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# RECOGNITION OF GLACIAL INFLUENCE IN NEOPROTEROZOIC SEDIMENTARY SUCCESSIONS

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## **Abstract**

This chapter provides an overview and key references of glacial processes and resulting sedimentary products in subglacial, terrestrial proglacial and glaciomarine or glaciolacustrine settings. This information will enable the readers to identify features that may be used in identifying the signature of glacial influence in ancient deposits. The chapter also outlines some of the important issues that require consideration when making palaeoclimatic reconstructions from Neoproterozoic sedimentary successions. A summary table outlining the characteristics of diamictite with different depositional origins is also included in order to assist with the interpretation of the Neoproterozoic sedimentary record.

The ability to recognise glacial deposits, or a glacial influence on sedimentation, has long been a subject of debate (e.g. Schermerhorn 1974; Deynoux & Trompette 1976; Jensen and Wulff-Pedersen 1996), and yet is critical for the accurate reconstruction of palaeoenvironmental conditions during past ice ages. This chapter summarizes the historical development of the terminology and approach used in identifying deposits of glacial origin, the characteristics of glacial environments in terms of processes and resulting sedimentary products as well as some key points to consider when reconstructing palaeoenvironmental conditions in ancient successions. The chapter is far from exhaustive since many have previously covered these topics in more detail elsewhere. Rather, it is meant to provide an overview with key references for workers who focus on other aspects of Neoproterozoic geology and may not necessarily be familiar with glacial deposits. As the focus of this book is on Neoproterozoic ice ages, characteristics related to micro- or macrofauna and biogenic indicators associated with glacial settings are not discussed. Similarly, geomorphic features are largely ignored as most Neoproterozoic successions do not have the pre-requisite outcrop exposure or preservation potential of glacial landforms found in more recent glacial settings.

### **Historical development**

The terminology used to refer to glacial deposits has evolved over the years with an increasing appreciation of the processes occurring in glaciated basins and a desire to refine palaeoenvironmental interpretations and include more information about the severity of climatic conditions, the nature of the ice mass and the depositional settings within glaciated basins (e.g. Flint *et al.* 1960; Dreimanis 1978; Hambrey & Harland 1978; Boulton & Deynoux 1981; Eyles 1993; Hambrey & Glasser 2003). The criteria used to identify glacial deposits in ancient

sedimentary successions has also evolved with this refined understanding of processes and the recognition of the non-uniqueness of many of the sedimentary characteristics that were once thought diagnostic of glacial deposits (e.g. Harland 1964; Crowell 1964; Harland *et al.* 1966; Schermerhorn 1974; Flint 1975; Hambrey & Harland 1978; Boulton & Deynoux 1981; Dreimanis & Schluchter 1985; Chumakov 1992; Eyles 1993; Crowell 1999). This improved understanding has occurred as a result of the emergence of modern sedimentological techniques and the application of facies and basin analysis, which have enhanced our ability to reconstruct palaeoenvironmental conditions from ancient sedimentary successions (see Eyles & Januszczak 2004 for a historical review).

For the purpose of this book, we encouraged authors describing deposits from around the world to use the non-genetic term diamictite to describe poorly sorted materials that contain a mixture of gravel-, sand- and mud-sized particles (Fig. 1). Terms such as tillite were only to be used in the interpretation section where poorly sorted materials could be shown to have been deposited directly by ice, without significant subsequent disaggregation and flow. In describing reworked glacial deposits, the interpretive term 'glacigenic' was recommended as a modifier (e.g. glacigenic debris flow). Readers are referred to Hambrey & Glasser (2003) for an up-to-date discussion of terminology.

### **Characteristics of glacial environments**

Deposition occurs within a number of different settings in glaciated basins, including subglacial, proglacial, glaciolacustrine and glaciomarine environments. Each of these depositional settings has characteristic processes, deposits and landforms (Menzies 1995, 1996; Benn & Evans 1998;

Evans 2005). Sedimentary analysis of Neoproterozoic successions can thus provide much needed palaeoenvironmental information when this variability is taken into consideration. In contrast to more recent glacial deposits, landforms tend not to be preserved or are poorly exposed in ancient successions, although there are some exceptions. An understanding of the processes together with the resulting deposits and their 3-D distribution in these settings is thus critical for palaeoenvironmental reconstruction.

Glaciomarine successions tend to be the most common in the Neoproterozoic geologic record as marine basins provide accommodation space away from subsequent ice advances and erosion, allowing preservation of thick packages of glacial sediments (Eyles 1993; Nystuen 1985). While these settings tend to provide the longest and highest resolution records of Neoproterozoic climate change, these depocentres tend to be dislocated from the glaciated shelves which acted as the sediment supply pathway, complicating efforts to reconstruct the distribution of palaeo-ice masses. An appreciation of other glacial settings is important as some successions will record conditions at the basin margin, close to land-based glaciers (e.g. Rieu *et al.* 2006; Arnaud 2008). Basin margin successions such as these are particularly useful in terms of palaeoclimate reconstruction as they can provide information regarding the nature of the ice mass (stagnant, active or fast-moving) and allow better control on the relative timing of the changes associated with that ice margin.

A discussion of the various settings in glaciated basins follows with particular emphasis on the nature of these environments, the processes that operate within them and the resulting sedimentary products. References provided herein are by no means exhaustive but were selected

as they focus on sedimentary characteristics and emphasize their connection to processes, thus facilitating the reconstruction of palaeoenvironmental conditions from the sedimentary record. Readers are referred to the “glaciers online” site of Alean & Hambrey (2008) as well as Eyles (1993), Crowell (1999), Hambrey & Glasser (2003) and Etienne *et al.* (2007) for helpful photographs and additional general discussions of criteria used in the recognition of ancient glacial deposits.

### ***Subglacial settings***

Conditions in subglacial settings are primarily controlled by the relationship between pressure and temperature, which ultimately controls the transition between solid and liquid phases and the constant alternation between melting and regelation in the basal traction zone. This in turn controls the ability of the ice to erode, transport and deposit debris in subglacial settings. The thermal characteristics of ice masses thus have a direct impact upon the accumulation of subglacial debris, with polythermal (variable distribution of warm and cold-based ice) and temperate glaciers (basal ice at or above pressure melting point) accumulating the most significant volumes of debris. While cold-based glaciers have been shown to entrain, transport and deposit sediment, generally they do not accumulate significant volumes of subglacial debris. Subglacial processes which are most relevant for palaeoenvironmental reconstructions include lodgement or smearing of debris onto the substrate, deformation of soft-sediment substrates, hydrofracturing of substrate, plucking of angular material from hardrock substrates as a result of freeze and thaw, abrasion of both the debris within the ice and the underlying substrate, as well as meltwater erosion. Meltwater processes are particularly significant in temperate glacial settings. The meltwater can be found in subglacial distributary channels, which comprise part of

the drainage system of the glacier, or as a thin film at the glacier base, which helps facilitate movement.

These processes are responsible for subglacial deposits such as lodgement and deformation tills, commonly characterised by diamicton (the unlithified equivalent of diamictite), in addition to conglomerate and sandstone deposited in subglacial meltwater tunnels. Subglacial processes also result in striated pavements, and clasts that show evidence of erosion and transport in the basal traction zone such as faceting, striations, chattermarks and a bullet shape (aka flat iron clasts or bullet-shaped boulders). Diamictite units may exhibit a gradational change from deformed and sheared at the base through chaotically stratified and massive at the top, indicative of the increasing stress profile with increasing proximity to the ice-sediment interface (Boulton & Hindmarsh 1987; Hart & Boulton 1991; Boulton 1996; Benn & Evans 1996). Other sedimentary characteristics that can be indicative of subglacial settings are boulder pavements (boulders preferentially aligned one behind the other) and soft sediment deformation features indicative of shear strain such as boudinage, tectonic lamination, rooted recumbent folding, and inclusions of underlying material that exhibit shear stress in a preferred direction (Hart & Boulton 1991; Hart & Roberts 1994; McCarroll & Rijdsdijk, 2003; Roberts & Hart 2005). Clastic dykes may also develop in areas where a frozen substrate and the overlying ice mass result in high pore water pressures (e.g. Le Heron & Etienne, 2005). Preferred orientation of the a-axes of clasts (fabric) has also been suggested to be indicative of subglacial conditions; however most recent studies have shown that clast fabric is not unique to any particular depositional setting and therefore has limited use in the recognition of glacial deposits (Bennett *et al.* 1999).

In terms of 3-D geometry, lodgement and deformation tillites tend to be tabular, relatively thin (<m - m scale) and can cover extensive areas (typically hundreds of km<sup>2</sup>). Basal contacts can be erosional or show evidence of deformation and incorporation of materials from the underlying substrate. Conglomerate and sandstone from subglacial tunnels will have sharp outer contacts and a pipe-like geometry in cross section. Associated sediments will depend on whether or not this ice mass overrode land or a marine shelf. Terrestrial subglacial deposits may be associated with coarse-grained glaciofluvial outwash sediments and other terrestrial proglacial sediments such as glaciolacustrine facies, whereas glaciomarine deposits will be associated with subaqueous proglacial sediments, tidal rhythmites, calcareous or clastic fine-grained sediments deposited by suspension settling and/or a range of fine- to coarse-grained sediment gravity flow deposits (e.g. turbidites, hyperconcentrated flows; Cowan & Powell, 1990; Anderson & Ashley 1991; Dowdeswell *et al.* 1996, 1998; Anderson 1999; Taylor *et al.* 2002).

### ***Terrestrial proglacial settings***

Conditions in proglacial settings are primarily controlled by the proximity to the ice margin and whether or not the ice margin is stagnant or actively advancing. Proglacial processes include *in situ* meltout of debris, remobilization of debris downslope, reworking by meltwater and melting of buried stagnant ice (Boulton 1972; Lawson 1982). These processes typically result in highly irregular topography, ponding of meltwater and development of proglacial lakes. The entire proglacial succession may be deformed and cannibalized by subsequent ice advances which bulldoze, thrust and re-work the deposits. Such events are known from modern environments (e.g. Huddart & Hambrey, 1996) and the ancient glacial geological record (e.g. Le Heron *et al.*, 2005). Stagnant ice margins will often have multiple recessional moraines and abundant



supraglacial debris with buried ice. In contrast, active ice margins will be characterized by multiple push moraines and ridges associated with the fluctuating ice margin (e.g. Boulton *et al.* 1999).

Highly variable depositional conditions (ponding, meltwater flow, bulldozing and remobilization of sediments) tend to result in highly variable sediment types. These processes are responsible for the deposition of diamictite (meltout, subaerial debris flow and bulldozing and deformation of glacial debris), conglomerate and sandstone (meltwater processes) and mudstone (ponding) in these settings. Clasts may show evidence of recent transport in the basal traction zone such as faceting, striations, chattermarks and bullet-shape, but surface features rarely survive fluvial transport. Deformation structures can be quite prevalent in these proglacial settings (e.g. Benn & Evans 1996; Philips *et al.* 2002). Extensional faulting and ductile folding of sediments associated with *in situ* melting of ice can be found in all facies types. In addition, reverse or thrust faults, shear planes and low angle décollement surfaces, nappes and complex folding and shear structures can be found resulting from bulldozing by ice.

The highly variable depositional conditions also lead to a complex distribution of sediment types; these settings are therefore often described as having high lateral facies variability. 3-D geometry will vary from irregular to channelized and lenticular with common intraformational unconformities and sudden bed termination. Basal contacts are variable from sharp to irregular and deformed or erosional to conformable and draping over irregular topography. Associated sediments are likely to be subglacial and glaciofluvial outwash deposits.

### ***Glaciolacustrine & glaciomarine settings***

Conditions in glacially influenced water bodies are primarily controlled by their proximity to the ice margin, whether or not the margin terminates in the water body, the thermal regime of the ice mass (e.g. temperate *versus* polar) and the configuration of the basin itself (lake *versus* ocean water body; deep sea, shelf, fjord or shoreline ; Eyles *et al.* 1985 ; Powell & Elverhoi 1989; Dowdeswell & Scourse 1990; Anderson & Ashley 1991; Dowdeswell *et al.* 1998; Evans & Pudsey 2002). Lakes which are dammed by ice or sediment (such as moraines) are also regulated by dam stability (Tweed & Russell 1999). Glacial processes dominate in settings that are close to the ice margin (< km's), whereas normal lacustrine/marine processes dominate in settings that are distal to the ice margin (>10's of km). Where ice terminates in a water body (ice-contact lakes or tidewater glacier marine settings), depositional settings are affected by grounding line fans, icebergs and meltwater plumes. In contrast, water bodies fed by glacier meltwater are primarily influenced by diurnal and seasonal fluctuations in meltwater discharge and seasonal ice cover. Meltwater processes are very important in settings influenced by temperate glaciers and limited to non-existent in polar settings. The configuration of the basin will influence the types of non-glacial processes that also contribute to the distribution and nature of deposits found in these settings. For example, lakes may experience thermal stratification and seasonal mixing, whereas deposition in oceans will be affected by tides and salinity. Sediment gravity flows resulting from high sedimentation rates are common in most water bodies but may be more prevalent in steep-sided lakes or fjords. However, it is important to note that subaqueous glacial debris flows have run-out distances in the order of hundreds of kilometres even on shallow slopes (Dowdeswell *et al.* 1996, 1998; Taylor *et al.* 2002). Oscillatory waves will affect shallow water settings, while storm waves will affect both shallow and shelf settings.

Processes include rapid deposition of coarse-grained sediments at the mouth of subglacial tunnels, density underflows and suspension-settling of fine-grained sediments related to buoyant meltwater plumes (Lønne 1995; O’Cofaigh & Dowdeswell 2001), as well as bulldozing and deformation of sediments related to ice advances. Remobilisation of debris by gravity flows is common in these settings and results from high sedimentation rates, oversteepening along the edges of grounding-line fans, normal sediment-transfer processes at the shelf-slope break or along steep-sided fjords. Gravity flows may also be initiated directly by subaqueous iceberg calving, or as a result of fluctuating water depths associated with calving or abrupt lake drainage events. Icebergs can have an impact on both proximal and distal settings through iceberg roll-over and dumping, meltout of entrained debris and scouring and bulldozing when grounded in shallow water (Thomas & Connell 1985; Woodworth-Lynas & Guigne 1990). Deposition of cold-water carbonates is also common in glacially influenced polar settings. Ikaite (hydrated calcium carbonate) is one such mineral which forms in near-freezing water temperatures. Unstable at higher temperatures, ikaite has poor preservation potential and typically undergoes replacement by calcite. Where the original crystal structure is preserved, these pseudomorphs are called glendonites and are an important palaeoenvironmental indicator of cold-water conditions (e.g. James *et al.* 2005; Halverson this volume)

Processes such as those identified above often lead to a predominance of diamictite and mudstone in glacially influenced lacustrine/marine settings, though conglomerate and sandstone can also be found associated with grounding-line fans and subglacial tunnel outflow (Lønne 1995; Nemeč *et al.* 1999). The suspension settling of fine-grained meltwater sediments and ice-

rafted debris (referred to as ‘rainout’) can lead to the formation of diamictite or mudstone with outsized clasts. Where these outsized clasts deform underlying laminated sediment (truncating laminae, loading sediment to develop compaction-related folds and/or water escape structures) they may be referred to as dropstones (Thomas & Connell 1985). Material of pebble-size or greater is generally considered as a good proxy for ice-rafting, although some care is needed in their interpretation (see below). Diamictite may also form as a result of sediment gravity flows, lodgement, deformation and bulldozing at the ice margin. Rhythmically laminated mudstone may result from tidal pumping in ice proximal marine setting (Smith *et al.* 1990) or from seasonal discharge fluctuations in non-ice contact lakes. The latter are referred to as varves in more recent deposits but the use of this term is discouraged in Neoproterozoic successions as a seasonal control cannot be clearly demonstrated due to limited geochronological control. Clasts may show evidence of recent transport in the basal traction zone such as faceting, striations, chattermarks and bullet-shape. Boulder pavements may develop on marine shelves as a result of winnowing of diamict and overriding by ice during sea level lowstands (Eyles 1994). Deformation may be found in ice-proximal grounding line fan deposits as a result of slumping and bulldozing, in remobilized glacial debris-flow deposits along the continental slope and in other deposits where iceberg grounding has occurred (Woodworth-Lynas & Guigne 1990; Hart & Roberts 1994).

### ***The record of climatic changes in glacial environments***

Ancient glacial sedimentary successions contain a record of fluctuating climatic conditions over time (Boulton 1990). Ice ages typically consist of interstadials (relatively warmer) and stadials (relatively colder) periods, which are recorded in the partial advance and recession of ice

and changes in the lateral and vertical distribution of sediments associated with these fluctuating environments (Allen *et al.* 2004; Arnaud & Eyles 2006). Changes from a glacial to a non-glacial period will similarly be recorded at the margins of marine basins. Here, glacioisostasy (crustal movements associated with ice loading and unloading) and glacioeustasy (changes in global ocean volume associated with changes in terrestrial ice volume) will combine with local tectonics to influence relative sea level (e.g. Råvnas & Steel 1998; Powell & Cooper 2002; Allen 2007). Glacio-eustatic variability can lead to significant correlative global cycles of deposition.

### **Reconstructing Neoproterozoic palaeoenvironmental conditions - Key considerations**

As with any discipline, the sedimentary record is at times difficult to interpret as many, if not most, sedimentary characteristics are not unique to specific environments. The following discussion highlights key points to consider when reconstructing palaeoenvironmental conditions from Neoproterozoic successions, focusing on indicators typically used to infer glacial conditions.

#### ***The palaeoclimatic significance of diamictite***

Diamictite can result from both glacial and non-glacial processes. In glaciated settings, diamictite results from lodgement and deformation of subglacial sediments, *in situ* meltout of ice and release of poorly sorted basal, englacial or supraglacial debris, slumping and reworking of glacial debris in proglacial, glaciolacustrine or glaciomarine settings and from 'rainout' of fine-grained sediment and ice-rafted debris. In non-glaciated settings, diamictite can form as a result of terrestrial or subaqueous debris flows (hyperconcentrated flows) or as a result of volcanoclastic flows. Studies of modern glaciated settings and of sediment gravity flows and

their deposits have greatly improved our ability to link depositional processes with their sedimentary products. However, careful consideration of sedimentary characteristics, geometry, as well as lateral and vertical distribution of diamictite and associated deposits is needed to distinguish between these various depositional origins (Arnaud & Eyles 2006; Table 1).

For example, a diamictite formed as a result of 'rainout' may have a gradational basal contact, whereas those related to sediment gravity flows or subglacial lodgement tend to have sharp conformable or erosional basal contacts. In a marine setting, diamictite showing draped upper contact can be attributed to a sediment gravity flow rather than subglacial processes. Diamictite formed as a result of subglacial lodgement may exhibit upwardly increasing deformation in contrast to deposits of sediment gravity flows where the maximum deformation will occur at the base of the deposit. Associated facies play a particularly key role in distinguishing between terrestrial or marine settings in these ancient successions where faunal indicators are lacking.

Careful analysis is particularly important in considering ancient glacial successions since many of them are preserved in tectonically-active settings where diamictite may record tectonically induced sediment instability rather than renewed glacial conditions and where sediment-landform associations cannot be used to confirm glacial conditions.

Even with the most careful examination, the depositional origin of diamictite will sometimes be difficult to demonstrate unequivocally as indicators are sometimes absent or obscured by post depositional tectonism. It is important to acknowledge this uncertainty where relevant as very different palaeoenvironmental conditions are implied depending on the depositional process

responsible for the formation of diamictite. In places where it is possible, careful consideration of exposures can greatly refine our depositional models, which can in turn contribute much needed palaeoenvironmental constraints on various palaeoclimate models that have been proposed for this time period.

### ***The palaeoclimatic significance of outsized clasts in bedded sediments***

Outsized clasts in laminated sediments have often been interpreted as ice-rafted debris or ‘dropstones’ and a clear indication of glacial conditions. However, such clasts can result as outrunners in turbidites (Postma *et al.* 1988), or can be rafted to deep water settings by seasonal ice and far-travelled icebergs (Gilbert 1990). In addition, diamictites or sediments bearing outsized clasts that have undergone a significant amount of post-depositional compaction or tectonic deformation can exhibit dropstone-like features as tectonic lamination form around clasts. Piercing or disturbance of underlying laminae and draping of sediment on top of the outsized clasts must be observed in order to confirm that the clast was likely dropped into place from floating ice (Thomas & Connell 1985). Distinction of seasonal ice, icebergs and far-travelled icebergs is very unlikely in ancient successions. It is therefore important to recognize that the occurrence of dropstones can have very different palaeoclimatic significance (cold climate, glaciated some (considerable) distance away, or locally glaciated).

### ***The palaeoclimatic significance of clast characteristics***

Clast characteristics suggesting transport in the basal traction zone of glaciers are also often used to infer glacial conditions. These include the presence of striations, chattermarks, faceting, bullet shaped boulder or flat iron clasts and extra-basinal provenance. It is important to note however,

that while these confirm a glacial source, these cannot be used to suggest glacial conditions prevailed at the time of deposition as a significant time lag may exist between glacial conditions in the basin and the final resting place of that glacial debris. While it is true that such surface markings are unlikely to survive with significant transport in meltwater glaciofluvial systems, many glaciomarine deposits - which tend to be the most common in ancient successions - will not have undergone any fluvial reworking. This is particularly relevant when considering the amount of time elapsed between the deposition of a diamictite thought to record glacial conditions and its associated 'cap' carbonate thought to record warmer post-glacial conditions in Neoproterozoic successions.

#### ***The palaeoclimatic significance of stratigraphic trends and sequence boundaries***

Many early studies of Neoproterozoic successions equated alternating beds of diamictite and other sediments as the product of multiple advances and recessional phases of ice margins and multiple diamictite-bearing intervals of successions separated by thick sections of non-diamictite bearing sediments as representing discrete ice ages. While this may turn out to be true, such interpretations must be made with caution considering the various depositional origins that can be ascribed to diamictite and the lack of geochronological control to constrain the amount of time represented by those thick non-diamictite bearing successions.

The lateral and vertical heterogeneity of lithofacies within glacially influenced successions can also be highly complex. In both terrestrial and shallow marine (neritic) environments, regional sequence boundaries may be developed as a result of subglacial erosion either directly by ice *via* processes of regelation, abrasion from subglacially entrained debris, or by meltwater drainage



under normal or elevated hydrostatic pressures. Multiple glacial advance-recessional cycles across marine shelf areas may result in stacked sequence boundaries, with lowstand packages of sediment in slope to bathyal environments providing the only continuous record of glacial-interglacial cyclicity. A cryptic shallow marine record provided by multi-storey stacking of subglacial drainage conduits such as tunnel valleys may also be preserved though these have not yet been identified in Neoproterozoic successions (see Ordovician examples in Le Heron *et al.* 2009). More localised disconformities may develop in marine environments as a result of iceberg keel-scour and processes of submarine mass-wasting related to high glaciomarine sedimentation rates or local tectonic activity. In terrestrial proglacial environments, the suite of erosion processes associated with braided fluvial systems, glaciotectonic deformation, and incision generated by glacial lake outburst floods or jökulhlaups resulting from subglacial eruptions can all lead to local or regional sequence boundary development. This picture can become even more complicated where thin cold-based ice occurs in accumulation areas and pre-existing sediments such as periglacial deposits can be preserved with little or no modification, effectively leading to a correlative surface lacking erosion.

In addition, as ancient glacial successions tend to be preferentially preserved in tectonically-active basins, the tectonic history of the basin and its development must be well constrained in order to assess its impact on accommodation space, sediment supply and ultimately stratigraphic changes and formation of sequence boundaries associated with relative sea level.

The points above highlight some of the issues in applying a sequence stratigraphic or purely lithostratigraphic analysis within glacially influenced successions.

## **Conclusions**

Criteria for the recognition of glacial deposits in Neoproterozoic sedimentary successions have developed over the last 50 years with an increasing appreciation for the different kinds of settings and processes that occur within glaciated basins. The analysis of modern glacial settings and processes has allowed us to better recognize the complexity of glaciated basins and the various challenges in confirming a glacial influence on deposition. This includes a better appreciation of the processes occurring in glaciomarine settings as well as the difficulty in distinguishing the nature of floating ice producing dropstones (local iceberg, distant iceberg or sea ice), the depositional origin of diamictite (glacial, glacially influenced or non-glacial) and the controls on large-scale stratigraphic trends in facies successions (alternating lithofacies or transgression and regression).

Poorly sorted deposits (diamictite), oversized clasts in laminated lithofacies (dropstones), high lateral facies variability in proximal settings and the presence of clasts that show evidence of subglacial transport are common features in glacial settings and these remain common indicators used in the study of ancient glacial successions. However, recent studies have shown that such sedimentary characteristics can have widely different climatic implications such that an understanding of the processes and products of glacial settings and sediment gravity flows as well as careful evaluation of sedimentary characteristics, geometry of deposits, deformation styles and associated facies are needed to enable identification of a glacial source and reconstruction of the extent and nature of glacial conditions at the time of deposition.

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### Figure Captions:

Fig.1: The Hambrey (1994) modification of the Moncrieff (1989) classification for poorly sorted sediments. Redrawn with permission of UCL Press, London.



Table 1: Characteristics of Neoproterozoic-age diamictite units of different origin.

Types of diamictite	Textural features	Compositional features	Sedimentary structures	Deformation	Basal contact	Geometry	Associated deposits	Useful references
<b>Lodgment &amp; deformation tillite</b>	-poorly sorted -boulder pavements -evidence of glacial transport on particle surface <sup>1</sup> -textural immaturity -wide range of stone roundness - -micromorphological characteristics associated with high stress conditions	-mixed provenance (intra-and extrabasinal clasts) -compositional immaturity -inclusions or rafts of other sediment types that exhibit ductile deformation	-Massive or chaotically stratified -gradational upward change from highly deformed to massive -preferred orientation of shear structures	-glacitectonic deformation such as shear structures (rooted folds, boudinage, attenuated bedding), nappes, imbricate structures, thrust or reverse faulting, shear planes and decollement surfaces. -clastic dykes	-Sharp -Erosional or deformed -basal shear plane	-Thin (<m – m) and tabular -laterally extensive (hundreds of km <sup>2</sup> ) -discontinuous if close to ice margin	-well bedded conglomerate and sandstone, commonly cross-stratified and exhibiting cut and fill geometry (glaciofluvial outwash) -thick deposits of windblown silt (loess), sandstone wedges, convoluted bedding from cryoturbation and <i>in situ</i> breccia <sup>2</sup> (periglacial) -laminated or massive mudstone with/without outsized clasts (lacustrine )	-Benn & Evans 1996 -Boulton 1972 -Boyce & Eyles 2000 -McCarroll & Rijdsijk 2003 -Hart & Roberts 1994 -Menzies 2000
<b>Meltout tillite</b>	-poorly sorted -localized sorting from meltwater reworking -evidence of glacial transport on particle	-mixed provenance (intra-and extrabasinal clasts) -compositional	Crudely stratified	-extensional faulting from melting of buried ice -convoluted bedding and	-Conformable -sharp	-rapid lateral facies changes	well bedded conglomerate and sandstone, commonly cross-stratified and exhibiting	-Boulton 1972 -Lawson 1982 -McDonald & Shilts 1975

Types of diamictite	Textural features	Compositional features	Sedimentary structures	Deformation	Basal contact	Geometry	Associated deposits	Useful references
	surface such as striations -textural immaturity -wide range of stone roundness	immaturity		folding			cut and fill geometry (Glaciofluvial outwash) -laminated or massive mudstone with or without outsized clasts from ponded water or lake deposits	
<b>'rainout' deposits</b>	-poorly sorted -evidence of glacial transport on particle surface <sup>1</sup> -textural immaturity -wide range of stone roundness	-mixed provenance (intra-and extrabasinal clasts) -compositional immaturity -clast clusters from iceberg dumping -diamict pellets from frozen debris on icebergs -dropstones	-Massive to crudely stratified - Discontinuous stringers of sand and gravel (boulder pavements) from winnowing -variable clast content from changing sedimentation rate or supply of ice-rafted debris	-Grounding ice berg structures and ice-keel furrows	-Gradational	-Variable thickness -tabular to blanket-like geometry, draping underlying topography -laterally continuous (distal) to rapid lateral facies changes (proximal)	-Lodgement till from ice advance onto shelf -sediment gravity flow deposits -laminated mudstone with/without outsized clasts -Subaquatic fan deposits in proximal settings -pelagic clastic or carbonate sediments	-Eyles <i>et al.</i> 1985 -Thomas & Connell 1985
<b>Terrestrial debris flows</b>	-poorly sorted -evidence of glacial transport on particle surface <sup>1</sup> if	-local (non-glacial) or mixed (glacigenic	-massive to chaotically stratified	-flow nose -basal shearing structures	-erosional with rip-up clasts	-extent (m-km)	-Lodgement or meltout tills	-Lawson 1982 -Benvenuti & Martini 2002 -Colella &

Types of diamictite	Textural features	Compositional features	Sedimentary structures	Deformation	Basal contact	Geometry	Associated deposits	Useful references
	glacigenic source -textural maturity depending on source -wide range of stone roundness depending on source	source) provenance -compositional maturity depending on source -inclusions or rafts of other sediment types that exhibit ductile deformation		-convoluted bedding or folding				Prior, 1990
<b>Subaqueous debris flows</b>	-poorly sorted -evidence of glacial transport on particle surface <sup>1</sup> -textural immaturity -wide range of stone roundness	-local (non-glacial) or mixed (glacigenic source) provenance -compositional maturity depending on source -inclusions or rafts of other sediment types that exhibit ductile deformation, some can be very large (10's of m in size)	-massive to chaotically stratified -graded bedding -coarse-tail grading	-flow noses -basal shear structures -folding and convoluted bedding -load casts, water escape structures	-Erosional with rip-up clasts -conformable when hydroplaning has occurred	-Moderate to thick -tabular to lenticular -channelized -extent (m-tens of km)	-Lodgement tills -'rainout' deposits -laminated mudstone with/without outsized clasts -subaqueatic fan deposits -pelagic clastic or carbonate sediments -other sediment gravity flow deposits (e.g turbidites)	-Nardin <i>et al.</i> 1979; Visser 1983; Prior <i>et al.</i> 1984; Postma <i>et al.</i> 1988; Hart & Roberts 1994 Mohrig <i>et al.</i> 1999; Eyles & Eyles 2000; Hambrey & McKelvey 2000; Laberg & Vorren 2000; Mulder & Alexander 2001; McCarroll & Rijdsdijk 2003

Note: Not one of these features is sufficient for identification of a glacial or glacially influenced origin and any one of the features may be absent.

<sup>1</sup>evidence of glacial transport: striations, chattermarks, polish, grooves, facets, bullet shape or 'flat iron'

<sup>2</sup> these sedimentary characteristics are not unique to periglacial settings; their origin may be difficult to confirm even with careful stratigraphic and sedimentological consideration.

Increasing gravel content →

**Figure 1**

Gravel (>2 mm) in whole rock, estimated from core (%)

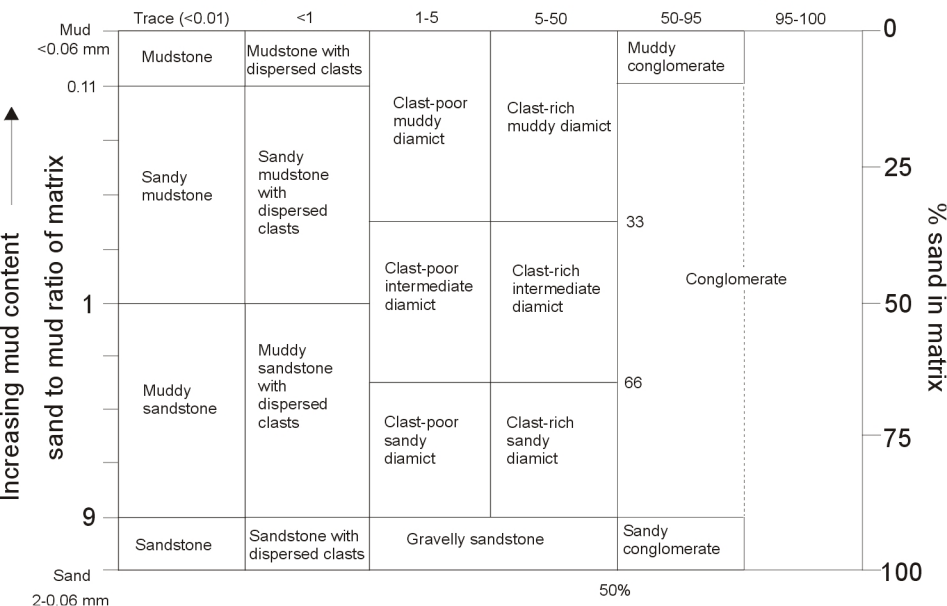


Table 1: Characteristics of Neoproterozoic-age diamictite units of different origin.

Types of diamictite	Textural features	Compositional features	Sedimentary structures	Deformation	Basal contact	Geometry	Associated deposits	Useful references
<b>Lodgment &amp; deformation tillite</b>	-poorly sorted -boulder pavements -evidence of glacial transport on particle surface <sup>1</sup> -textural immaturity -wide range of stone roundness - -micromorphological characteristics associated with high stress conditions	-mixed provenance (intra-and extrabasinal clasts) -compositional immaturity -inclusions or rafts of other sediment types that exhibit ductile deformation	-Massive or chaotically stratified -gradational upward change from highly deformed to massive -preferred orientation of shear structures	-glacitectonic deformation such as shear structures (rooted folds, boudinage, attenuated bedding), nappes, imbricate structures, thrust or reverse faulting, shear planes and decollement surfaces. -clastic dykes	-Sharp -Erosional or deformed -basal shear plane	-Thin (<m – m) and tabular -laterally extensive (hundreds of km <sup>2</sup> ) -discontinuous if close to ice margin	-well bedded conglomerate and sandstone, commonly cross-stratified and exhibiting cut and fill geometry (glaciofluvial outwash) -thick deposits of windblown silt (loess), sandstone wedges, convoluted bedding from cryoturbation and <i>in situ</i> breccia <sup>2</sup> (periglacial) -laminated or massive mudstone with/without outsized clasts (lacustrine )	- -Benn & Evans 1996 -Boulton 1972 -Boyce & Eyles 2000 -McCarroll & Rijdsdijk 2003 -Hart & Roberts 1994 -Menzies 2000 <a href="#">- Evans et al. 2006</a>
<b>Meltout tillite</b>	-poorly sorted -localized sorting from meltwater reworking -evidence of glacial transport on particle	-mixed provenance (intra-and extrabasinal clasts) -compositional	Crudely stratified	-extensional faulting from melting of buried ice -convoluted bedding and	-Conformable -sharp	-rapid lateral facies changes	well bedded conglomerate and sandstone, commonly cross-stratified and exhibiting	-Boulton 1972 -Lawson 1982 -McDonald & Shilts 1975 <a href="#">-Evans et al. 2006</a>

Types of diamictite	Textural features	Compositional features	Sedimentary structures	Deformation	Basal contact	Geometry	Associated deposits	Useful references
	surface such as striations -textural immaturity -wide range of stone roundness	immaturity		folding			cut and fill geometry (Glaciofluvial outwash) -laminated or massive mudstone with or without outsized clasts from ponded water or lake deposits	
<b>'rainout' deposits</b>	-poorly sorted -evidence of glacial transport on particle surface <sup>1</sup> -textural immaturity -wide range of stone roundness	-mixed provenance (intra-and extrabasinal clasts) -compositional immaturity -clast clusters from iceberg dumping -diamict pellets from frozen debris on icebergs -dropstones	-Massive to crudely stratified - Discontinuous stringers of sand and gravel (boulder pavements) from winnowing -variable clast content from changing sedimentation rate or supply of ice-rafted debris	-Grounding ice berg structures and ice-keel furrows	-Gradational	-Variable thickness -tabular to blanket-like geometry, draping underlying topography -laterally continuous (distal) to rapid lateral facies changes (proximal)	-Lodgement till from ice advance onto shelf -sediment gravity flow deposits -laminated mudstone with/without outsized clasts -Subaquatic fan deposits in proximal settings -pelagic clastic or carbonate sediments	-Eyles <i>et al.</i> 1985 -Thomas & Connell 1985
<b>Terrestrial debris flows</b>	-poorly sorted -evidence of glacial transport on particle surface <sup>1</sup> if	-local (non-glacial) or mixed (glacigenic	-massive to chaotically stratified	-flow nose -basal shearing structures	-erosional with rip-up clasts	-extent (m-km)	-Lodgement or meltout tills	-Lawson 1982 -Benvenuti & Martini 2002 -Colella &

Types of diamictite	Textural features	Compositional features	Sedimentary structures	Deformation	Basal contact	Geometry	Associated deposits	Useful references
	glacigenic source -textural maturity depending on source -wide range of stone roundness depending on source	source) provenance -compositional maturity depending on source -inclusions or rafts of other sediment types that exhibit ductile deformation		-convoluted bedding or folding				Prior, 1990
<b>Subaqueous debris flows</b>	-poorly sorted -evidence of glacial transport on particle surface <sup>1</sup> -textural immaturity -wide range of stone roundness	-local (non-glacial) or mixed (glacigenic source) provenance -compositional maturity depending on source -inclusions or rafts of other sediment types that exhibit ductile deformation, some can be very large (10's of m in size)	-massive to chaotically stratified -graded bedding -coarse-tail grading	-flow noses -basal shear structures -folding and convoluted bedding -load casts, water escape structures	-Erosional with rip-up clasts -conformable when hydroplaning has occurred	-Moderate to thick -tabular to lenticular -channelized -extent (m-tens of km)	-Lodgement tills -'rainout' deposits -laminated mudstone with/without outsized clasts -subaquatic fan deposits -pelagic clastic or carbonate sediments -other sediment gravity flow deposits (e.g turbidites)	-Nardin <i>et al.</i> 1979; Visser 1983; Prior <i>et al.</i> 1984; Postma <i>et al.</i> 1988; Hart & Roberts 1994 Mohrig <i>et al.</i> 1999; Eyles & Eyles 2000; Hambrey & McKelvey 2000; Laberg & Vorren 2000; Mulder & Alexander 2001; McCarroll & Rijdsdijk 2003

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<sup>1</sup>evidence of glacial transport: striations, chattermarks, polish, grooves, facets, bullet shape or 'flat iron'

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Gravel (>2 mm) in whole rock, estimated from core (%)

