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Review

The paleoclimatic significance of deformation structures in Neoproterozoic successions ☆

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ABSTRACT

This paper reviews the different types of soft sediment deformation structures that can form in glacial and non-glacial settings and explores the potential use of these structures in resolving long standing debates in paleoenvironmental reconstructions of Neoproterozoic glacigenic successions. Soft sediment deformation structures are created when compressional, gravitational or shear stress is applied to unlithified sediments during or shortly after deposition. In subglacial or ice marginal glacial settings, shear and compressional stress imparted by ice moving on top of a deformable substrate or advancing ice buldozing unlithified ice marginal sediments can result in a wide range of folding, faulting and shear structures. In glaciofluvial or stagnant ice marginal setting, gravitational collapse and remobilization of sediments associated with the melting of buried ice can result in normal faulting and broad folding. In glaciolacustrine or glaciomarine settings, compressional, shear and gravitational types of deformation structures can occur as a result of grounding ice or icebergs, rapid sedimentation and reworking downslope associated with high sedimentation rates. In non glacial settings, similar deformation structures can form as a result of slope instability and reworking of sediments downslope, rapid sedimentation, seismic shaking, wave induced shearing or loading.

In this context, two case studies are presented to demonstrate the type of paleoenvironmental information that an analysis of deformation structures can provide. In the first case study, analysis of deformation in the Port Askaig Formation (Scotland) reveals a distinctive stratigraphic distribution of deformation structures. The types of deformation observed together with their recurrence over several 100s of meters and their basinal context are used to infer a seismic origin for the deformation, which in turn suggests a significant tectonic control on sedimentation atop a record of ice margin fluctuations in a glaciomarine setting. In the second example, analysis of deformation in the Smalfjord Formation (northern Norway) provides strong evidence for deformation by active ice overriding glaciofluvial deposits. The types of deformation in this example, together with its complexity, scale and associated facies, provide the strongest case for ice marginal deformation. In sum, analysis of deformation structures together with analysis of structural geology, stratigraphy, facies and facies associations can provide additional constraints on paleoenvironmental conditions at the time of deposition, which can help us refine or test paleoenvironmental models proposed for this critical time period in Earth history.

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1. Introduction

Deformation of unlithified sediments occurs in a wide range of depositional settings and as a result of different syn- to post-depositional triggers including tectonic processes, downslope reworking of sediment, wave loading or frictional drag associated with currents, rapid sedimentation, thermal expansion and contraction in periglacial settings and stresses related to advancing, grounding or stagnating glacier ice. In many studies of modern and recent glacigenic sediments, it is used to infer the presence and dynamics of active ice (e.g. Aber et al., 1989; Woodworth-Lynas and Guigne, 1990; Benn and Evans, 1996; Phillips et al., 2002; McCarroll and Rijsdijk, 2003). In contrast, deformation in ancient glacigenic successions has primarily been attributed to non-glacial or periglacial processes, with much fewer studies referring to examples of ice marginal, subglacial or grounded ice deformation (Visser et al., 1984; Rocha Campos et al., 1994; Rocha Campos and Canuto, 2000; Le Heron et al., 2005; Arnaud, 2008; Domack and Hoffman, 2011). This is likely in part due to a preservational bias towards glaciomarine facies in ancient strata (Bjørlykke, 1985; Eyles, 1993). However, some Neoproterozoic successions do contain terrestrial facies (e.g. Deynoux, 1985; Rieu et al., 2006; Arnaud, 2008) and records of grounded ice or drifting icebergs should be preserved in relatively shallow marine settings, given sufficient accommodation space, and therefore preservation potential, as the basin develops over time. In many Neoproterozoic successions, the focus however remains on identifying the more typical indicators of glacial conditions such as

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diamictite with striated, faceted or extrabasinal clasts, and laminated sediments with outsized clasts interpreted as ice rafted debris (Arnaud et al., 2011). In some cases, excellent exposures have permitted a detailed facies approach where sedimentary facies associations are attributed to various glacial and interglacial settings (e.g. Allen et al., 2004; Rieu et al., 2006; Domack and Hoffman, 2011; Le Heron et al., 2011). But even in these, deformation, while mentioned in some cases, has rarely featured prominently. The data presented here suggests that a detailed analysis of all types of deformation structures can yield significant paleoclimatic information by providing evidence for glacial, periglacial and/or non-glacial processes. These data can then be used together with other sedimentary characteristics in their stratigraphic context to identify periods of time where deposition is dominated by glaciogenic, periglacial and/or non-glacial processes, allowing for more robust and refined paleoclimatic reconstructions.

Deformation is defined as any change in form or shape resulting from an applied force (Twiss and Moore, 2007; Fossen, 2010). Deformation in unlithified sediments can be characterized as brittle or ductile and described using standard structural terminology to document the type, offset, strike and dip of fault planes as well as the scale and type of folding (Evans and Benn, 2004; Twiss and Moore, 2007; Benn and Evans, 2010; Fossen, 2010). Owen (1987) suggested that deformation structures in unconsolidated sand form as a result of a driving force (such as gravity, uneven confining load, tangential or vertical shear stress or reverse density gradient), a deformation mechanism (commonly liquefaction or fluidization) and a trigger (such as a seismic event, ice advance, or rapid deposition). This framework underscores the fact that deformation structures, as with other sedimentary structures, are not diagnostic of any one depositional environment or trigger. Although folds can be linked to a specific stress or driving force, they clearly occur as a result of a variety of triggers in a range of depositional settings (e.g. ice front, sediment gravity flow deposit, and seismically-active region). Similarly, ball and pillow structures are known to develop in sediments that exhibit reverse density gradients but triggers include rapid sedimentation or seismic shaking. Ultimately, the scale and types of deformation structures and inferred paleostress orientations together with the associated undeformed facies, their stratigraphic context, and the nature of the depositional setting and sedimentary basin in which they formed must be used to infer the most plausible trigger for deformation and the most likely paleoenvironmental conditions associated with that deformation (McCarroll and Rijsdijk, 2003; Owen et al., 2011).

In this paper, deformation structures observed in two Neoproterozoic glacigenic successions are presented to demonstrate how these can be used to refine depositional models and shed light on the environmental conditions of Neoproterozoic glaciations. The refined paleoenvironmental reconstructions can then be used more effectively to test existing global climate change models for the Neoproterozoic time period. To provide context, deformation of unlithified sediments in glacial and non-glacial environments is first reviewed.

2. Deformation in glacial environments

Deformation of unlithified sediment can occur as a result of a variety of processes in glacial environments (Hart and Roberts, 1994; McCarroll and Rijsdijk, 2003; Evans et al., 2006; Benn and Evans, 2010). In some cases, the applied force is shear or compressional stress from the moving ice, whereas in others, the applied force is related to gravitational instability, gravitational collapse or reverse density gradients (Fig. 1). Most research has focused on the former with many special volumes and case studies focusing on the glacitectonic forces common in subglacial and ice marginal settings (e.g. Croot, 1988; Aber et al., 1989; Benn and Evans, 1996; Maltman et al., 2000; Benediktsson et al. 2008). The following review is by no means exhaustive. Specific references have in part been chosen as they contain illustrations focused on the sedimentary and structral characteristics of the deformation that in turn can become useful analogs for Neoproterozoic successions. This review provides a summary of the various conditions that result in deformation, the types of deformation structures found in different glacial settings and the types of facies associations in which these are commonly found. This will hopefully assist in future recognition and interpretation of deformation structures in Neoproterozoic glacigenic successions.

2.1. Subglacial settings

In subglacial settings, ice movement over an unlithified substrate creates shear stress that results in a variety of deformation structures (Figs. 1–3). Typically, deformation occurs in the top meter under the sediment–ice interface as shown by the seminal studies at Breiđamerkerjökull of Geoffrey Boulton and others, although deformation has been documented up to 10s of meters below the interface (Rijsdijk et al., 1999; Evans et al., 2006). The style and extent of deformation will in part depend on the ice characteristics (velocity and basal shear stress), sediment characteristics (texture, bedding, and degree of heterogeneity) and subglacial hydrology (Hart, 1995; Benn and Evans, 1996; Boulton et al., 2001; Evans et al., 2006). Benn and Evans (1996) suggested that the increase in stress towards the ice–sediment interface would result in an upward increase in the severity of strain signatures. As a result, a typical vertical facies succession would include a basal zone with visible deformation structures, transitioning gradually into an upper zone of completely homogenized sediments. Although primarily affected by shear stress, subglacial sediments closer to the ice margin may experience compressional stresses (Hart and Boulton, 1991).

Deformation structures formed as a result of subglacial shear and compressional stress include attenuated bedding and boudins, shear folds and shear planes, and faulting (normal, thrust and reverse) (Figs. 2 and 3; Hart and Boulton, 1991; Benn and Evans, 1996; Boyce and Eyles, 2000; Phillips et al., 2002; Evans et al., 2006). These represent a continuum of strain with rooted or open folds representing low strain and highly attenuated bedding to tectonic laminae representing high strain (Hart and Boulton, 1991). In addition, the confining pressure of the ice and a frozen substrate or foreland can lead to overpressurized subglacial conditions, hydrofracturing and injection of sediments that result in upward directed, downward directed or 'burst out' clastic dikes (Fig. 2; Larsen and Mangerud, 1992; Boulton and Caban, 1995; Dreimanis and Rappol, 1997; Rijsdijk et al., 1999; Le Heron and Etienne, 2005; Benn and Evans, 2010).

Subglacial deformation structures range in scale from cm to m and have been documented in subglacial tills and in a range of other sedimentary facies that have been overriden by ice such as glaciofluvial sand and gravel, variable ice marginal sediments or glaciomarine sand and mud.

Micro-scale structures related to subglacial deformation have also been documented and are commonly used in the analysis of recent glacial deposits (see Menzies, 2000a for a review). However, considering the potential for post depositional overprinting by tectonic forces, micro-morphological analysis has largely not been applied to ancient glacigenic deposits, with one exception known to the author (Menzies, 2000b).

2.2. Ice marginal settings

Ice marginal settings are highly dynamic, with sediments being affected by ice margin fluctuations, ice surging, gravitational instability or collapse related to differential melting of buried ice and topographic inversion, as well as reworking by glaciofluvial processes (Boulton, 1972; Lawson, 1982). This results in high facies variability that, in turn, responds very differently to applied driving forces, forming a wide, and at times highly complex, range of deformation structures

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