS), P.O. Box 15, N-9171 Longyearbyen, Norway
[c] Environmental Geology, Natural Resource Management Department, New Mexico Highlands University, Las Vegas, NM 87701, USA

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ABSTRACT

North Norfolk is a classic area for the study of glacial sediments with a complex glaciotectonic deformational history, but the processes leading to the formation of some structures can be ambiguous. Anisotropy of magnetic susceptibility (AMS) analyses, providing quantitative fabric data, have been combined with the analysis of visible structures and applied to the Bacton Green Till Member, exposed at Bacton, Norfolk. Thermomagnetic curves, low temperature susceptibility and acquisition of isothermal remanent magnetism (IRM) reveal that the magnetic mineralogy is dominated by paramagnetic phases. The magnetic foliation is parallel to fold axial planes and weakly inclined to bedding, whilst the magnetic lineation is orientated parallel to stretching, indicated by the presence of stretching lineations and the trend of sheath folds. Variations in the orientation of the magnetic lineation suggest that the Bacton section has been subject to polyphase deformation. After subaqueous deposition, the sequence was overridden by ice and glaciotectonically deformed which involved stretching initially north–south, then east–west. These results show that AMS can be used to detect strain in three dimensions through a glaciotectonite where paramagnetic mineralogy is dominant. This approach therefore provides further support to the use of AMS as a fast, objective and accurate method of examining strain within deformed glacial sediments.

1. Introduction

In this paper we demonstrate the power of an under-utilised geophysical technique for determining the fabric of dynamically deposited glacial deposits and the directions of the flows that created them. The role of deformable materials beneath glaciers is currently one of the most important topics in glaciology, and various authors have suggested that glacier motion is facilitated by shearing of the glacier bed (e.g., Alley et al., 1986, 1987; Boulton, 1986). Sub-sole deformation is considered to be the primary mechanism for sustaining fast flow in ice streams and outlet glaciers and is therefore of great importance for investigations into ice sheet stability (Clark, 1994; MacAyeal, 1992). Deformation of the bed has been successfully measured in several cases (e.g., Boulton et al., 2001; Boulton and Hindmarsh, 1987; Hart et al., 2011; Iverson et al., 2003); however, the study of basal conditions in active glaciers is challenging because of the inaccessibility of the bed and the short length of time over which data can be recorded. Instead, the primary evidence used to infer dynamic processes has been through the properties of the glacigenic sediments and landforms left behind by the large ice sheets that covered much of North America and Europe during the Pleistocene Epoch (Licciardi et al., 1998; Piotrowski et al., 2001).

Glaciotectonism is the structural deformation of the upper horizon of the lithosphere by glacial stresses (Slater, 1926; van der Wateren, 2002). Glacially deformed sediment is often referred to as a glaciotectonite, a term first introduced by Banham (1977) to describe penetrative, subglacially sheared sediments analogous to mylonites in metamorphic rocks. In most studies, a wider definition is used to encompass a body of unlithified or weakly lithified sediment deformed by glacial stresses (Benn and Evans, 2010; van der Wateren, 2002). Within such sediments, distinct structures form such as folds, faults, boudins and fabrics (Hart and Rose, 2001). These structures can be analysed on both macroscopic scales (e.g., Benediktsson et al., 2010; Hart, 1990; Hart and Boulton, 1991; Lee and Phillips, 2008; Lesemann et al., 2010) and microscopic scales (e.g., Menzies et al., 2006; Phillips and Auton, 2000; Phillips et al., 2007, 2011; van der Meer, 1993; van der Wateren et al., 2000) and can provide considerable information about the genetic environment and deformational history. For example, in a subglacial environment, deformation is typically

* Corresponding author at: School of Geography, Earth and Environmental sciences, University of Birmingham, B15 2TT, UK. Tel.: +44 01214 146165.
E-mail address: ejf011@bham.ac.uk (E.J. Fleming).

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dominated by simple shear coupled with extreme extension (Hart and Boulton, 1991; Kluiving et al., 1991), whilst in proglacial settings, glaciotectonic compression may facilitate the formation of structures analogous to fold and thrust belts in an orogenic foreland setting (Bennett, 2001; Hambrey et al., 1997; Huddart and Hambrey, 1996; Phillips et al., 2008). Similar structures, however, can be seen in both settings and may not be readily distinguishable (Phillips et al., 2007). Variation in lithology and the dynamic nature of subglacial conditions means that earlier deformation structures can be overprinted (Evans and Hiemstra, 2005; Piotrowski et al., 2004). Moreover, fold structures, similar to those found in glaciotectonic environments, are also found in other environments, e.g. slumping on glaciomarine slopes (Arnaud and Eyles, 2002; Eyles and Kocsis, 1988; Kurtz and Anderson, 1979). This makes the interpretation of specific structures ambiguous, and in some stratigraphic sections the same evidence has been interpreted as being formed by very different processes. For example, the soft sediment deformational structures in the 'North Sea Drifts' of Norfolk, UK, are traditionally interpreted as subglacial (Banham, 1975) but have also been reinterpreted as slumping in a glaciomarine setting (Eyles et al., 1989). The objectivity and usefulness of certain techniques used to study subglacial deformation has been doubted (Bennett et al., 1999; Zaniewski and van der Meer, 2005), and it is apparent that there is a clear need for objective and quantitative approaches to the analysis of strain within glacial sediments.

In North Norfolk, England, although exposures provide classic sections from which original work on glaciotectonics emerged (Banham, 1977, 1988; Banham and Ranson, 1965; Slater, 1926), considerable debate remains over the pattern of lowland glaciation (Banham et al., 2001; Eyles et al., 1989; Gibbard and Clark, 2011; Hamblin et al., 2005). Here, we reinvestigate sediment genesis and flow vectors using the analysis of the anisotropy of magnetic susceptibility (AMS) technique. The AMS technique is widely used in structural geology but has seldom been used in glacial geology until recently. Fuller (1962), through comparisons with pebble fabrics, was the first to suggest that magnetic fabrics could be a viable technique for petrofabric analysis. The magnetic properties of till sequences in North America, relating to the Laurentide ice sheet, have since been investigated (Eyles et al., 1987; Gentoso et al., 2012; Stewart et al., 1988; Stupavsky and Gravenor, 1975; Stupavsky et al., 1974a,b). Recent laboratory work (Hooyer et al., 2008; Thomason and Iverson, 2006) has increased confidence in the reliability of the technique as a quick and objective method of examining strain within deformed sediments.

2. The development and interpretation of AMS fabrics in glacial sediments

When subjected to an external magnetic field, an induced magnetism is generated in a rock or sediment that is dependent on the magnetic susceptibility. This can be represented by the equation $M = KH$, where M is the induced magnetisation, H is the applied field and K is the magnetic susceptibility (Tarling and Hrouda, 1993). Variation in K with direction can be visualised by a second rank symmetrical tensor through the maximum (K_1), intermediate (K_2) and minimum (K_3) principal susceptibility axes. The orientation of the susceptibility axes is controlled by the alignment, distribution and crystalline properties of magnetic minerals; thus AMS can be used to detect very weak or subtle fabrics.

In a subaqueous environment, the alignment of minerals is controlled by gravitational and hydrodynamic processes (Tarling and Hrouda, 1993). When deposition occurs in still water, gravitational settling is the only significant force and causes platy grains to become aligned parallel to the depositional surface, giving rise to a strongly oblate fabric confined to the bedding plane. The notable exception to this is fine-grained ferromagnetic grains, which can become aligned parallel to the Earth's magnetic field. If hydrodynamic disruption occurs, i.e. from currents acting on the sea floor, then the long axis of grains can rotate and become preferentially aligned, and lineations can develop reflecting flow directions (Rees and Woodall, 1975). Post-depositional, soft-sediment processes can also have a significant impact on such primary depositional fabrics (Schwehr and Tauxe, 2003). Stress acting on the sediment can cause grains to rotate resulting in the preferential alignment of their long axes to shear direction and short axes perpendicular to the shear plane. In this way, AMS has been used to resolve strain that is difficult to detect using other petrofabric techniques (Borradaile and Tarling, 1981; Cifelli et al., 2009; Kissel et al., 1986; Mattei et al., 1997).

Previous work that has been carried out on the AMS of glacial sediments has largely focussed on determining ice flow directions and bed dynamics from fabrics within tills (Shumway and Iverson, 2009; Thomason and Iverson, 2009), and flow directions from mass flow units (Archanjo et al., 2006; Eyles et al., 1987). In a subglacial environment, Iverson et al. (2008) showed through ring shear experiments that when an intact till sample was sheared under conditions similar to those expected to operate at the bed, microfaults develop that facilitate the rotation of the long axis of particles into the plane of shear, where they remain. This evidence was used to support the idea of *March-type rotation* (March, 1932), where behaviour is consistent with Coulomb-plastic rheology, as opposed to *Jeffery-type rotation* (Jeffery, 1922), where particles can roll continuously in a shearing viscous medium (Benn, 1995; Thomason and Iverson, 2006). No published data, however, exist for the measurement of cumulative strain through AMS within glaciotectonites, where pre-existing unconsolidated sediment has been glacially deformed such that relicts of the original structures remain.

3. Geological background

The bedrock geology of North Norfolk consists of gently dipping Cretaceous chalk. Pleistocene aged sediments consisting of pre-glacial fluvial and shallow marine deposits overlie the Cretaceous chalk, which in turn are overlain by a sequence of tills separated by outwash sediments (Banham, 1968). These glacial sediments were previously considered to have been deposited by oscillations at the margins of coexisting British and Scandinavian ice sheets during the Anglian glaciation (478–424 Ka, Marine Isotope Stage 12) (Bowen et al., 1986; Fish and Whiteman, 2001; Lunkka, 1994; Perrin et al., 1979). A new glacial lithostratigraphy has been proposed (Hamblin, 2000; Hamblin et al., 2005; Lee et al., 2004; Rose et al., 2001), subdividing the sequence into four formations; the Happisburgh, Lowestoft, Sheringham Cliffs and Briton's Lane. These authors suggested that the deposition of the tills were associated with an entirely British-based, as opposed to Scandinavian, ice sheet (Hamblin et al., 2005; Lee et al., 2002). This interpretation has been disputed (Banham et al., 2001; Gibbard and Clark, 2011; Preece et al., 2009) because of its inability to explain biostratigraphical evidence.

The study site in North Norfolk is located in a cliff section near the village of Bacton (National Grid Reference TG 338345; Fig. 1). The lithology consists of a stratified diamicton sequence, previously referred to as the 3rd Cromer Till (Banham, 1968; Lunkka, 1994) but reassigned to the Bacton Green Till Member of the Sheringham Cliffs Formation (Hamblin et al., 2005; Lee and Phillips, 2008) through tectono-stratigraphic relationships and petrological analyses. Although not directly exposed at the section, further along the coastline, the Bacton Green Till Member overlies the Walcott Till member, previously referred to as the 2nd Cromer