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Strain pathways, till internal architecture and microstructures – perspectives on a general kinematic model – a 'blueprint' for till development

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ABSTRACT

A kinematic model of strain pathways for till formation is developed. This model is linked to microstructures found within tills indicative of multiple styles of deformational regimes and polyrheological conditions during formation. Tills are subdivided into three types. Type A tills are found under high strain rates and a pervasive deformation regime and may be regarded as lodgement tills and are relatively rare. Type B tills are the dominant group formed under variable strain deformation conditions of pervasive and non-pervasive deformation containing evidence of brittle and ductile failure and can be classified as tectomicts (or glacial mélange). Type C tills are found under limited to zero deformation regimes and are melt-out tills of limited preservation potential. Examples of till forming under various strain pathways conditions are presented with photomicrographs of thin sections of such tills. A new till classification scheme is offered that accounts for the deformation regimes till undergo under varying strain pathways. This new model should help to place microstructures obtained from micromorphological analyses within the context of till genesis and subsequent development. This kinematic model is a first attempt to integrate the fields of glacial micromorphology, structural geology and glacial sedimentology into a coherent 'blueprint' for till development leading to deposition and/or emplacement.

1. Introduction

It is generally accepted that a significant portion of ice sheet and glacier basal motion is attributable to the deformation of subglacial sediments (cf. Alley et al., 1987; MacAyeal, 1989, 1992; Boulton, 1996a, b; Hindmarsh, 1997; Licciardi et al., 1998; Tulaczyk, 1999, 2006; Truffer et al., 2000; Porter and Murray, 2001; Fowler, 2003; Dowdeswell et al., 2004; Evans et al., 2006; Kavanaugh and Clarke, 2006; Truffer and Harrison, 2006; Thomason and Iverson, 2009; Benn and Evans, 2010; Reinardy et al., 2011a, b). However, the style of deformation, the areal extent, and the precise nature of the deformation process(es) remains largely unknown. A rich source of data has been forthcoming and continues to come from West Antarctica and other modern glacier areas (cf. Engelhardt et al., 1990; Tulaczyk, 1999; Tulaczyk et al., 2000a, b; Anderson, 2001; Shipp et al., 2002; Hart and Rose, 2001; King et al., 2004; Clarke, 2005; Heroy and Anderson, 2005; Kavanaugh and Clarke, 2006; Ó Cofaigh et al., 2007; Kilfeather et al., 2011). Much as these modern analogues provide invaluable information, there remains a paucity of data on basal sediment deformation processes with reference to Pleistocene and earlier ice sheets (cf. Jenson et al., 1995; Piotrowski and Kraus, 1997; Evenson et al., 2000; Murray et al., 2000; Bennett, 2003; Iverson et al., 2003; Lian et al., 2003; Dowdeswell et al., 2004; Piotrowski et al., 2006; Evans et al., 2008; Lee and Phillips, 2008; Phillips et al., 2008; Thomason and Iverson, 2009). The only source of such information therefore must be proxy data gleaned from indirect sources. Subglacial sediments provide such a source.

Subglacial tills, both terrestrial and subaqueous, cover vast areas of the world's continents and continental shelves (Piotrowski et al., 2001; Eyles and Januszczak, 2004). These tills exhibit a wide array of deformation structures and fabrics indicative of the environment(s) from which they are derived (cf. Van Der Meer, 1987; Lian et al., 2003; Van Der Meer et al., 2003; Menzies et al., 2006; Aber and Ber, 2007). It is apparent from macro- and microscopic examination of tills that a complex set of deformation processes is ongoing during and following till deposition/emplacement (cf. refs in Boulton and Hindmarsh, 1987; Schokking, 1990; Hart et al., 1990; Boulton et al., 1996; Lian and Hicock, 2000; Murray et al., 2000; Hart and Rose, 2001; Menzies and Shilts, 2002; Iverson et al., 2003; Lian et al., 2003; Van Der Meer et al., 2003; Dowdeswell et al., 2004; Clarke, 2005; Rathbun et al., 2008; Phillips et al., 2011a). These tills possess relict signatures indicative of deformation events and/or other processes involved in till deposition. The

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deformational signatures act as strain markers (Hatcher, 1990; Maltman, 1994; Murray, 1994; Fuller and Murray, 2000; Phillips and Auton, 2000; Menzies, 2000a, b; Treagus and Treagus, 2002; Lian et al., 2003; McCarroll and Rijsdijk, 2003; Van Der Meer et al., 2003; Menzies et al., 2006; Phillips et al., 2011b). These strain markers in tills can be utilised to reveal the kinematics of subglacial deformation, strain pathways and strain 'histories'. It is the understanding of these pathways within a general kinematic model of a till's internal architecture that forms the basis of this paper. This kinematic model is a first attempt to integrate the fields of glacial micromorphology, structural geology and glacial sedimentology into a coherent 'blueprint' for till development leading to deposition and/or emplacement.

2. Deformation in glacial environments

Evidence of deformation within glacial environments is commonplace. However, macro- and microstructures indicative of various styles of deformation are often ignored (cf. *macrostructures*: Eyles et al., 1983; Brodzikowski & van Loon, 1991; and *microstructures*: van der Wateren et al., 2000; Hart and Rose, 2001; Lian et al., 2003; McCarroll and Rijsdijk, 2003; Van Der Meer et al., 2003; Carr, 2004; Menzies et al., 2010; Phillips et al., 2011a). In reality, since these deformation structures and their mode of formation are products of the strain conditions under which they have developed and evolved along strain pathways, these signature markers are of immense relevance to understanding till rheology and sedimentation.

Sediment deformation may be defined as the progressive bulk change in shape of aggregate units as result of the application of stress (Jones and Preston, 1987; Maltman, 1994; Davis and Reynolds, 1996; Harrington, 2001; Aber and Ber, 2007; Sane et al., 2008). Processes of deformation encompass sliding of particles, grains and unit sediment packages past one another, internal grain crushing events, rotations complete or partial, and faulting and folding of individual particles or groups of particles and sediment units. Deformation occurs as particles slide past each other in what has been termed independent particulate flow (Borradaile, 1981). This change in bulk shape is usually termed strain (Means, 1990; Williams et al., 1994; Marrett and Peacock, 1999). Within glacial environments stress application typically is the result of ice loading, ice shear, sediment loading and/or sediment shear (cf. refs in Aber, 1988; Banham, 1988; Hooke and Iverson, 1995; Benn and Evans, 1996; Piotrowski, 1997; Lian and Hicock, 2000; Murray et al., 2000; Tulaczyk et al., 2000a, b; Tulaczyk, 2006; Piotrowski et al., 2004; Phillips et al., 2002, 2008, 2011a, b). Often this stress is indirectly applied since ice loading, for example, may be translated into porewater pressure and resultant porewater movement thus applying internal stress to a sediment unit (cf. Lian and Hicock, 2000; Phillips et al., 2011b). Over the past few decades considerable discussion has centred upon the kinematics of subglacial soft bed deformation (cf. Alley et al., 1986; Clarke, 1987, 2005; Hart et al., 1990; Murray, 1994; Boulton et al., 1996; Hindmarsh, 1997; Murray et al., 2000; Fischer and Clarke, 2001; Hart and Rose, 2001; Porter and Murray, 2001; Phillips et al., 2002, 2008; Fowler, 2003; Kavanaugh and Clarke, 2006; Iverson et al., 2008; Rathbun et al., 2008; Hart et al., 2011). In summary, as an active, temperate ice mass progressively moves across its bed subjacent sediment may become mobilized where applied basal stress (τ_b) overcomes till bulk shear strength (τ_s) at its critical yield strength if conditions of stress, sediment porewater content, thermal regime, and sediment rheology permit. The depth of mobilization then becomes a function of these same conditions (Boulton, 1987; Menzies, 1989, 2002; Hart et al., 1990; Murray, 1994; Murray et al., 2000; Tulaczyk et al., 2000a, b; Tulaczyk, 2006; Hart and Rose, 2001; Murray and Porter, 2001; Porter and Murray, 2001; Smith et al., 2002; Iverson et al., 2008). Depths of mobilization can range from a few centimetres to decimetres (cf. Alley et al., 1986; Humphrey et al., 1993; Murray, 1994; Jenson et al., 1995; Hart et al., 1999; Alley, 2000; Murray et al., 2000; Tulaczyk et al., 2000a, b, 2001; Murray and Porter, 2001; Iverson et al., 2003; Dowdeswell et al., 2004; Clarke, 2005; Kavanaugh and Clarke, 2006; Rempel, 2009). The rate of mobilization of the subglacial sediment can also be expected to vary as a function of applied stress from overlying ice and the effective stress of the sediment (cf. Tulaczyk, 2006). It has long been recognised that till, as a granular material, deforms in a complex manner either as a linear viscous material or as a (nearly) perfectly plastic material that may or may not be scale dependant (Clarke, 1987, 2005; Hindmarsh, 1997; Iverson et al., 1998; Tulaczyk, 1999, 2006; Fowler, 2003; Piotrowski et al., 2004; Kavanaugh and Clarke, 2006; Rathbun et al., 2008; Hart et al., 2011). Recent work by Tulaczyk (2006) suggests that till deforms independent of scale and in a (near) perfectly plastic rheological manner. However, Humphrey et al. (1993) demonstrated that deformation may be non-pervasive distributed flow in a viscous-style deformation mode. What is clear is that tills deform in a non-linear manner that possibly preclude the application of certain standard laws such as the Coulomb-Mohr model under certain circumstances. One of the problems faced by granular material models is that they are often limited at the particle-level where response to stress is difficult to measure and characterize (Desai, 2001; Desai and Wang, 2003). If, in contrast, a till is regarded as a mixture of several component parts typical of granular mixture, then the application of the Disturbed State Concept (DSC) may lend itself to broad application in understanding till deformation beneath an active ice mass (Desai, 2001; Desai and Wang, 2003; Sane et al., 2008; Hart et al., 2011) (For an introduction to DSC readers are referred to Desai, 2001 and Sane et al., 2008, 269–272.). In addressing the problem of granular mixtures the DSC assumes that there is an initial relative intact state (RI) that can be characterized using continuum models of elasticity, plasticity and visco-plastic states. However, as deformation begins the bulk material undergoes 'microstructural transformation' or readjustments at the microscale level involving particle to particle relative motion, localized discontinuity formation, particle rotation and sliding relative to other parts of the granular material. As deformation continues and material 'transforms' and self-adjusts attaining a fully adjusted (FA) state that over time leads to an asymptotic or ultimate FA state (FA_∞). Rarely if ever in natural systems will this FA_∞ be attained. Instead *en route* to this ultimate state both RI and FA zones will coexist, transform and alter such that, as will be shown below, microtextures of tills, typically, reveal both stressed and unstressed domains and/or previously stressed zones juxtaposed with newly stressed zones. All of these microtextural fluctuations as a result of deformation processes, as shown below, are manifest at the microscale level thus demonstrating the inherent value of micromorphological analyses.

2.1. Styles of deformation in subglacial deformable beds (SDB)

The deformation of subglacial sediments is complicated by the fact that sediments derived, deposited and/or emplaced within the subglacial environment are subject to a complex multi-strain history which is time-progressive and in which remnant structures may survive various previous deformation phases (cf. Karig and Morgan, 1994; Bolton et al., 1998; Sane et al., 2008; Phillips et al., 2011b). The interpretation of soft sediment structures is fraught with problems (Maltman, 1994; Passchier and Trouw, 1996; Jiang and Williams, 1999; Owen et al., 2011; Phillips et al., 2011b). In the past, such structures in tills were often perceived as localized and of limited value in broader interpretations of soft sediment