Sedimentary Geology 344 (2016) 57–70

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Invited review

A kinematic unifying theory of microstructures in subglacial tills

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ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form 9 February 2016
Accepted 18 March 2016
Available online 8 April 2016

Keywords:
Till
Deformation
Glacial geology
Micromorphology
Microsedimentology
Structural geology

ABSTRACT

A key aspect of all subglacial tills is the nature and form of microstructures present. Microstructures are symptomatic of repeated deformation phases prior to, during, and after emplacement. Critical to understanding microstructures in subglacial tills are the probable interrelationship that exists between all of these structures. In analyzing subglacial tills a kinematic deformation relationship can be observed existing between all microstructures. Based upon the rheological conditions at the ice basal interface, a close evolving paleo-strain link can be established that relates levels of deformation to all subglacial till microstructures. As subglacial till undergoes strain during transport and emplacement involving fluctuating conditions of porewater content, percentage of clays present, and changing thermal circumstances, a series of microstructures sequentially evolve. Initially, brittle edge-to-edge grain events occur, followed by grains stack development, often allied closely in time, with microshear formation as the sediment deforms, and is consequently followed by the development of ductile rotation structures. Likewise, deformation bands, shear zone formation, and typically "isolated" domains form. As strain and other factors vary over time so many of these microstructures may be obliterated, altered, or re-oriented. Much remains to be understood regarding paleo-strain conditions and subglacial deformation but a first step has been establishing this temporal sequence of microstructure stage development and thus achieving a theory that unifies these disparate microstructures observed in all subglacial tills.

1. Introduction

Macro- and microstructures within subglacial tills have long been described and recognized as forms symptomatic of subglacial conditions developing during subglacial till deposition and emplacement. Subglacial till situated beneath an overlying active ice mass, and the underlying bed is analogous to fault gouge, a comparison made in the past but largely under-examined (Eyles and Boyce, 1998; McCarroll and Rijsdijk, 2003). Microstructures within subglacial tills are important geologic structures since they reveal types and phases of deformation, and their kinematic geometries are illustrative of paleo-strain levels. Although these microstructures have been described for some time now, the genesis and development of the structural elements during shear, deposition, and emplacement and their cross-interrelationships remain poorly established. Closely aligned to microstructure development in subglacial tills is the recognition of the subglacial till types themselves. Subglacial till formation and classification remain a contentious issue as a clearly established classification that accepts both macro and micro-sedimentological characteristics has still to be established. With the dominant microstructures now well recognized and mapped within subglacial tills, it is timely to re-assess their geologic, structural, and rheological significance within the context of the mechanics of subglacial till deposition. In this paper, we review these subglacial till microstructures and discuss the relationship of these microstructures to one another, to the mechanics of subglacial till formation and present a possible unifying theory of microstructures in subglacial tills.

2. Subglacial till

Subglacial till is one of the most pervasive sediments in the world. As a Quaternary sediment whether on land or in the ocean, margins on the continental shelves, tills, or perhaps more accurately glacial diamictons, occur across a very wide sweep of the northern hemisphere in North America and Eurasia. Tills occur on all continents, including mainland Australia and tropical areas like Indonesia. Subglacial tills in modern settings occur in all presently glaciated areas of the world. As to Pre-Quaternary tillites (diamictites), they were deposited in most geological terrains from the Oligocene through the Permo-Carboniferous to the Archean in most parts of the world (Young, 1996, 2016; Eyles, 2008; Arnaud et al., 2011; Tait et al., 2011; Le Heron et al., 2013).

Subglacial tills (glacial diamictons) are sedimentologically complex earth materials. They are formed by accretion in the basal space between ice sheets and glaciers and their beds, by deformation of the bed without input from within the ice or formed at the margins

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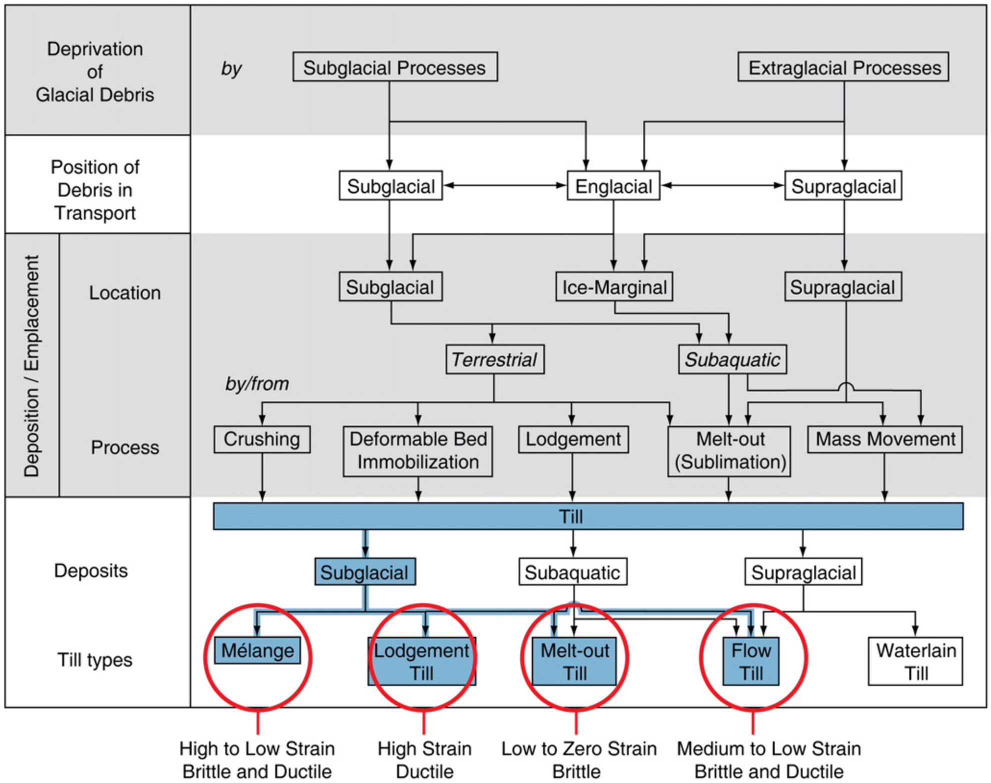
http://dx.doi.org/10.1016/j.sedgeo.2016.03.024
0037-0738/

Table 1
Classification of Till types (modified after Menzies, 2003). Note the various strain levels and styles of deformation for the different subglacial till types.



(or near marginal surfaces) of ice masses and derived from the glacial system as debris flows or meltout by-products or rainout within bodies of water proximal to ice masses (subglacial rainout in cavities may also contribute to subglacial till emplacement) (Table 1) (Bennett et al., 2006; Livingstone et al., 2012). In terms of subglacial tills where once it was commonplace to think that this subjacent zone between ice and its bed was comparatively simple in a modeling sense, today it has become apparent that this an extremely complex environment, that is dynamic, in relatively constant flux over time and space, enlarging and shrinking over time as an ice mass advances and retreats across the landscape (Alley, 1991; Menzies, 2003, 2012; Piotrowski et al., 2004, 2006; Kjær et al., 2006; Larter et al., 2009; Knight, 2010; Leysinger Vieli and Gudmundsson, 2010; Narloch et al., 2012; Larson et al., 2015; Menzies et al., 2016). Subglacial tills have complex strain histories (Menzies, 2012). Table 1 illustrates that different subglacial till types are emplaced/ deposited in the subglacial environment that are subjected to range of strain conditions in which the tills may deform in brittle and ductile styles. Subglacial tills are repeatedly stressed over time, and these stress conditions can be reflected in the microstructures developed within these tills. It has been previously discussed (Menzies, 2003, 2012) that where tills have undergone subsequent high strain following on from low strain impacts; previous low strain microstructures may be drastically altered or obliterated while the opposite effect of high strain followed by low strain may permit high strain microstructures to survive. Since subglacial tills have likely undergone many repeated strain changes, microstructures in the "final" till "end product" may only allow a glimpse into the chronology of till strain subjected conditions. One aspect in studying till microstructures is to establish strain conditions and a chronology of those strain changes over time. Subglacial tills can be subdivided into four dominant types. Mélange tills are similar to the "subglacial traction" tills of Evans et al. (2006) and form under soft deforming subglacial bed polythermal conditions of high to low strain with evidence of brittle and ductile deformation styles. These tills contain elements of all other subglacial till types that have been scavenged and incorporated into this "end product." Lodgement tills that, although perhaps much less common than previously considered (van der Meer et al., 2003; Menzies et al., 2006; van der Meer and Menzies, 2012; Menzies, 2012), are subject to high strain conditions and dominantly, if not completely, ductile deformation. Melt-out tills formed under more passive conditions (Fitzsimons, 1990; Munro-Stasiuk, 2000; Möller, 2010; Pisarska-Jamroży and Zieliǹski, 2012; Larson et al., 2015) in which these tills exhibit low to zero strain effects and brittle deformation conditions. Finally, flow tills formed, likely within subglacial cavities where mass movement has resulted in relatively moderate to low strain conditions and dominantly brittle deformation with occasional ductile deformation where internal porewater content has allowed ductile deformation under low strain to occur (Piotrowski et al., 2006; van der Meer and Menzies, 2011). In volumetric terms it is thought that mélange tills make up the vast majority of subglacial tills in Pleistocene and pre-Quaternary till sediments.

Since the mid-twentieth century, the macro-sedimentological aspects of subglacial tills have become well recognized and have been the basis of a well-established subglacial till classification scheme (Dreimanis, 1989; Evans et al., 2006). Many of these established macro-sedimentological aspects, however, are not well understood and assumptions have often been made with comparatively little real understanding of subglacial till depositional mechanics. The science around macro-subglacial till fabrics is a good case in point (Carr and Rose, 2003; Thomason and Iverson, 2006; Phillips et al., 2011). It has generally been accepted that particles within subglacial tills orientate under stress to exhibit an azimuth approximately parallel with the dominant principal stress application that, in turn, is assumed to be the dominant ice direction. Exactly how these particles orient and under what conditions of porewater content and pressure, and overall strain field remains largely unknown or speculated. Various particle