Glaciation or not? An analytic review of features of glaciation and sediment gravity flows: introducing a methodology for field research

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Abstract

For more than 150 years, geological features claimed to be evidence for pre-Pleistocene glaciations have been debated. Advancements in recent decades, in understanding features generated by glacial and mass flow processes, are here reviewed. It is timely to make renewed comparisons and to re-visit the interpretations of data used to support pre-Pleistocene glaciations. Similarities and differences of Quaternary glaciogenic and sediment gravity flow features, which are most often referred to as proxies and evidence of ancient glaciations, are documented, discussed and closely examined, in order to uncover the origin of more ancient deposits. It is necessary to use multiple proxies to develop a correct interpretation of ancient strata. Analyses and evaluation of data are from a) Quaternary glaciations and glaciers, b) formations which have been assigned to pre-Pleistocene glaciations, and c) formations with comparable features associated with mass-flow deposition (and occasionally tectonics). The aim is not to reinterpret specific formations and past climate changes, but to enable data to be evaluated using a broader and more inclusive conceptual framework. To achieve this goal, detailed descriptions of field evidences are documented from papers that may suggest different interpretations of these data. This is not in an intention to present revised interpretations of these papers, but to collect data and develop a foundation for enhanced analysis of geologic processes and features. Regularly occurring features interpreted to be glaciogenic and are contemporaneous with pre-Pleistocene diamictites which have been interpreted to be tillites, have often been shown to have few or no Quaternary glaciogenic equivalents. These same features commonly form by sediment gravity flows or other non-glacial processes, which may have led to misinterpretations of ancient deposits. These features include, for example, appearances and documented data from the extent and thickness of diamictite deposits, environmental and depositional affinity of fossils in close connection to diamictites, grading and bedding of diamictites, fabrics, size of erratics, polished and striated clasts and surfaces ("pavements"), boulder pavements, lineations, valleys, glaciofluvial deposits, dropstones, laminated sediments, glaciomarine sediments, periglacial structures, soft sediment tectonics, and surface microtextures. The analysis of these features provide detailed documentation that may be used to help identify the origin for many pre-Pleistocene diamictites. Recent decades of progress in research relating to glacial and sediment gravity flow processes has resulted in proposals by geologists, based on more detailed field data, more often of an origin by mass movements and tectonism than glaciation. The most coherent data of this review, i.e. appearances of features produced by glaciation, sediment gravity flows and a few other geological processes, are summarized in a Diamict Origin

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ABSTRACT

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Keywords:

tillite

sediment gravity flow (SGF)

striation

groove

dropstone

paleoclimate

fossil vegetation

glaciogenic proxies

surface microtexture

Late Paleozoic Ice Age

Terminology

Dropstone and lonestone: Dropstone is a genetic label for a clast that has been dropped into water from ice. This label may also be used for clasts dropped by other agents, like from floating vegetation. In the current paper the label dropstone will refer to any outsized clasts which have been interpreted in the literature to be dropped from ice, even if that interpretation may not be valid. A non-genetic term for outsized clasts is lonestone. This term would be better to use than dropstone, but as lonestones are commonly interpreted to be dropstones and the terms sometimes even are used interchangeable, the label dropstone is used whenever it has been done so by earlier researchers. Otherwise, the interpretation of the origin has to be discussed for every clast that is referred to.

Groove: Commonly defined in width as >10 mm up to a few meters or more. Marine geologists may label any large linear erosional (V-shaped) forms as grooves (Nwoko et al., 2020a), even if they are kilometers in width, but in the current paper the definition is used for erosion by tools.

Striation: Commonly defined as <10 mm in width. Marine geologists may label large erosional (wide and flat-bottomed) channels made by megaclasts on the sea bottom as striations (Nwoko et al., 2020a), but that definition is not used in the current paper.

Tillite and"tillite": This label is a genetic term, and by definition a lithified till. Any ancient diamictite which has been classified as tillite by former researchers, even if the evidence from recent geological research indicates a non-glacial origin of the deposit, will here also be labeled tillite. If the word diamictite should be used instead of tillite, then the current or most common interpretation of the deposit will be missed. Therefore, for the discussions concerning the interpretation of the origin of a deposit, the term will be marked within quotation marks, i.e. "tillite," independent of the most recent interpretation.

1. Introduction

1.1. Structure of the current paper

The basic assumption for the current paper is that the recent is better known than the past. This is an actualistic approach, i.e., the principle that the same processes and natural laws applied in the past are the same as those active today. By not using models or longstanding interpretations, but recent field studies and experiments, this actualistic approach is followed. Recent progress in studies of sediment gravity flow (SGF) (used interchangably with mass flow), glaciogenic and a few other processes which may be relevant, are applied when documenting the origin of ancient deposits. Where there is a lack of published data, documentation is compiled or otherwise acknowledged as missing. It may be questioned that mainly Quaternary examples of geologic features are used in comparison to features from the much longer pre-Quaternary time scales, but as it is assumed that natural laws have not changed, this will not be much of a problem.

Diamictites are often interpreted to have been formed in a cold climate environment based on the general structure of the deposits, associated geologic features, and polar wander paths. Geochemical data may be used to strengthen the interpretation of glaciation, but these display apparent shortcomings (Frimmel, 2010; Bahlburg and Dobrzinski, 2011; Garzanti and Resentini, 2016; Macdonald, 2020; Caetano-Filho et al., 2021; Mikhailova et al., 2021; Rogov et al., 2021; Scotese et al., 2021; Retallack et al., 2021). Similarities in outcrop of most of the features of glaciation may, however, be produced by different geologic processes (Isbell et al., 2021), mainly SGFs, and therefore more detailed criteria are needed for interpretation. The current paper analyzes and reviews a broad range of such geologic features. The intention is to design questions for field research, rather than to present solutions to all problems of interpretation. Only the appearance of geologic features which are described in great detail will be documented, and former general inferred interpretations of glaciation may not be followed. Different processes which may create similar features are documented in a way of using process-related or “process-sedimentological” principles “to consider alternative hypotheses” (Shanmugam, 2012). Relevant field data is summed up in a

Diamict Origin Table, as a guide to the interpretation of the geologic features which have been documented and discussed (Appendix).

Even if there is an awareness of the importance of gathering data from different research disciplines, it may be difficult to evaluate what data shall be used while constructing and interpreting models. Areas which have been described to have formed by ancient glaciations have to be discussed from data compilation from many research disciplines. It may also be insufficient to use interpretations from different research disciplines or articles as facts, if the research data may be better described from a different geological and climatological aspect than is currently done.

The current paper concentrates on features which are most often reported and also documented in detail in association with "tillites," and these are compared to similar features from Quaternary glaciations and SGFs that mimic (or are) these features. Therefore, unintentionally, this work may have become controversial, not because of the compilation of research data, but because of longstanding interpretations of many ancient deposits. The documentation is to a large part biased by reference to well documented and extensive outcrops. The main exception is the documentation of outsized clasts, because lonestones are often interpreted to be dropstones and therefore are commonly suggested to be evidence for glaciation (e.g., Rodríguez-López et al., 2016; López-Gamundí et al., 2021; Le Heron et al., 2021a; Bronikowska et al., 2021).

1.2. Historical sketch

Ever since diamictites were first interpreted to be pre-Pleistocene ice age deposits, by Ramsay in 1855 for some Permian boulder deposits in England (Harland and Herod, 1975; Hoffman, 2011), there has been much controversy over their interpretation. The first steps of SGF research can be said to have started in 1827, with the introduction of the term flysch (Studer, 1827). The first mention of a submarine fan was in 1955 (Menard, 1955), and the first mention of a turbidite-fan link in ancient fans was in 1962 (Bouma, 1962; Shanmugam, 2016). The importance of SGFs in the geologic record has often been underestimated (Shanmugam, 2016, 2020, 2021b), even if SGF deposits have often been documented in papers concerning diamictites. Lately, hyperpycnal flows have been recognized to transform, after deposition, into a full spectrum of SGF deposits, including cohesive debris flows and rhythmites, which adds one more dimension to this research area (Zavala and Arcuri, 2016; Shanmugam, 2019, 2021b; Zavala, 2019, 2020).

Since the early 1970s, starting with an earlier paper by Crowell (1957), it has been recognized that many “ice-age remains” have been deposited by different kinds of SGFs, for example by turbidity currents but especially by cohesive debris flows. For example, in the Tertiary of Alaska, twelve major glaciations were reinterpreted as formed largely by SGFs (Plafker et al., 1977; Eyles and Eyles, 1989). Schermerhorn published a comprehensive review which documented the evidence for a SGF origin of ancient diamictites, shown in his classic work on Late Precambrian diamictites (Schermerhorn, 1974a, 1976a, 1976b, 1977). The current paper is partly inspired by the work of Schermerhorn, but is also influenced by published work on fan deposits and SGFs (Shanmugam, 2016; Peakall et al., 2020). Many researchers in addition to Schermerhorn have compared tills, glaciomarine sediments and different kinds of SGFs, but the work may have been hampered by the assumption that outcrops with equivocal origin are ice-age deposits (Hambrey and Harland, 1981; Boulton and Deynoux, 1981; Anderson, 1983; Wright et al., 1983; Eyles, 1993). The documentation in Schermerhorn´s classic paper (1974a) has to a large part gone unnoticed, even though this article may be referred to in passing (e.g., Le Heron et al., 2017). Eyles (1993) wrote: “ ... unfortunately, the inclusion of strata that were indisputable of a glacial origin weakened the essential correctness of Schermerhorn´s argument.”

Pre-Pleistocene formations which are, or have been, interpreted to have formed by glaciations are documented from the Archean, the Paleoproterozoic, the Neoproterozoic, and during all periods of the Phanerozoic (Hambrey and Harland, 1981; Caputo and Santos, 2020; Youbi et al., 2021) sometimes even in the tropics and indicating low elevations (Soreghan et al., 2014), including during five different episodes of the Cretaceous (Alley et al., 2020). The most accepted and geologically important glaciations are in the Paleoproterozoic, the Neoproterozoic, the Upper Ordovician, and the Late Paleozoic Ice Age (LPIA; recently dated to 372-259 million years; Pauls et al., 2021) (Hambrey and Harland, 1981).

1.3. Bias in diamictite research

Glaciogenic proxies are documented in order to find stratigraphic intervals displaying glaciations, as there, on the basis of uniformitarianism, had been many glaciations throughout earth history (e.g., Williams, 2005). The current interpretation of a stratigraphic interval commonly biases the research questions and which observations and measurements are made, and frequently it is mainly data supposed to be relevant for the current interpretation that are reported. These circumstances have resulted in that alternative interpretations were not always fully investigated. Therefore the features which are described in the literature often contain too few details to establish if the deposits have originated from glacial action, SGF or by any other means. For example, a clast or a surface with striations is often reported to have been glacially striated if present in connection to a diamictite (Atkins, 2003). In other words, features which may be formed in different environments are reported, but diagnostic features may not be documented or discussed. Single or even groups of features which display appearances partly similar to and interpreted to be glaciogenic features, may subsequently be shown to be very different from Pleistocene and more recent glaciogenic features. In short, the question of the origin of diamictites has become a part of a scientific paradigm (Kuhn, 1970; Shanmugam, 2016) connected to long-term climatic correlations (Young, 2013; Shields et al., 2022).

As recent research uncovers growing evidence of non-glacial transport, diamictites worldwide have more often been interpreted as glaciomarine and often considered as parts of interglacial periods. This includes approximately 95% of all "glaciogenic" deposits, i.e. sediments which may contain an abundance of marine fossils, and to a large part are made up of SGF deposits (Eyles 1993; González and Glasser, 2008; Isbell et al., 2016; López-Gamundí et al., 2016, 2021; Assine et al., 2018; Vesely et al., 2018; Rosa et al., 2019; Sterren et al., 2021; Isbell et al., 2021; Molén and Smit, 2022). These interpretations make it more difficult to discover if the deposits had been produced primarily by glaciation or are non-glacial marine. In this case often the only "unequivocal" evidence for glacial influence is considered to be dropstones, especially if outsized clasts occur in rhythmites, but also if SGF deposits or stratified diamictites display outsized clasts (e.g., Ezpeleta et al., 2020). Apart from dropstones, striated clasts and surfaces ("pavements") are commonly referred to as evidence for glaciation without discussing alternative interpretations in depth (e.g., different examples in Molnia, 1983a; Miall, 1983, 1985; Eyles, 1993; Hoffman et al., 1998; Carto and Eyles, 2012a; Rodríguez-López et al., 2016; Le Heron et al., 2017; Le Heron and Vandyk, 2019).

1.4. Geologic features produced by sediment gravity flows

Gravity-induced slope processes include variations of rock fall, slides, slumps, debris flows and turbidites. In some outcrops there is an almost complete visible sectioned sequence, horizontally and/or vertically, which shows how mass movements have changed from e.g., slides, to debris flows, and finally to turbidity currents (Ogata et al., 2019; Rodrigues et al., 2020; Kennedy and Eyles, 2021). Sedimentary and erosional features which commonly form from such processes, especially those originating from cohesive debris flows, share many similarities in appearance to glaciogenic features and are present in many diamictites which had been interpreted to be glaciogenic (e.g., Molén, 2017, 2021). Another process which shows similarities to slope processes are land derived hyperpycnal flows. Such flows can in some cases last for months. Even though they have a different origin from slope processes, they display similarities in the sedimentation process and the deposits may be reworked and transform into a full spectrum of SGFs (Zavala and Arcuri, 2016; Shanmugam, 2019, 2021b; Zavala, 2019, 2020). Hyperpycnal flow deposits are therefore included here in what is commonly described as SGF deposits.

Below is a list of features that commonly originate by especially cohesive debris flows, but which also may originate from other slope processes like turbidites and slides that commonly co-occur with debris flows. These geologic features are important to acknowledge as there are differences between features of glaciation and SGFs which will be outlined herein. The features below are well known in the geologic community within the discipline of slope processes, but the details are often not well known outside of this community. All the features listed have to be acknowledged. An assemblage of these are commonly present in close connection to diamictites, i.e. they are parts of ancient diamictites and other erosional and depositional features which have been interpreted to be glaciogenic, and are by definition also present in areas displaying non-glacial SGF deposits. If the features in the list below are studied more in detail, it may be possible to demonstrate if an area or outcrop was formed mainly by SGFs or by glaciation. A subsample of references from a complete research discipline, which may be the most important from the discipline of SGF research, which all document many of the features in the list below, are Middleton and Hampton (1976), Shanmugam et al. (1994), Schneider and Fisher (1998), Major et al. (2005), Moscardelli et al. (2006), Talling et al. (2007, 2012, 2015), Watt et al. (2012), Dakin et al. (2013), Pickering and Hiscott (2015), Shanmugam (2016, 2020, 2021), Peakall et al. (2020), Cardona et al. (2020), Baas et al. (2021); Dufresne et al. (2021).

a) diamict texture, but deposits often may be in streaks and display some sorting and grading,

b) grooves and striations on clasts and surfaces/pavements, especially below debris flows that may hold clasts in fixed positions,

c) lonestones which may be interpreted as dropstones,

d) sharp and irregular fronts,

e) a great degree of scatter and variable thickness of the deposits,

f) variable erosion and depth of deformation of the underlying substratum (e.g, sharp, undulating, interdigitating, ripple-type, grooved),

g) deposition in or at the end of channels,

h) reworking at the top of the deposits by bottom currents,

I) conformably draping by mass flow beds of rapid deposition (mainly turbidites),

j) soft sediment structures, like load casts, clastic dykes, boudinage, folds and convolute bedding,

k) scour and fill structures,

l) rhythmites,

m) climbing ripples,

n) contorted rip-up soft slabs of sandstone or other sediments,

o) mud-flakes or clasts which have often been pressed down into the underlying sediments from above, and therefore the beds also display holes or depressions below debrites, where embedded clasts have been eroded out,

p) a thickness-to-width ratio commonly thicker than 1:50,

q) more than 3-5% clay, or otherwise may transform distally into hyperconcentrated flow or sediment-laden floods,

r) an appearance of crossbedding,

s) a basement which has been rounded with a superficial appearance of having been glaciated, e.g. displaying bedrock forms similar to roches moutonnées, even with evidence of plucking,

t) brecciation of the substratum, which may also display cataclasis,

u) a thin basal layer of debris, i.e. a traction carpet or liquefied sandstone,

v) rip up soft sedimentary megaclasts with intact stratigraphy,

x) entrainment of sediments, including processes that may be defined as plucking, during the complete path of movement,

y) laminar behavior,

z) uphill movement,

za) no or rare evidence of fossils,

zb) an upper hummocky terrain,

zc) drop formed landforms which are erosional remnants.

2. Similarities and differences between glaciogenic and other geologic features

Ancient outcrops commonly are visually restricted, and therefore it may be difficult to document appearances of features from the action of glaciers or any other processes. Many different geological features which may be misinterpreted in restricted outcrops, are documented below. Some researchers state that it may be impossible to confidently identify a specific environment of deposition by macroscopically features and textural criteria (Kilfeather et al., 2010), but as is documented in the current paper there are more unequivocal critera than is usually recognized.

If there is glaciogenic material which has never been processed by but only transported by a glacier, such as supraglacial till, it will not acquire many of the characteristics imposed by glacial forces. The same holds for flow tills, if they are supraglacial mass flows that have never been covered by a glacier. This may also hold for some aspects of squeezed flow till (Hicock, 1991; Hicock and Dreimanis, 1992b). Flow tills are in any case difficult to differentiate from non-glaciogenic mass flows, especially if they are formed subaqueously (Evenson et al., 1977). Englacial till which has been deposited as melt-out till also may not acquire many glaciogenic features. However, all material that is deposited in a subglacial environment will display evidence of this process (Mahaney, 2002; Molén, 2014). Furthermore, supraglacial tills and other tills that have not been transported at the base of a glacier are usually a minor part of glaciogenic sediments, and they are easily removed by later erosion, in contrast to basal till.

Many features which are interpreted to be evidence of glaciation form in a wide range of environments (e.g., Eyles, 1993; Eyles and Boyce, 1998; Atkins, 2003; Thompson, 2009). If clasts from one environment are incorporated by a new process, e.g., tectonic material that is mixed with finer material and beach/slope material in a debris flow, the origin of the deposit may be difficult to uncover (e.g., Festa et al., 2019). This mixing of different materials is common in SGFs, and up to 50% of the material may be entrained through erosion from the substrate along the path of the flow (e.g., Thompson, 2009; Carto and Eyles, 2012a, 2012b; Ortiz-Karpf et al., 2017; Ogata et al., 2019; Nugraha et al., 2020; Rodrigues et al., 2020). Eyles and Eyles (2000) described a “cement-mixer-model” of how different sediments could mix.

Each of the features reviewed in the sections 2.1.-2.18. is commonly referred to when exploring evidence of glaciation. There is, however, an increasing understanding that similar features, which more or less mimic the typical glacial features, also can originate as a consequence of different kinds of SGFs and other non-glacial processes. In addition, there are many geologic features from “ancient ice-ages” which have rarely or never been formed by Pleistocene or younger glaciers. These features may be at odds with a glaciogenic interpretation, but often at the same time indicate a SGF or/and tectonic origin. Also, there are some general problems in regard to “tillites” that do not apply to SGFs, e.g. climate and correlations, which are also discussed below.

2.1. Geographical extent, dating, climate and fossils

2.1.1. Geographical extent

SGFs occur worldwide, independent of latitude, and are therefore present in the same areas as the more geographically restricted glaciers. Mountain glaciers are areally restricted, but are present worldwide if above the equilibrium-line altitude (e.g., Mahaney, 1990).

The geographic extents of deposits from "ancient ice-ages" are often comparatively small and "tillites" are often dispersed as separate outcrops (e.g., Lindsay, 1966; Finkl and Fairbridge, 1979; Fairbridge and Finkl, 1980; Deynoux and Trompette, 1981b; Le Heron et al., 2018a). There are two exceptions. The first is the Ordovician deposits in northern Africa which cover between 8 x 10^6 (Biju-Duval et al., 1981) and 20 x 10^6 km^2 (Fairbridge, 1979). The size difference depends on whether the Arabian diamictites are included or not. If the lesser Ordovician outcrops in South Africa, Europe and South America are included, the maximum hypothetical glaciated area is c. 40 x 10^6 km^2 (Le Heron et al., 2005, 2018a; Ghienne et al., 2007). The second exception is the LPIA outcrops which cover maybe 30 x 10^6 km^2 if deposits from separate basins in South America, Antarctica, Australia, India, South Africa, Congo and Madagascar are included (Gravenor, 1979). Parts of the Arabic Peninsula, Ethiopia, Chad and a few other areas may also be included in the LPIA (e.g., Bussert, 2010, 2014; Le Heron, 2018). The LPIA has lately been alternatively interpreted as many smaller glaciations, to a large part marine and including SGFs, and parts of the area have even been described as formed in a large glacial lake (Horan, 2015; Dietrich et al., 2019; Fedorchuk et al., 2019; López-Gamundí et al., 2021; Isbell et al., 2021; Ives and Isbell, 2021).

Neoproterozoic diamictites are commonly present in downwarping or deep basins, otherwise close to rifts, and rarely on stable bedrock (Schermerhorn, 1974a; Eyles, 1993; Arnaud, 2008; Frimmel, 2018; Kennedy and Eyles, 2019, 2021), and many Precambrian "tillites" can be correlated with tectonic movements apparently connected to continental breakup (Eyles, 1993; Williams, 2005; Carto and Eyles, 2012a, 2012b; Delpomdor et al., 2016; Gómez-Peral et al., 2017; Kennedy and Eyles, 2019, 2021; Molén 2021). Recent active areas of tectonism/volcanism may display similar geologic features as in Precambrian “tillites” (Carto and Eyles, 2012a). Peperites are mixed with Neoproterozoic diamictites in Argentina and Paleoproterozoic diamictites in Canada, indicating that volcanism was the triggering process for the origin of some diamictites (Young et al., 2004b; Pazos et al., 2008). Deposits from Phanerozoic ice-ages have accumulated on more stable bedrock than during the Precambrian (Schermerhorn, 1974a), but the LPIA formations in both southern Africa and South America, have been deposited in tectonically controlled former sinking basins or close to areas of tectonic movements (Johnson et al., 1997; Barbolini et al., 2018; Hansen et al., 2019; Dietrich and Hofmann, 2019; Fedorchuk et al., 2019; Limarino and López-Gamundí, 2021; Creixell et al., 2021; Veroslavsky, 2021; Molén and Smit, 2022). The overall geological framework of the Ordovician glaciated area was a continuous transgression over a slowly subsiding cratonic platform (Ghienne, 2003), and there is evidence of recurrent magmatic activity in the area from the Precambrian to the Holocene (Ghuma and Rogers, 1978; El-Makhrouf, 1988; Young et al., 2004a; Permenter and Oppenheimer, 2007; Liégeois, 2006). Consequently, even the Paleozoic glaciations may in some aspects be connected to tectonism. Quaternary glaciations commonly were and are on more stable bedrock.

Many ancient sedimentary deposits which are interpreted to be glacially influenced are hundreds of meters to many kilometers thick (Volkheimer, 1969; Schermerhorn, 1974a; Woolfe, 1994: Visser, 1989a; Vesely and Assine, 2014; Ali et al., 2018; Kennedy and Eyles, 2019; Rosa et al., 2019), as are mass flow deposits (Kuenen, 1964; Komar, 1970). As an example, a median thickness value for 197 mass flows (mainly Pliocene and younger) is 66 m, but thicknesses of hundreds of meters are common and there are examples of kilometers (Moscardelli and Wood, 2016; Ogata et al., 2019; Alves and Gamboa, 2020). Large mass movements may even generate isostatic uplift or downwarping of the lithosphere (Kneller et al, 2016). Sedimentation will in general be more massive in areas where there is rapid subsidence in tectonically active basins (Kennedy and Eyles, 2021). SGF deposits may be complex, multi-layered units which may have been deposited during an event or a very short time period (e.g., Shanmugam, 2012, 2021b).

Even though the examples below are mostly from sediments deposited on oceanic crust, marine fossils are present almost worldwide, from former transgressions, and marine fossils are present next to geologic features which are interpreted to be glaciogenic (see examples in sections 2.1., 2.13, 2.15). Massive debris flows may travel 200 km without depositing any sediment (Talling et al., 2007), and therefore the resulting deposits may appear to be isolated “tillite” mounds. Many SGFs travel long distances, e.g., 900-2000 km outside off the coast of northwestern Africa (Georgiopoulou et al., 2010; Moscardelli and Wood, 2016), and there have been suggestions of 4000 km for less dense turbidity currents (Pickering and Hiscott, 2015). Such flows affected extensive areas, e.g., 95 000 km^2 for the Storegga Slide (Haflidason et al., 2004) and 132 000 km^2 in the Canada Basin (Moscardelli and Wood, 2016). The largest known Late Pleistocene debris flow influenced an area of 45 000 km^2 (Embley, 1982) and the largest known recent turbidity current influenced an area of 500 000 km^2 (Heezen and Hollister, 1971), but SGFs are usually much more restricted in areal extent than these two deposits, with a median value less than 100 km^2 (Moscardelli and Wood, 2016).

In contrast to “tillites” and SGF deposits, separate till beds, with characteristic structure and mineral content, can be traced over hundreds of kilometers and are often less than five meters thick (Schermerhorn, 1974a). Most layers are less than 100 m and usually not more than 10 m thick. In Canada the thickness of the till is 2-10 m (Eyles et al., 1983), in Norway the mean till layer is 5 m (Haldorsen, 1983), in Finland 2-3 m and in Sweden 5-15 m (Flint, 1971). At the southern limit of the North American inland ice sheet, separate till beds are superposed and in total often thicker, e.g., from 10 to 52 m in a 300 km wide band (Flint, 1971), but in Europe the tills often thin out at the southern limits (Piotrowski et al., 2001). The thickest known accumulation of till beds from the Pleistocene is 400 m (Flint, 1971; Schermerhorn, 1974a).

The late Cenozoic exceptions, which exhibit thick glacial sequences, are in places with glaciomarine sedimentation, at the continental shelf of Antarctica and the Yakataga Formation of the Gulf of Alaska (Anderson, 1983). Most of these deposits have originated by SGFs but under the influence of nearby glaciers (Eyles and Lagoe, 1998).

Valley glaciers commonly merge into larger glaciers. Similarly "glacial" paleo-flows may be in one main direction and a few smaller merging valley flow directions (Visser, 1981). This is similar to what may take place during large slides/SGFs (e.g., Haflidason et al., 2004). Also, SGFs may diverge, bend and split into many smaller flows (Moscardelli et al., 2006; Sobiesiak et al., 2018; Kumar et al., 2021), somewhat similar to what may take place if a glacier is spreading out over a more planar surface.

Erosion has reduced the extent of many Pleistocene glaciogenic deposits. This explanation must not, however, be used only to defy the small and discontinuous extent of ancient deposits without documentation of evidence of erosion subsequent to a glacial period.

2.1.2. Correlations and dating

In general, there are always intricate problems with correlations, especially if these are long distance (Blauw, 2012; Gaucher et al., 2015). Commonly diamictites do not contain material that may be isotopically dated. Diamictites and "glaciogenic features" have therefore sometimes been interpreted to be glacial, only if they are of the "correct" age. Furthermore, diamictites which commonly are regarded as glaciogenic today have earlier been regarded as not glaciogenic, because they have been considered to have been in the wrong paleogeographic area (Caputo and Santos, 2020). In some cases, diamictites have been redated, even four times, in order to correlate these to other deposits which have been interpreted to be glaciogenic. There are examples of redating from the Neoproterozoic throughout the Phanerozoic and occasionally even into the Pleistocene (Dow et al., 1971; Schenk, 1972; Schermerhorn, 1974a; McClure, 1980; Rehmer, 1981; Carto and Eyles, 2012b; de Wit, 2016a, 2016b; Moxness et al., 2018; Caputo and Santos, 2020; Hore et al., 2020). All these reinterpretations show that there are many difficulties and unknowns in the studies of diamictites and other geologic features which have been referred to as being glaciogenic.

2.1.3. Fossil vegetation

Fossil vegetation, including coal deposits, is often present adjacent to or in between deposits from "ancient ice-ages" (e.g., Plumstead, 1964; Lindsay, 1970a; Finkl and Fairbridge, 1979; Rocha-Campos and Santos, 1981; Gravenor and Rocha-Campos, 1983; Gravenor et al., 1984; Stavrakis and Smyth, 1991; Woolfe, 1994; Fedorchuk et al., 2019; Kent and Muttoni, 2020). Even if the time scales are long, these sedimentary proximities are so common that they have to be discussed.

Plants are better climatic indicators than rocks and would indicate any deviation from a polar climate. However, the ecology of plants often is interpreted from geology and not from plant physiology or ecology, which may be circular reasoning. For example, old editions of books may describe the Glossopteris flora as subtropical or tropical, but not so in more recent editions (e.g., Dott and Batten, 1976, compared to e.g., Prothero and Dott, 2003).

Current experiments and observations show different levels of ^{13}C and ^{12}C in living plants, depending on e.g. latitude, temperature, precipitation and species (Cernusak et al., 2008; Kohn, 2010; White, 2015; Porter et al., 2017; Stein et al., 2021). Furthermore, there are different sensitivities to pCO_2 and other environmental factors for different plants (Klein and Ramon, 2019; Wilson et al., 2020; Stein et al., 2021), and many plants are insensitive to environmental drivers for isotope discrimination including pCO_2, water and temperature (Stein et al., 2021). Some researchers have even sampled data only from plant studies that show isotope discrimination, to calculate former pCO_2 (Stein et al., 2021). All these different data make ancient pCO_2 model calculations based on plant fossil carbon-isotope data suspicious.

2.1.3.1. Association between vegetation and glaciogenic sediments

Macrofossils are rarely found in diamictites. However, in the LPIA of South Africa, fossils of plants of Gangamopteris of the Glossopteris flora have been found within the diamictites and squeezed in between the Dwyka “tillite” and the underlying “ice-polished bedrock” (du Toit, 1926; Sandberg, 1928). Coalified plant fragments occur within massive “tillites,” and coal seams are often present on or between “tillites” (du Toit, 1926; Sandberg, 1928; Adie, 1975; Anderson and McLachlan, 1976; John, 1979; Bond, 1981a, 1981b; Le Blanc Smith and Eriksson, 1979; Visser, 1983a, 1989a; Stavrakis, 1986; Stavrakis and Smyth, 1991; Von Brunn, 1994; Hancox and Götz, 2014; Caputo and Santos, 2020). Coal seams that may be interbedded with “glaciogenic” diamictites have in many instances coalesced with other coal seams to form one thick coal seam (Stavrakis and Smyth, 1991). Interlayering of diamictite and coal beds is often considered to be a result of reworking of diamictites (Hancox and Götz, 2014), but that explanation does not hold well for plant fossils within massive diamictites and coalesced strata. Geologic evidence of long time periods are commonly missing. Coal seams that are interbedded between diamictites are often thin, and complete sequences may appear to be a kind of debrites (Hancox and Götz, 2014).

In the LPIA of Antarctica, diamictites intrude strata upward as diapirs (nearest plant fossils are c. 0.5 m above the “tillite”; Cuneo et al. , 1993), and boulders and conglomerates from the upper strata protrude downward into the diamictite. Furthermore, “glaciotectonic structures” are present both in the “tillite” and the lower part of the coal bearing strata (mainly sandstones and conglomerates; Isbell, 2010). In some places the boundary between the beds are gradational, and in other places the deposits are interfingering (Cuneo et al. , 1993; Isbell, 2010). Considered as a whole, these evidences indicate a short time period. Isbell (2010) concluded that the evidence suggested “temperate glacial conditions.”

Deposits containing fossil plants close to diamictites may be considered to be hyperpycnites, i.e. deposits formed by dense water flows laden with sediment and large plant parts. These may be sorted into dense and diluted parts, with or without plant material, but plant material may also be transported with turbidities, cyclones and tsunamis (Zavala and Arcuri, 2016; Shanmugam, 2019, 2021b; Zavala, 2019, 2020; Dou et al., 2021). Plant parts have been transported into deep marine basins at estimated paleodepths of approximately 400-600 m (Pickering and Corregidor, 2005).

The evidence from the absence of plant fossils within most Paleozoic diamictite deposits may be an indication of water depth or transport distance, i.e. in deeper water, or during longer transport, plant material and other organisms may be sorted out. The $\delta^{13}C_{carb}$ in the Dwyka Group diamictites appear to be of primarily algal origin, which may be an indication of water depth (Scheffler et al., 2003). Fossils are seldom reported from within debris flow deposits. On the other hand, Holocene glaciogenic deposits may hold an abundance of trees and other plants, if forests have grown nearby (Ryder and Thomson, 1986; Fleisher et al., 2006). This would not be considered to be uncommon in areas with Alpine glaciation or at the southernmost parts of continental glaciers, but less common if there was polar climate.

2.1.3.2. Ecology

The vegetation present next to "glaciogenic" facies of the LPIA deposits does not include typical cold-climate plants (Anderson and McLachlan, 1976; McLoughlin, 2011; Hancox and Götz, 2014; Caputo and Santos, 2020). The LPIA fossil plants, i.e. the Glossopteris flora, do not display any typical appearances of cold climate peats or other cold climate environments, and no indication that they could have thrived in polar climates (Srivastava and Agnihotri, 2010; McLoughlin, 2011; Isbell et al., 2016; Götz et al., 2018; Gastaldo et al., 2020a, 2020b; Mays et al., 2020; Tripathy et al., 2021). The main argument for a cold climate adaptation of the vegetation (if this question even is raised) is the close connection to sedimentary deposits which are regarded to be from an ice age. Similar plant fossils are present even at a paleolatitude of 75-85°S, even if there are not always diamictites close by, and the estimated range of productivity of these far southern forests is similar to that of modern forests (Cuneo et al., 1993; Isbell et al., 2016; Miller et al., 2016; Decombeix et al., 2021). There also are indications that at least some plants were evergreen (Gulbranson et al., 2014), and no evidence of frost rings (Taylor et al., 1992). But growth rings would be expected from a shift from light to dark seasons, or amount of precipitation (e.g., Glock, et al., 1960; LaMarche, 1969; McLoughlin, 2011). Even if all these fossil plants are not close to diamictites in time or space, they are in a paleopolar area. It would seem as reasonable to argue that because there are temperate or possible subtropical plant fossils present close to many diamictites, as these are also present where there is no diamictites, such deposits cannot be glaciogenic and might instead be SGF deposits. Although the Glossopteris flora species are gymnosperms, and not angiosperms which have been better studied, leaf size and appearance may be an indicator of paleoclimate. Hence, the physiology of the fossil plants, displaying complete (non-toothed) and also large sized leaves, suggests that the Glossopteris flora of Gondwana could even be considered to be evidence for a tropical or subtropical climate zone (e.g., Gastaldo et al., 2020a; DeVore and Pigg, 2020).

The Paleozoic ferns, gymnosperms and other plants are present in many climatic zones. The same genus or even species of plants that are present next to Paleozoic “tillites,” are also present in many places with non-glacial climate (e.g., compare Gateway to the Paleobiology Database, 2020, to Barbolini, 2014). For example, Glossopteris flora, which is present over most of Gondwana (McLoughlin, 2011), have been discovered in the Late Permian of Jordan, i.e. in the northern, tropical/subtropical part of Gondwana (Blomenkemper et al., 2020), in Mongolia (Naugolnykh and Uranbileg, 2018), and also in deposits at the Permian-Triassic border of Pakistan which are considered to have been laid down during a greenhouse climate (Schneebeli-Hermann et al., 2015). Meyerhoff et al. (1996), Srivastava and Agnihotri (2010), McLoughlin (2011), and Mays et al. (2020) describe more examples of Glossopteris flora outside of the Gondwana area, but there is skepticism whether all these fossils really are Glossopteris (Mays et al., 2020). Coal-forming plants showing affinities to plants which are present in North America and Europe and are interpreted to be from tropical or subtropical areas, are also present in Gondwana, but these fossils have not been clearly described or are reassigned to other species, which may make the interpretation of paleoclimate from these fossils at least equivocal (Charrier, 1986; Spiekermann et al., 2020). However, well documented Sigillaria is present in northern Gondwana (Seward, 1932) and lepidodendroid lycopsids (Lepidodendrales) in the Devonian of Australia (Peyrot, et al., 2019).

From the evidence of the vegetation, it may be possible that the climate during the LPIA was similar to the Middle/Late Permian, Mesozoic and early Cenozoic “near-tropical” “Greenhouse World” climate, the latter displaying no large glaciers and mean annual temperatures from maybe +5°C to +20°C (or at least no long periods of time with temperatures below the freezing point) close to the poles (Leonard et al., 1981; Sloan and Barron, 1990; Bickert and Heinrich, 2011; Rose et al., 2013; Mori et al., 2016; Bernardi et al., 2018; Decombeix et al., 2021), with e.g., dinosaurs (Mori et al., 2016; Fiorillo et al., 2019; Takasaki et al., 2019) and subtropical and temperate forests growing close to the poles

(Wolfe, 1977; Morris, 1985; Francis, 1990; Kerr, 1993, 2008; Wilf et al., 2009; Cerda et al., 2012). There is a lack of evidence of continuous glaciation in Gondwana during the LPIA, even if the South Pole was situated close by from the Late Proterozoic until the Early Triassic (e.g., Horan, 2015). And there are very few and no unequivocal evidences of glaciation in the northern hemisphere during the LPIA (Isbell et al., 2012, 2013, 2016; Montañez and Poulsen, 2013; Craddock et al., 2019; Griffis et al., 2019; Fedorchuk et al., 2019, 2021; Rosa and Isbell, 2021). The LPIA is immediately followed by a period of "Triassic Hothouse extremes" (Götz et al., 2018). Even during the Neogene the Antarctic continental mean summer temperatures were +5°C, i.e. possible 30°C warmer than today (Rees-Owen et al., 2018).

All the evidence from fossils show that there is no need to ascribe a polar climate to polar areas, as may be done when referring to polar wander paths and also to the recent climate at the poles.

2.2. Till structure

In many aspects SGF deposits may be indistinguishable from subglacial tills (section 1.4. and e.g., Mountjoy et al., 1972; Schermerhorn, 1974a; Kurtz and Anderson, 1979; Lowe, 1982; Visser, 1983a; Wright et al., 1983).

Transverse and irregular moraine forms are not common in diamictites, but are regularly present in Pleistocene and younger tills. However, compressional transverse ridges, hummocky terrain, and flow lines similar to those on the surfaces of some glaciers, are formed by SGFs (e.g., Haflidason et al., 2004; Pickering and Hiscott, 2015; Nugraha et al., 2020; Dufresne et al., 2021; Procter et al., 2021).

2.2.1. More mass flows and marine sediments than basal glaciogenic sediments

"Tillites," in comparison to glaciogenic depoits from the Holocene and Pleistocene, more often have been disturbed by SGFs, or have been interpreted to be deposited mainly by glacial marine sedimentation (i.e. 95%, section 1.3.), and, therefore, it is especially difficult to distinguish such deposits from non-glaciogenic SGF deposits (e.g., Aalto, 1971; Martin, 1981a; Von Brunn and Stratten, 1981; Gravenor et al., 1984; Molén and Smit, 2022). The natural explanation for this – erosion of higher lying terrestrial source areas – has not been substantiated by reports concerning possible evidence of erosion of "tillites," and there may still be much sedimentary material close to the central areas of "glaciation" (Biju-Duval et al., 1981; Gravenor and Rocha-Campos, 1983; Visser, 1988, 1989a; Le Heron et al., 2010).

Often ancient basal "tillites"/diamictites are overlain and/or underlain by SGF deposits or marine strata (e.g., Banerjee, 1966; Visser, 1983b; González and Glasser, 2008; Caputo and Santos, 2020) – a less common observation in Pleistocene deposits. Slides, slumps and debris flows often trigger turbidity flows that will retain some coarse sediment and will be deposited on top of, or downslope from, the denser flow (Hampton, 1972; Middleton and Hampton, 1976; Embley, 1980, Lowe. 1982). This can explain why diamictites often are surrounded by, or draped with, shale or rhythmites with lonestones (e.g., Molén, 2017, 2021; Rampino, 2017; López-Gamundí et al., 2021).

2.2.2. No rock flour and density of deposits

Till contains a large component of rock flour, i.e. material with a grain size <2 µm, as opposed to many "tillites" (Frakes, 1979; Molén, 2017). For example, the Saharan and Saudi Arabian Ordovician diamictites which are interpreted to be glaciogenic are composed of similar sized material as the underlying sandstones, i.e. sand/silt and no (or very little) grinded rock flour (Le Heron et al., 2005, 2006; Yassin and Abdullatif, 2017). Diamictites in China also are sandy to silty (Chen et al., 2021).

Deposits formed by direct sedimentation from dense suspension are among the most loosely packed natural sediments (Lowe, 1982), i.e. different from subglacially deposited material. However, SGF deposits appear to consolidate quickly, which may mimic compression of sediments by glaciers in tills (Moscardelli et al., 2006). Also, as diamictites are lithified, the cementing agent might obscure indices of the former ratio of pore spaces.

2.2.3. Correlation between clast size and thickness of strata

The largest boulders in "tillites" are often present in the thickest sedimentary horizons (Schermerhorn, 1974a; Martin et al., 1985; Eyles and Januszczak, 2007). This indicates transport by SGFs (Dott, 1963; Kuenen, 1964; Larsen and Steel, 1978; Derbyshire, 1979; Lowe, 1982; Walton and Palmer, 1988; Middleton and Neal, 1989; Eyles and Januszczak, 2007; Kennedy and Eyles, 2021). Ice distribute boulders more randomly.

2.2.4. Grading in sediments

There is much grading in diamictites which have been or are interpreted to be "tillites," including lodgement/basal "tillites," i.e. a) graded bedding, upwards fining, or the largest boulders deposited at the bottom of the sequences (Kulling, 1951; Lindsay, 1968; Bowen, 1969; Schermerhorn, 1975; Visser and Kingsley, 1982; Visser, 1982; Deynoux, 1985b; Gravenor and Von Brunn, 1987; Le Heron et al., 2018b, Le Heron et al., 2021b), b) "tillites" grading upwards to shales, dropstone bearing shales or fluvial sediment (Dow et al., 1971; Frakes and Crowell, 1969; Visser et al., 1987; Mustard and Donaldson, 1987b; López-Gamundí, 2010), c) reverse grading from "sandstone with rounded dropstones" to "clast-rich diamictite" (Hoffman et al., 2021), and d) conglomerates or breccias grade upwards to, or are directly overlain, by diamictites which have been interpreted to be "tillites" or SGFs (Kulling, 1951; Lindsay, 1966, 1970; Lindsey, 1969; Cahen and Lepersonne, 1981;

Deynoux and Trompette, 1981b; Visser, 1981, 1983b, 1997; Mustard and Donaldson, 1987a, 1987b; Isbell et al., 2008; Festa et al., 2016; Kennedy and Eyles, 2021; Molén, 2021).

The occurrence of breccias might indicate that the process of movement was triggered by tectonism, or that the bedrock broke to pieces by the impact of a SGF (Dakin et al., 2013; Molén, 2021). Grading is an indication of transportation by SGFs (section 1.4; Cecioni, 1957; Eriksson, 1991), but may be present in glacogenic deposits. Even if there is not any evidence of grading in all stratigraphic successions, many pre-Pleistocene "glaciogenic" and also SGF deposits display a general sequence, with a few or many of the following facies, starting from the bottom: breccia, conglomerate or clast supported diamictite, massive diamictite, stratified diamictite, sand or siltstone, and rhythmites with finer material displaying lonestones (e.g., Molén, 2017, 2021; Le Heron et al., 2021b López-Gamundí et al., 2021; Molén and Smit, 2022). Furthermore, massive diamictites which have been studied in more detail, have been shown to be stratified, and may indicate a non-glacial origin (Stavrakis, 1986; Stavrakis and Smyth, 1991; Von Brunn, 1994; Visser, 1997; Visser et al. 1997; Huber et al. 2001; Haldorsen et al. 2001; Isbell et al., 2008; Dietrich and Hofmann, 2019; pers. commun., Johan N. J. Visser, 2020; Molén and Smit, 2022).

2.2.5. Bedding and amalgamation

Sandstones which have been interpreted to be "tillites" may be faintly bedded and display structures similar to dish structures (Biju-Duval et al., 1981; Gravenor and Rocha-Campos, 1983; Deynoux 1985b), which might indicate deposition by debris flows (Middleton and Hampton, 1976; Lowe, 1982; Visser, 1983a). But, fissility textures in tills, and dewatering of two component glaciomarine facies, may occasionally display an appearance similar to dish structures.

Ancient diamictites often display amalgamation of debris flow deposits (Kennedy and Eyles, 2021), which Domack and Hoffman (2011) interpreted as amalgamation of tillites. The number of "tillite" beds also had been interpreted as the number of glaciations (Ali et al., 2018).

2.2.6. Presence of soft sediment structures

In SGFs, large rip-up contorted slabs of soft sediments are commonly transported (Crowell, 1957; Lindsay, 1966; Lowe, 1979; Shanmugam, 2012, 2021b; Vesely et al., 2018; Rosa et al., 2019; Rodrigues et al., 2020; Isbell et al., 2021), but sometimes such "clasts" have been taken as evidence for glaciation (Deynoux and Trompette, 1981b; Runkel et al., 2010). Even though soft-sediment rafted material may occasionally be transported by and not become shattered by glaciers, "tillites" often contain contorted transported sheets of sediment, thus indicating a more probable transport by SGFs (Lindsay, 1966; Bowen, 1969; Frakes et al., 1969; Visser, 1983b; Deynoux, 1985b; Molén, 2017; Kennedy and Eyles, 2019, 2021).

Other structures which are commonly present in SGF deposits, but also in a lesser amount in what is or have been considered to be glaciogenic sediments/tillites are: rotational structures, necking structures (squeezing of material between clasts), wisps, flame structures, sediment diapirs, load casts, intra-clasts of diamictite (not to confuse with intra-tills; Evans et al., 2006), and dykes (e.g., Shanmugam, 2012, 2017b, 2021b; Isbell et al., 2016; Moxness et al., 2018; Molén, 2021; Kennedy and Eyles, 2019; Caputo and Santos, 2020; Molén and Smit, 2022).

2.2.7. Clasts pressed into underlying surface

Clasts in "tillites" have been pressed down into the underlying surface, which actually is not always considered to had been soft (Lindsay, 1970a, 1970b; Hambrey, 1983; Caputo and Santos, 2020). This can be better explained by a SGF over unconsolidated sediment than a glacial origin (Molén, 2017).

2.2.8. Channels below or next to "tillites"

In the sedimentary strata just below or next to "tillites" there are occasionally erosional channels (Lindsay, 1970a; Biju-Duval et al., 1981; Schatz et al., 2011; Molén, 2017). These structures indicate that water, debris flows or slides eroded the underlying sediments before deposition took place, but these may not be incompatible with a glaciogenic origin (Mountjoy et al., 1972; Karlsrud and Edgers, 1982; Walton and Palmer, 1988; Eyles and Eyles, 1989; Eyles 1990; Eriksson, 1991; Talling et al., 2007; Dakin et al., 2013; Shanmugam, 2016; Baas et al., 2021).

2.2.9. Fabrics

The long axes of pebbles in Pleistocene tills often show a 10-20° dip in the direction of the ice movement, but there may also be a transverse fabric present (Lindsay, 1968, 1970a, 1970b; van der Meer et al., 2003; Evans et al., 2016).

In SGFs the fabric of outsized clasts can be similar to a till fabric, including a bimodal fabric and transverse oriented clasts, but it also display differences changing with the height in the sedimentary sequence (Lindsay, 1968; Best, 1992; Kim et al., 1995; Major, 1998; Kennedy and Eyles, 2019). In many SGF deposits the fabric is planar or sub-parallel to bedding (Evenson et al., 1977; Hill et al., 1982; Gravenor, 1986; Eriksson, 1991; Rodrigues et al., 2020), but it may be (sub)vertical, in places displaying protruding large clasts, or, about 30% of the clasts have a dip in excess of 20º (Lawson, 1979; Visser, 1996; Dasgupta, 2003; Liu et al., 2021). The variation of the fabric sometimes makes it possible to find support for an origin by SGF. It is more difficult to provide conclusive evidence for a glacial origin of a diamictite only from fabrics, if the deposits are not in widespread horizons, even if doubts about the origin may not be strong (Lindsay, 1968; Lawson, 1979; Hicock and Dreimanis, 1992b; Piotrowski et al., 2001, 2002).

Pre-Pleistocene “tillite” fabrics typically display no systematic patterns and appearances which are indicative of tills, i.e. there are many varied directions and dips (Bigarella et al., 1967; Lindsey, 1969; Lindsay, 1970a, 1970b; Lindsay et al., 1970; Rehmer, 1981; Young, 1981a; Gravenor and Rocha-Campos, 1983; Miall, 1983; Deynoux, 1983, 1985b; Visser et al., 1987, 1997; Visser 1996). Many “tillite” fabrics seem to be more or less planar, but sometimes the dips are not reported (Visser, 1983b).

2.2.10. Flutes

Flutes may be formed behind obstacles in any environment. In glacial environments, obstacles are commonly at least 0.3-0.5 m higher than a lodged till surface, the flute is commonly lower and thinner than the obstacle, and the length may be many kilometers (Woodworth-Lynas, 1996). These are different from flutes described from areas which are interpreted to have been produced by glaciation, e.g. different appearance next to obstacles or no evidence of obstacles (e.g., Rosa et al., 2019; Le Heron et al., 2019).

2.2.11. Impact structures, meteorites

Deformed en echelon-fractures, hinged and crushed stones, which are followed by brittle fracture, such as so-called “bread-cut-to-slices”structures are typical for impact-cratering events (Oberbeck et al., 1993a, 1993b, 1994; Rampino, 2017). Such evidence has been proxies to reinterpret "tillites" as originating by impact-generated debris flows (Rampino, 1994, 2017). Other criteria for impacts are shocked clast and minerals, and distinctive surface microtextures on quartz grains (Rampino, 1994, 2017; Mahaney, 2002).

2.3. Erratics

2.3.1. Erratics, transport and inclinations – similarities

Except for by glaciation, erratics can be transported by e.g. mass flows, tsunamis and cyclones (Carter, 1975; Malahoff et al., 1979; Elfström, 1987; Shanmugam, 2012, 2021b; Lascelles and Lowe, 2021). The largest clasts transported by tsunamis are 40x27x6 m (Lascelles and Lowe, 2021; see also Shanmugam, 2012, 2021b). Probably the largest known erratics in "tillites" are 40 m, 100 m, and 320 m long, respectively, and the structures in the surrounding diamictites indicate that these clasts have been transported by SGFs (Schermerhorn, 1975; Molén, 2017). Large clasts are often deposited at the margin of mass flow deposits (Ortiz-Karpf et al., 2017).

Large slide blocks are often more than one kilometer long and hundreds of meters high. The largest known blocks are hundreds of square kilometers in area. Some of these have been moved many tens to hundreds of kilometers (Maxwell, 1959; Wilson, 1969; Mountjoy et al., 1972; Schermerhorn, 1975; Moore et al., 1989, 1995; Alves, 2015; Ortiz-Karpf et al., 2017; Hodgson et al., 2018; Sobiesiak et al., 2018; Soutter et al., 2018; Alves and Gamboa, 2020; Nwoko et al., 2020a, 2020b; Puga Bernabéu et al., 2020; Kennedy and Eyles, 2021; Kumar et al., 2021). This long distance transport of material, whether debris flows or slides, is possible because of processes labeled hydroplaning, shear wetting or substrate liquefaction (de Blasio, 2006; Moscardelli et al., 2006; Sobiesiak et al. 2016, 2018; Alves and Gamboa, 2020).

Turbidity currents and other mass flows have transported debris many hundreds (Wilson, 1969; Komar, 1970; Embley, 1976; Embley and Morley, 1980; Wright et al., 1983; Middleton and Neal, 1989; Stoopes and Sheridan, 1992; Shanmugam, 2016) to thousands (Kuenen, 1964; Stevenson et al., 2014) of kilometers. Far-transported clasts may become incorporated in existing sediments, whereafter the deposits turn unstable and move as dense SGFs, which after deposition displays characteristics similar to tills (Crowell, 1957; Jansa and Carozzi, 1970; Walton and Palmer, 1988; Eyles 1990).

Slopes beneath Pleistocene and younger glaciers may vary, but often it is close to zero over large areas, i.e. close to 0.001°. Slopes recorded for coarse grained turbidity flows (containing gravel sized clasts) are commonly as low as 0.02-0.05° (Kuenen, 1964; Komar, 1970; Wright et al., 1983; Stevenson et al., 2014; Sobiesiak et al., 2018). For debris flows the angle commonly is below 1° but in places less than 0.1° (Mountjoy, 1972; Carter, 1975; Middleton and Hampton, 1976; Embley, 1976, 1982; Shanmugam, 2021b), but even debris flows may move over an area with lower slopes than 0.05° (Stevenson et al., 2014). Subaqueous landslides have been recorded to travel on slopes of approximately 1° for almost 1000 km (Yincan et al., 2017). If these slopes are compared with those in ancient "tillites," some of the gentler slopes in "tillites" are steeper than for glaciers, thus indicating a possibility of SGF transport, for example, in the Ordovician in Sahara 1° (Fairbridge, 1971), and in different places in South America 0.25-1° (Caputo and Crowell, 1985).

Even though all researchers may not be aware of how common this is (de Wit, 2016a, 2016b), SGFs and slides may climb upwards (e.g., Pickering and Hiscott, 2015; Nugraha et al., 2020), sometimes for horizontal distances of more than 100 km (Stevenson et al., 2014). A recent slide started from above the sea surface, then moved submerged for 1.5 km down to a depth of 80-90 m below sea level, before it re-emerged on land and was deposited at a height of 15 m above sea level (Dufresne et al., 2018). A submarine slide moved uphill 500 m against a

16° slope (Tucholke, 1992), and another travelled upwards for 140 km to a height of 300 m (Moore et al., 1989). One slide (or "debris avalanche") traveled uphill to a height of 100 m at a velocity of approximately 52 m/s (Watt et al., 2012). Submarine hills and overbank levee sites which are covered by turbidites may be more than 180 m above the surrounding bottom of the sea (Abbot and Embley, 1982; Mountjoy et al., 2018), but heights between 5-120 m are commonly recorded (some covers may just by because of the thickness of the flows), and for debris flows 20 m uphill flow has been documented (Stevenson et al., 2014).

2.3.2. Erratics, transport and inclinations – differences

2.3.2.1. Size dependence

In glaciers there is no clear maximum size for transported clasts, as the competence of ice sheets is almost limitless. The Pleistocene glaciers transported scores of large clasts (both sedimentary and magmatic, e.g., Bukhari et al., 2021; Fig. 1). Even if there has been no large systematic study, Quaternary glaciations have accumulated innumerable quantities of large clasts in boulder size, which are evident almost everywhere. The accumulation of large boulders in Fig. 1D, in this single spot (which is not exceptional, but common), is more abundant than the total number of boulders present in many "tillites" covering large areas. Both in "tillites" and SGFs boulders are rarer (e.g., Molén, 2021). In Pleistocene deposits great areas are covered with thousands upon thousands of boulders even with diameters larger than one meter (Fig. 1). Erratics with diameters larger than 5-10 m are not rare, and some erratics are hundreds of meters (Embleton and King, 1968) and even many kilometers in length (Stalker, 1975, 1976). The largest known block, which might have been transported with glacier ice, measures 4000x2000x120 m (Sugden and John, 1982).

In all deposits from ancient "ice-ages" the erratics are usually not larger than a few meters in diameter, and even erratics one meter in diameter are rare (e.g., Kulling, 1951; Flint, 1961; Schwarzbach, 1961; Hambrey and Harland, 1981; Visser and Kingsley, 1982; Visser, 1982, 1983b; Caputo and Crowell, 1983; Martin et al., 1985; Deynoux, 1985b; Haldorsen et al., 2001; Zimmerman et al., 2011; Bechstädt et al., 2018; Vesely et al., 2021). Blocks larger than five meters in diameter have rarely been reported. A common maximum clast size is 1.5-2 m, but often the largest erratics have a diameter less than 25-50 cm, and over large areas the size is only around 5 cm (e.g., Von Brunn and Stratten 1981; Le Blanc Smith and Eriksson, 1979; Visser, 1983b; Chen et al., 2020, 2021; Le Heron et al., 2021b; Vesely et al., 2021; Molén 2021).

In beds from the same area, which have been deposited by verified SGFs, or at least showing indication of quick deposition, the clast size is often larger than in supposed "tillites" or other glaciogenic material which has not been deposited by SGF processes (Molén, 2021). When these differences are documented, which is not often done, there is a clear systematic trend. For example, in LPIA deposits in South America, the "glaciogenic" beds commonly carry clasts of cobble size, while gravity or water flow deposits carry boulders of many meters in size (Rosa et al., 2019; López-Gamundí et al., 2021). And in the Neoproterozoic Namibian deposits the largest clast, many meters in size, are in massive debris flows or slides, even though these clasts at the same time had been interpreted to be dropstones (Domack and Hoffman, 2011). This systematic difference is opposite to what is expected, because glaciers can in general transport larger clasts than SGFs, without showing any evidence of flow structures.

If a SGF moves at a low velocity, if there is less water and less turbulent movement involved, and if the SGF is denser, i.e. a high-strength cohesive debris flow, then the final deposit ought to display an appearance more similar to a till than deposits from other mass movements. This might be the explanation of why deposits from "ancient ice-ages" do not contain many large erratics. If a deposit from a dense SGF should not exhibit easily recognizable and extensive evidence of turbulence, SGF currents and tectonic slide and slip structures, it might be that a size of 1-3 m in diameter is most often the maximum size of the clasts that can be transported (Komar, 1970; Clark, 1991; Talling et al., 2012; Dakin et al., 2013; Peakall et al., 2020). This size of clasts is often the maximum size that has been observed moving with slow (Shepard and Dill, 1966; Carter, 1975; Middleton and Hampton, 1976) and fast (Elfström, 1987) SGFs. When the clasts are larger, a stronger current and/or higher buoyancy in the matrix is necessary, and the sedimentary structures (e.g., fluvial, bedding and different kinds of slide and load structures) will more clearly indicate that there has been a SGF, and the difference between the deposit and a till is clear cut.

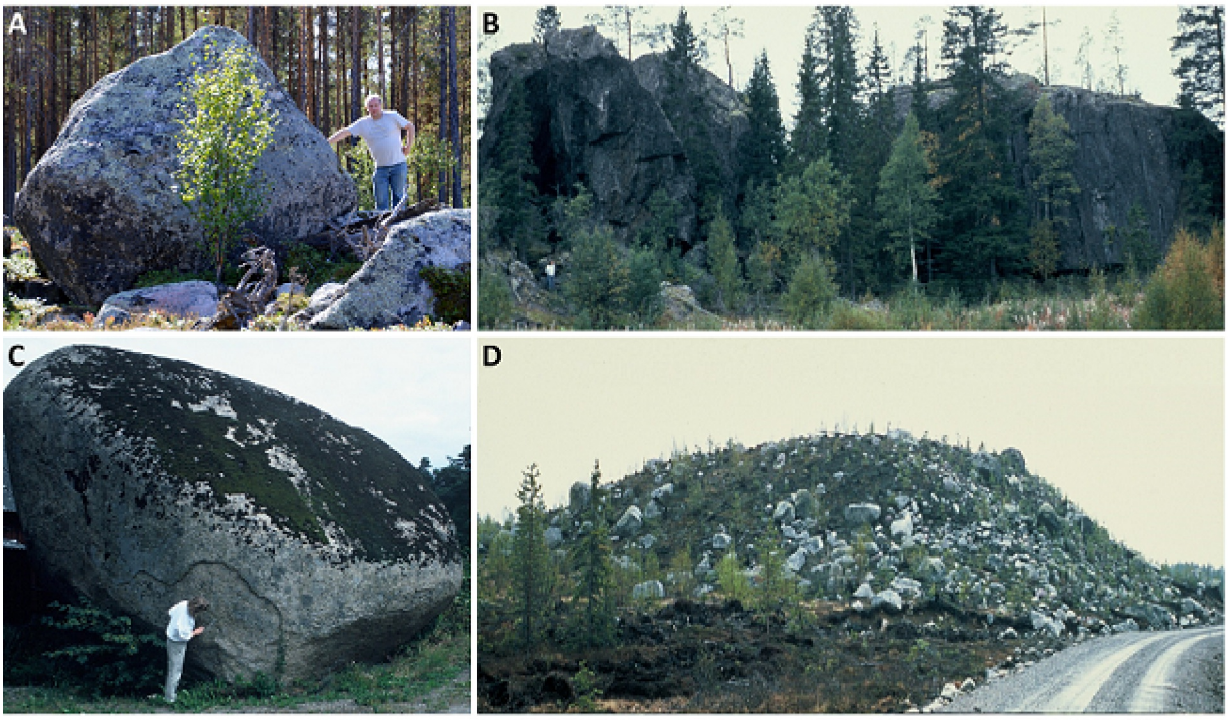

Fig. 1. This is the common appearance of tills and other glaciogenic material in most parts of Sweden, i.e. there are innumerable large boulders everywhere. A. Clast in the jökulhaup or sandur of Mettjaur, Västerbotten county, Sweden. This size of clasts is common. B. The probably largest erratic clast in Europe, the Botsmark rock (split into pieces probably by a local postglacial earthquake; Mörner, 2008). There is till under this piece of a mountain, so it

has not only been transported on top of the underlying bedrock. (See person in white shirt for scale.) C. Large boulder in southern Sweden, Scania. D. A Blattnick moraine, a special kind of Rogen moraine, displaying large boulders (Markgren and Lassila, 1980).

2.3.2.2. Jigsaw puzzle texture

A jigsaw-puzzle texture, where sediment has been pressed in between separate pieces of fractured clasts, are often present in mass flow deposits (Costa, 1984; Scott, 1988b; Stoopes and Sheridan, 1992; Schneider and Fisher, 1998; Legros et al., 2000; Capra and Macias, 2002; Thompson, 2009: Thompson et al., 2010; Dufresne et al., 2018, 2021). These have also been documented from “tillites” that display SGF facies (Harker and Giegengack, 1989; Bose et al., 1992; Harker, 1993; Arnaud and Eyles, 2006; Ali et al., 2018; Molén, 2021). Jigsaw-puzzle textures have not been reported from basal tills (Ui, 1989; Thompson, 2009). In stony tills clasts have been single fractured with pieces still nearly in place, and soft or weathered clasts have been transported with glaciers, but these do not display a typical jigsaw-puzzle texture (Broster and Seaman, 1991; Piotrowski et al., 2004).

In areas that may be interpreted to be subglacial, the basal unconformity below diamictites may be highly irregular and heterogenous, with areas of sediment injections into sedimentary bedrock, and “elongated boulders” of sediment displaying jigsaw-puzzle texture, but all these features are common in SGFs (Dufresne et al., 2021; Molén 2021; Le Heron et al., 2021b).

*2.4. Polished, faceted and striated clast*s

It is often assumed that glacially transported clasts exhibit more striations than clasts that have been transported by SGFs. This assumption is not well documented as there is a great difference in the frequency of striated clasts reported from different kinds of environments (Table S1, Supplementary material).

Polished, faceted and striated clasts can form by different kinds of mass movements and by tectonic movements including by folding (Crowell, 1957; Flint, 1961; Schermerhorn and Stanton, 1963; Winterer, 1964; Schermerhorn, 1974a; Doré, 1981; Eisbacher, 1981; Rehmer, 1981; Hambrey, 1983; Martin et al., 1985; Eyles and Boyce, 1998; Atkins, 2003; Dakin et al., 2013). In SGFs there may be more striated clasts where there are more clasts (Kennedy and Eyles, 2021). Even hard quartzite can be striated in SGFs (Van Houten, 1957; Schermerhorn 1974a; Eyles, 1993), but usually most striations are exhibited by sedimentary clasts (Winterer, 1964). Clasts formed under these circumstances may be impossible to distinguish from clasts polished, faceted and striated by the action of ice-movement.

In the LPIA "tillites" of South Africa the shapes and sizes of clasts exhibit a very complex pattern which do not give any independent support to a glaciogenic origin (Hall and Visser, 1984). "Glacially shaped" so-called flat-iron clasts in the Gowganda Formation are slightly concave or convex "para-flat" with many small protuberances which shows that they cannot have been shaped by ice, and the deposits having an appearance more like a breccia that has been transported a short distance (Miall, 1985; Molén, 2021).

Even if there may be differences between striations on clasts from different environments, there are many similarities, and not all environments have been compared (Atkins, 2003, 2004). Striations on clasts in SGFs may be random and also curve around corners. Striations on glacially striated clasts may display one or more sub-parallel, or parallel, directions, usually on a flat side of the clast. But, glacially transported clasts may display striations that turn around edges or curvatures (Hicock, 1991; Hicock and Dreimanis, 1992a). Clasts that are tectonically scratched usually display strictly parallel striations, and occasionally in more than one direction (Frakes, 1979; Kennedy et al., 2019). Photographs and reports on striated clasts in SGFs reveal that they usually have random but frequently parallel to sub-parallel striations (Winterer, 1964; Lindsay, 1966; Winterer and von der Borch, 1968; Atkins, 2004) similar to clasts from "tillites" which have striations that are random (Kulling, 1951), bend around corners (Frakes, 1979; Deynoux, 1985b) display single parallel (du Toit, 1926; Deynoux and Trompette, 1981b), and crossing parallel and sub-parallel striations (Deynoux, 1985b). Occasionally clasts in "tillites" display both tectonic and "glacial" striations so the evidence is equivocal (Aitken, 1991).

Occasionally clasts displaying "glaciogenic" climate features, like einkanter, "flutes" and ventifacts, may be described from conglomerates and interpreted to have been formed at an earlier time by glaciers (Williams, 2005). The internal structure of clasts may display an appearance of being striated, some clasts appear to be faceted after having been cleaved in flat planes, including bullet shaped clasts, and as a result, mistakes have been made in the interpretation of ancient deposits as "tillites" (Vellutini and Vicat, 1983; Rowe and Backeberg, 2011). Stoss and lee-forms on clasts may be formed in different environments where there is mechanical erosion, but in lodgement tills clasts may have double stoss-lee forms (Krüger, 1984, Benn and Evans, 1996). Double stoss-lee forms on clasts may be the only unequivocal criteria for glaciation (Krüger, 1984).

In "tillites" soft sedimentary clasts may be subangular, fresh and commonly striated, while harder basement clasts are rounded, commonly weathered and rarely striated (Schermerhorn, 1976b; Deynoux and Trompette, 1981b; Eisbacher, 1981; Deynoux, 1985b). This may be an indication for SGFs which transport older pre-weathered and pre-rounded basement clasts together with newly ripped up sedimentary clasts.

2.5. Striated, grooved and polished surfaces/pavements

2.5.1. Presence of striated, grooved and polished surfaces/pavements

Pavements/striated surfaces can form by many different processes, including by glaciers, sea ice (Hume and Schalk, 1964; Flint, 1971; Hoppe, 1981), icebergs (section 2.7), mass transport and tectonism (Sandberg, 1928; Flint, 1961; Schermerhorn and Stanton, 1963; Frakes et al., 1969; Hambrey, 1983; Iverson, 1991; Eyles and Boyce, 1998; Legros et al., 2000; Vandyk et al., 2021). Subaqueous flow tills may generate tool marks, but these would be very restricted (Evenson et al., 1977). There are many similarities displayed by surfaces produced by these diverse processes. There are also many differences in appearance which usually, if they are thoroughly documented, may be sufficient to reveal the origin of various striated/grooved surfaces.

Erosional marks are almost always formed beneath glaciers, but it is not always recognized how commonly these form by different kinds of mass flows (e.g., Scott, 1988b; Dakin et al., 2013; Peakall et al., 2020). Striated, grooved and polished bedrock, including chevron structures/crescentic gouges/chattermarks, grooves, nailhead striae (which may be labeled prod marks by SGF researchers), and deposition of fluted ridges, form as a result of different kinds of mass movements. These have been documented in both ancient and recent formations, including from debris flows, volcanic flows, avalanches, earth slides, tectonism and other kinds of mass movements (Pettijohn and Potter, 1964; Glicken, 1996; Shepard and Dill, 1966; Enos, 1969; Wilson, 1969; Harrington, 1971; Daily et al., 1973; Allen, 1984; Scott, 1988b; Waitt, 1989; Blatt, 1992; Schneider and Fisher, 1998; Eyles and Boyce, 1998; Atkins, 2003; Draganits et al., 2008; Dakin et al., 2013; Hu and McSaveney, 2018; Sobiesiak et al., 2018; Peakall et al., 2020; Vandyk et al., 2021). Cohesive SGFs may move plastically, sometimes almost like a glacier, and therefore striations, grooves and polishing will appear more similar to erosion by glacier ice, at least on a local scale. This may also happen from pure tectonic movements, i.e. slickensides or fault grooves which locally may display an apperance very similar to glaciogenic striated and abraded formations including presence of crescentic fractures, flute ridges, nail head striations and striated clasts (Eyles and Boyce, 1998; Atkins, 2003; Vandyk et al., 2021). The most common tools producing marks in soft sediment, including striations and grooves, appear to be shale clasts (Hampton, 1972; Middleton and Hampton, 1976; Lowe, 1979; Clark, 1991; Peakall et al., 2020).

Debris flows may overlie grooved surfaces that are tens of kilometers long, 15 m deep and 25 m wide (Posamentier and Kolla, 2003; Peakall et al., 2020). Detailed studies of grooves formed by SGFs, have documented flows covering distances in excess of 40 km and areas of c. 300 km^2 (Peakall et al., 2020). That may explain why most pre-Pleistocene pavements are in soft sediments (e.g., Le Heron et al., 2020), as opposite to the Pleistocene and Holocene.

Examples of misidentified pavements include several meters long grooves and striations in the Triassic of Australia, which are clearly non-glacial (Gore and Taylor, 2003). On the island of Svalbard 2-3 m long striations and “ice-polished bedrock” (sandstone and shale) have been formed under the action of sea-ice and waves (Hoppe, 1981). Other “glaciogenic” surfaces exhibiting nail-head striae and “possible” crescentic gouges (Schenk, 1965) have been reinterpreted as tectonic in origin (e.g., Miall, 1985). In certain cases pavements are mentioned as evidence of glaciation, but upon investigation the descriptions appear to be erroneous and there are not even any indications of pavements (Dey et al., 2020).

2.5.2. Formation of striated, grooved and polished surfaces/pavements

Striations formed by clasts frozen to the bottom of glaciers consist of sub-parallel sets, commonly accompanied by chattermarks and/or nailhead striae (Anderson, 1983). Similar striations can, however, also be formed by SGFs, and be both parallel/sub-parallel and somewhat curved and show crosscutting to 90° but commonly < 40°, both on rock surfaces and on soft sediment (Pettijohn and Potter, 1964; Enos, 1969; Harrington, 1971; Middleton and Hampton, 1976; Allen, 1984; Ricci Lucchi, 1995; Hu and McSaveney, 2018; Peakall et al., 2020). Tectonic striations will mostly be parallel. Soft sediment slickensides may form internally in tills (Evans et al., 2006), but commonly the appearance of slickensides is very different from striations and grooves.

At the sole of warm-based glaciers clasts gradually reorient, horizontally and vertically, such that striations and grooves will always change their appearances (Iverson, 1991). There is a debate concerning whether cold-based glaciers move, but a clast at the bottom of a glacier is never frozen with no internal movement within the ice and striations are varied in appearance (Atkins, 2004, 2013). Glacial striations of Pleistocene age, on sedimentary bedrock may display a superficial appearance similar to striated surfaces below SGFs, as they are parallell and straight for short distances (Fig. 2A). But such glaciogenic striations bear evidence of sideways horizontal and vertical movements (Iverson, 1991), and commonly are short (e.g., 0.05-1 m; Sokołowski and Wysota, 2020), even if the features are not incompatible with some mass flow striations.

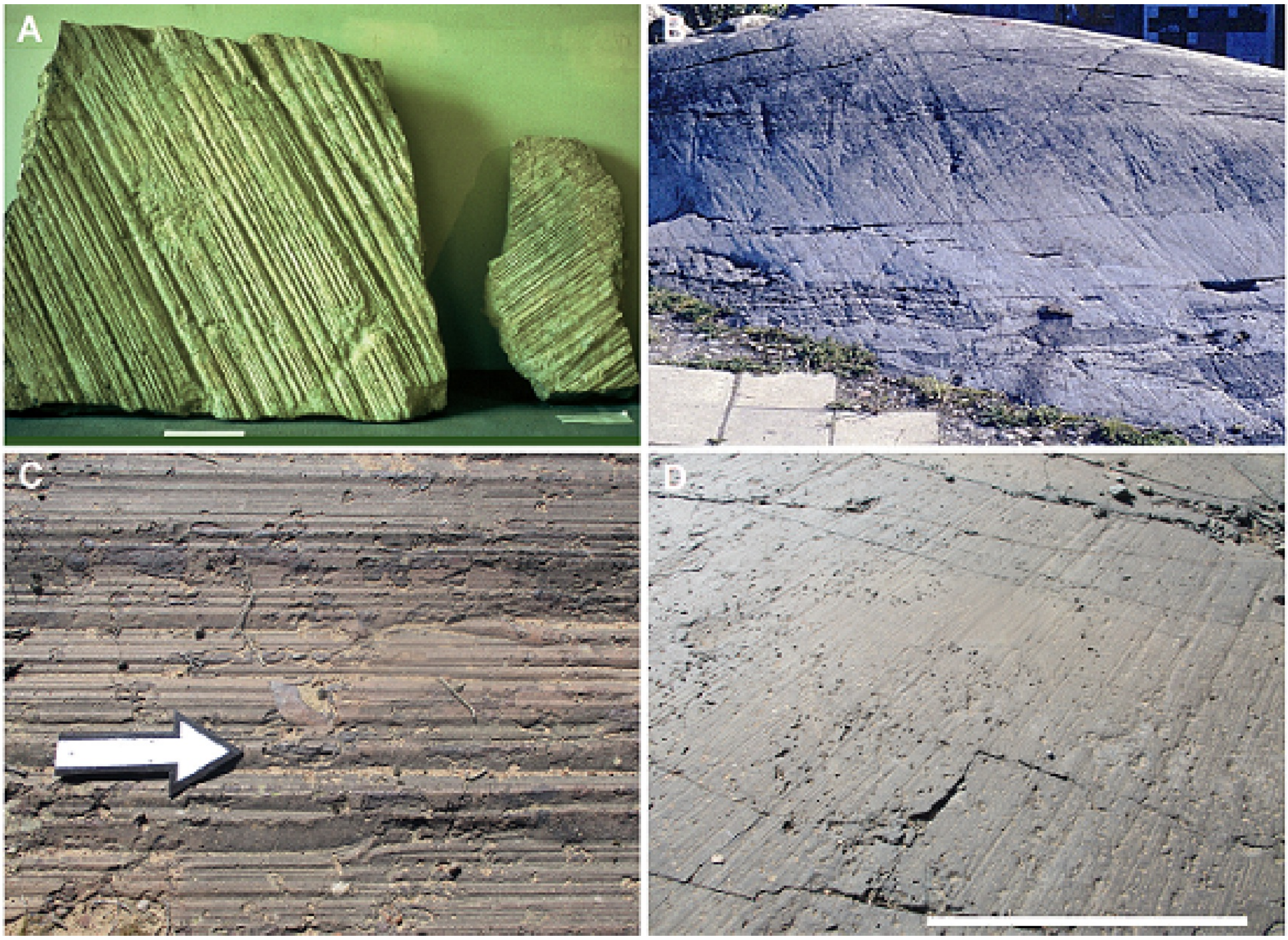

Fig. 2. Pavements. A and B are Pleistocene (Weichselian), C and D are LPIA. A. Glacial striations in Silurian limestone (Gotland, Sweden). The striations in the limestone show superficial similarities to some striations from SGFs in soft sediments. But, the evidence of horizontal and vertical wobbles of the clasts from within the glacier is clearly apparent, if only looking a little bit more in detail on the picture. (Gotlands Museum, 1986. Pieces of paper are c. 10 cm.) B. Glacial striations on the stoss side of a roche moutonée in magmatic bedrock (University of Stockholm, Sweden). At the roche moutonée the striations and grooves are short, irregular, and subparallel. C. Soft sediment LPIA "glaciogenic" striations which are perfectly similar to those formed by SGFs, i.e. straight an parallell and no or little evidence of vertical or sideways wobbles of the tools making the striations and grooves (Oorlogskloof, South Africa, arrow is 25 cm) (Draganits et al., 2008; Peakall et al., 2020; Molén and Smit, 2022). D. LPIA striations on Precambrian andesitic lava (marker is c. 1 m) (Douglas, South Africa). The striations are almost exactly parallel for a distance of more than

50 m (variation is reported as approximately 1° by Stratten and Humphreys, 1974).

2.5.3. Differences displayed by striated, grooved and polished surfaces/pavements

SGFs and slides generate a number of features on surfaces, including different grooves and striations, which are seldom or never generated with similar appearances below glaciers. Striated and grooved surfaces displaying such appearances, i.e. those that are generated by mass flows, are common in areas where there are pre-Pleistocene "tillites." For example, during the Paleozoic the majority of "subglacially formed pavements" are in unlithified sand (Le Heron et al., 2020; Fig. 2C), whereas similar surfaces are very rare or non-existent in Pleistocene and more recent deposits. A number of the appearances of striated surfaces displayed by SGFs are documented in the list below. Most of these appearances are documented by Peakall et al. (2020) and Baas et al. (2021).

a) SGFs commonly display straight movements, often for hundreds of meters or more, and extensive striated and grooved surfaces may be generated in time periods of only seconds or minutes (Piper et al., 1999; Peakall et al., 2020; Baas et al., 2021). Debris flows have traveled at a speed of 500 km/h (Shanmugam, 2002).

b) Grooves are often parallel, display constant rounding, depth and width, may display parallel internal striae, and occasionally raised lateral ridges (Peakall et al., 2020, Baas et al., 2021).

c) SGFs may pass areas without leaving much traces. This is shown by the presence of bypass zones, which can be tens of kilometers, where there is no erosion (Moscardelli et al., 2006; Georgiopoulou et al., 2010; Talling et al., 2012; Stevenson et al., 2014; Cardona et al., 2020; Peakall et al., 2020; Baas et al., 2021).

d) Stacked striated surfaces are common in SGFs, with more or less vertical and horizontal distance between these surfaces, i.e. in some areas the striated surfaces even shift stratigraphic position and move up and down through the beds as a result of different movements during deposition (Enos, 1969; Petit and Laville, 1987; Draganits et al., 2008; Le Heron et al., 2014; Peakall et al., 2020). (Fig. 3.) Similar stacked striated surfaces are not observed from Pleistocene or more recent deposits where it is known that glaciers were the depositional agent (Trosdtorf et al., 2005a). Stacked striated/grooved surfaces commonly display similarities to what has been labeled "tectonic hydroplastic slickensides" or "internal grooves and striations" in SGFs that form in soft sand (Enos, 1969; Petit and Laville, 1987; Deynoux and Ghienne, 2004, 2005; Le Heron et al., 2005, 2014), while some are stacked slickensided (or slickenlined) clay or mud (Simms, 2007; Cesta, 2015; Rodrigues et al., 2020). Woodworth-Lynas and Dowdeswell (1994), Vesely and Assine (2014), and Rosa et al. (2019) interpreted single and stacked soft sediment surfaces as evidence for ice-keel scouring by icebergs. Such an interpretation was not accepted for "glaciogenic" striated surfaces in the Ordovician of northern Africa, that was interpreted as hydroplastic and formed simultaneously by tectonics and pressure from below thick glaciers (Deynoux and Ghienne, 2004, 2005; Le Heron et al., 2005, 2014). (Iceberg keel grooves are discussed in section 2.7.)

e) Traction carpet sediments are common between striated surfaces and superposed diamictite debrites. The sediments may be striated, and may be a stratigraphic plane where clasts commonly glide (Moscardelli et al., 2006; Georgiopoulou et al., 2010; Talling et al., 2012; Dakin et al., 2013; Cardona et al., 2020; Peakall et al., 2020; Molén and Smit, 2022). Thin basal layers of sediment are not present between Quaternary tills and pavements, even if a process for the origin of such sediments could be hypothesized during special circumstances in rare and confined environments.

f) Contacts below "tillites" may display overhanging walls (Miall, 1985; Molén 2021) or channels (Moncrieff and Hambrey, 1988) which may exhibit striations (Frakes and Crowell, 1970; Armentrout, 1983). This may result from erosion by SGFs rather than from glaciation, with or without striations (Scott, 1966; Shepard and Dill, 1966; section 1.4.).

Table S2 (Supplementary material) lists striated surfaces which display similar appearances as mass flows, from striated surfaces/pavements which had been interpreted to have formed by glacial ice. Even though all appearances of pre-Pleistocene striated surfaces have not been observed in recent deposits, and some are difficult to fully explain, the evidence documented in Table S2 display similarities to striated surfaces which have a mass transport or a tectonic origin, rather than a glaciogenic origin. In conclusion, similar pavement features commonly do not form, or have never formed, by Pleistocene or younger glaciers, and therefore these "pavements" are better explained by a mass transport origin rather than by glaciation.

Fig. 3. Four soft sediment stacked sandstone striated surfaces, LPIA, Dwyka Group, Oorlogskloof, South Africa. These surfaces are perfectly similar to those made by SGFs (Draganits et al., 2008; Peakall et al., 2020). The regular appearance of the grooves show no similarity with glaciogenic surfaces.

2.6. Striated, grooved and polished surfaces, rock polish

Mechanically abraded rock surfaces formed beneath glaciers may display a thin glossy coating layer. Such glacial polish is typically a few micrometers thick, consisting of minute transported clasts and mineral fragments in a fine-grained amorphous matrix of nano-sized phyllosilicates. The observations suggest bending and fracturing of the uppermost part of the original bedrock, followed by smearing of clast fragments and amorphous material on top of the bedrock surfaces (Siman-Tov et al., 2017). Variants of such surfaces may also be generated in fault zones. Except for formation by mechanical shearing, an appearance of rock polish may result from purely chemical precipitation (Bussert, 2010; Molén, 2017).

Striated and grooved surfaces below Neoproterozoic diamictites, commonly interpreted to be “tillites,” have been shown to be at least partly formed by post-depositional chemical modification, and there is “polish” even on striations with rugged surfaces (Molén, 2017). Surfaces on Ordovician “glaciogenic” soft sandstone surfaces display cataclasis of mineral grains, but not amorphization and smearing of clast fragments (Denis et al., 2010). Ichno-fossil Tigillites burrows at this striated surface remains undeformed, which would be quite exceptional if a glacier would have passed the soft sediment area (Denis et al., 2010). In Chinese Ediacarian-Cambrian sediments “glaciogenic” polish is mentioned to occur on apparently soft sediment surfaces, where striations also have been formed inside the diamictite, above a surface displaying perfectly straight striations in two directions, but occasionally curvilinear (Le Heron et al., 2018b). None of these polished surfaces displays more than superficial similarities to polish on Quaternary pavements.

A recent rock avalanche in China, initially moving as a “water-saturated, dense grain flow,” passing over dolomitic black shale, formed a surface “highly reminiscent of a classical striated rock pavement from beneath a glacier,” displaying polish and chemical precipitation (Hu and McSaveney, 2018). Polish, melting and precipitation are formed in realistic mechanical experiments and from landslides (Legros et al., 2000; Hu and McSaveney, 2018).

Heat is always produced by friction, and large mass flows or slides could under certain circumstances probably generate high temperatures, capable of creating polish and lithifying the underlying surface (compare to a pavement where temperatures of c. 1000°C have been suggested below an outcrop commonly interpreted to have been deposited below glaciers; Bestmann et al., 2006; Molén, 2017).

2.7. Striated, grooved and polished surfaces, iceberg keel scour marks

Ice scour marks form when keels of icebergs and sea or lake ice press up ridges and plough through unconsolidated sediments. Some of the pre-Pleistocene soft sediment surfaces which have been interpreted to be formed by glaciers, had been interpreted to be from icebergs or sea ice (Woodworth-Lynas, 1992; Woodworth-Lynas and Dowdeswell, 1994; Vesely and Assine, 2014, who reinterpreted 17 soft sediment surfaces as generated by icebergs; Rodríguez-López et al., 2021: Table S2, Supplementary material) while others refrain from such an interpretation (Deynoux and Ghienne, 2004, 2005; Le Heron et al., 2005, 2014, 2020). Similarities between SGFs, single moving clasts, and iceberg scours, include cases where the underlying sediments become depressed. Similarities also include berms that may be pushed up next to iceberg scours, in size from a few centimeters to many meters high, and similar linear ridges which may form by SGFs next to single clasts which are moving at the bottom, and even sometimes by running water. Non-glacial push up and sedimentary linear structures may be labeled lateral ridges, flowbands, or sometimes levees (e.g., Dufresne and Davies, 2009; Kneller et al., 2016; Peakall et al., 2020; Procter et al., 2021).

Quaternary ice keel scour marks may be more than 20 km long, depth may be 80 m, and they may be up to 1 km wide. They may form at depths of more than 600 m, but are more common at depths of 60-400 m or less (Woodworth-Lynas, 1992; Woodworth-Lynas and Dowdeswell, 1994; Dowdeswell and Hogan, 2016). In SGFs isolated outrunner blocks, up to many hundreds of square meters in size, are common, and have traveled many kilometers over very low gradients e.g., 0.3-0.4°, and have made long glide tracks and scour marks in the sea bottom (Prior et al., 1982; Nissen et al., 1999; Ilstad et al., 2004; Moscardelli et al., 2006; Festa et al., 2016, Nwoko et al, 2020b, Kumar et al., 2021). Larger outrunner blocks, in kilometer-sizes, have outrun the main slide deposits for c. 10 km and have excavated megascours that, including the basal erosion within the main slide deposit, are 1 km wide, 150 m deep and 70 km long (Soutter et al., 2018). SGFs may make deep scours that turn through about 45°, and then split into many smaller <10 m deep scours (Moscardelli et al., 2006). There may therefore by at least superficial similarities between ice keel scour marks and mass flow processes, and in at least one case they are known to have formed in a non-glacial turbidity current environment (Scott, 1966). “Iceberg grooves”in the Paleoproterozoic of India were only between 1.2-7.8 cm wide, and 9.2-13.1 cm deep, and pointing in the direction of 66-68° from the surface (instead of close to 90°) (Rodríguez-López et al., 2021). This gives them an appearance of small fractures induced only by short sediment movement, and these were later (quickly) filled with sandy laminated sediments.

In a few instances grooves below “tillites” are curved (Bryan, 1983), up to an angle of 90° in one meter (Fairbridge, 1979), and they may still be parallel after they changed direction (Allen, 1975). This is believed to result from overturning of iceblocks, or from changed wind or current direction that diverted icebergs with clasts frozen to their bottom. However, from different mechanisms, SGFs may turn, at occasions even 180°, and therefore the direction of sole structures also will change (Enos, 1969; Kneller et al., 1991; Pickering et al., 1992; Butler and Tavarnelli, 2006; Draganits et al., 2008; Peakall et al., 2020).

Woodworth-Lynas (1996) published a detailed list of features generated by icebergs, and an update of a few of the more important of these which can be readily studied in ancient lithified restricted outcrops in the field, are mentioned below:

a) In the Quaternary there is an abundance of ice-keel scours generated by icebergs over a total approximate area of $10x10^6$ km^2 (Woodworth-Lynas and Dowdeswell, 1994). The complete bottom surface may be covered by a network of ice-scour marks, occasionally displaying straight directions but commonly curvilinear and often in many different directions (Woodworth-Lynas, 1992; Woodworth-Lynas and Dowdeswell, 1994; Batchelor et al., 2020). Because of e.g. tides, there are examples of looped or spiralling iceberg scour marks (Woodworth-Lynas et al., 1985; Newton et al., 2016). Different from Quaternary sediments, large grooves which have been interpreted as ice scour marks in pre-Pleistocene environments (commonly in sand) are often single, but if many soft sediment surfaces are superposed or next to each other they are pointing in the same direction (different from stacked soft striated surfaces in recent tidal mud sediments; Woodworth-Lynas, 1996), and they often display exactly parallel grooves and striations within the scour.

b) There may be grooves and striations within ice-scour marks (Batchelor et al., 2020), and if so these are subparallel, i.e. different to parallel grooves and striations commonly generated beneath SGFs (section 2.5.).

c) Commonly pre-Pleistocene surfaces which have been interpreted to be iceberg keel scours, are horizontal, while more recent marks may be undulous in cross-section and display small scale faults induced by iceberg loading (Thomas and Connell, 1985; Woodworth-Lynas and Guigné, 1990). Wave action and diurnal tides are documented from ice-berg keel scour marks in Quaternary sediments (Woodworth-Lynas and Guigné, 1990; Bennett and Bullard, 1991), and there should be evidence of constant changing vertical movements below icebergs. There is also documentation of up to 2 m high and 20-40 m wide orthogonal or perpendicular ridges, asymmetric in cross-profile, that are interpreted to have been produced from tides during the Quaternary (Dowdeswell and Hogan, 2016; Batchelor et al., 2020).

d) Ring structures, a few decimeters high and wide, made from up to 50 m large chunks of shore ice, are formed today in Canada (Dionne, 1992). Similar forms produced by icebergs, i.e. grounding pits, may be 10 m deep and 50 m in diameter (Dowdeswell and Ottesen, 2013;

Batchelor et al., 2020). Similar structures have not been reported from the pre-Pleistocene.
e) There are micromorphological criteria for iceberg keel scours (Linch and Dowdeswell, 2016) which have been used to interpret the origin of a pre-Pleistocene soft-sediment striated pavement as not formed by icebergs but by a grounded icemass (Le Heron et al., 2020).
f) There are grounding-zone wedges showing clear evidence of still-stands or re-advances of glaciers, up to 15 m high, which have not been registered from the pre-Pleistocene (Batchelor et al., 2020).
g) Large areas (kilometers) display up to 2 m high asymmetric or sinuous corrugation ridges that are transverse to the strike of the glaciers, which are easily explained by tide-water fluctuations during glacial retreat (Batchelor et al., 2020). Similar structures have not been documented in the pre-Pleistocene.

In conclusion, if there is evidence of a series of vertical and sideway movements, from tides, waves wind or currents, and subparallel grooves/striations, an iceberg keel origin of scour marks may be a better option of interpretation than other processes. Other data may be of help, as mentioned above, but the evidence from movement is diagnostic.

2.8. Boulder pavements

There are many boulder accumulations with a more or less flat upper surface which geologists have described as boulder pavements. Hansom (1983) described boulder pavements which probably originated by winnowing out of fine material from glacial till on beaches. Close to the continental shelf/continental slope boundary (Boulton, 1990), or anywhere below sea level where there is net erosion, the fine material will be winnowed out and leave the boulders. In other places, pavements originated where sea ice had forced boulders into the underlying substrate (Hansom, 1983). Hara and Thorn (1982) described fluvial boulder beds which had been modified by periglacial processes as “subnival boulder pavements,” and frost heaved boulders that display “flat” tops because of gravity but not paving. During drainage of dammed lakes, boulders can accumulate to form a deposit exhibiting a flat upper surface, called a boulder delta (Elfström, 1987). The Mount St. Helens eruption generated a lahar that cut volcanic boulders and produced “... a surface similar to a glacial pavement cut in conglomerate” (Scott, 1988a), and more or less planar boulder accumulations are present in other SGF deposits (Best, 1992). What appears to be boulder or pebble trains (which may be described as boulder pavements) may be formed by SGFs, but are often present in “tillites” (Bussert, 2014; Kennedy and Eyles, 2019).

The Pleistocene “classical” inter- and intra-till boulder pavements are usually only one layer thick (Clark, 1991; Hicock, 1991). These have been suggested to originate possible by a process slightly similar to debris flows, where boulders sink down into fine-grained till and after that deforms by overriding glaciers (Clark, 1991; Hicock, 1991). It would therefore be difficult to differentiate this kind of pavement from boulders that have accumulated from debris flows (Lowe, 1979, 1982).

Boulder pavements are common in pre-Pleistocene “tillites” (e.g., Lindsay, 1970a; Gravenor, 1979; Rocha-Campos and Santos, 1981; Martin, 1981a; Von Brunn and Stratten, 1981; Visser, 1983b; Caputo and Crowell, 1985; Visser and Hall, 1985, López-Gamundí et al., 2016). but are more seldom reported from the Pleistocene (Derbyshire, 1979).

Pre-Pleistocene boulder pavements are often located at the base or top of “tillites.” Boulder pavements have been a) traced back to channel deposits (Lindsay, 1970a), b) described as bevelled dropstones (Moncrieff and Hambrey, 1988), c) formed by a local fault and covered by calcite (González and Glasser, 2008), and d) described as boulders lined up after each other, with a decrease in size both upstream and downstream, thus showing affinities to pebble trains in streams (Dal Cin, 1968). Boulder pavements are most common in the Dwyka

Group in South Africa, and display many different appearances. The basal “tillite” in the southern part of the Dwyka Group commonly is capped with a bed of boulder “tillite” at the top of an upwards coarsening sequence (Visser and Loock, 1982), and boulder accumulations may grade upwards into conglomerates labeled boulder rudites. One boulder pavement displays single imbricated beds (Visser and Hall, 1985) more typical of debris flow, tsunami or cyclone deposits (Shanmugam, 2012, 2021b). Boulder beds may be up to 12 m thick, and display moderate sorting (Visser and Hall, 1985). In places boulders have accumulated on the lee side of an obstacle (Visser and Loock, 1988) or are described as a lag deposit of a single layer of boulders at the base of sandstones (Visser et al., 1987).

An origin of boulder pavements by SGFs seems at least as possible as an origin beneath a glacier, by winnowing out of material, by reversed grading, or simply by the common upwards movement of large clasts which takes place in SGFs (section 2.13.1.1.). The differences between ancient and Pleistocene inter/intra-till boulder pavements may be considerable.

2.9. Erosional landforms, lineations

There will always be superficial similarities between landforms generated by different processes, including at the boundary layer in different environments (Stokes, 2018), whether it be glaciers, running water or mass movements. The direction of movement and the cohesiveness or plasticity of the moving medium will generate features which may display different appearances.

Commonly sea bottoms are sculptured and grooved over large areas by SGFs or slides. Ice streams mold large areas into streamlined landforms, i.e. lineations, sediment into drumlin-like forms, and through erosion of bedrock they produce linear landforms (Eyles et al., 2018).

Lucchitta (2001) studied subaqueous (glaciogenic) lineations at the Antarctic shelf, and concluded that they were similar to glaciogenic lineations on Mars. However, the lineations on Mars, including gigantic outflow channels, are probably formed by catastrophic water release from subsurface groundwater reservoirs, i.e. large scale tectonism and fissures releasing water, and not by glaciers (Baker and Milton, 1974; Baker and Kochel, 1979; Burr et al., 2002; Plescia, 2003; Rodriguez, 2005; Leask et al., 2007). Similar lineations were produced by catastrophic release of water and debris flows triggered by the failure of Mount St Helens stratocone (Major et al., 2005), the formation of the English Channel and the Channeled Scablands in Washington (Plescia, 2003; Gupta, 2007; Gupta et al., 2007, 2017). Other landforms in unconsolidated sediments or bedrock, heading in different directions, formed subaqueously or subaerially, including 60 km long channels/megascours and lineations with dimensions of up to many tens of km long, 6-8 km wide, and 600 m deep, from SGFs, and in places they are U-shaped (Best, 1992; Moscardelli et al., 2006; Robinson et al., 2017; Ortiz-Karpf et al., 2017; Nwoko et al., 2020a, 2020b). Lineations, tens of kilometers long, up to 10 m high, and with wavelengths of 100 m, also are formed by density-driven sediment and water movement, during seasonal weather conditions (Canals et al., 2006). A slide generated c. 30-120 km long, 100-600 m wide and 10-30 m deep grooves (Gee et al., 2007), which may be labeled lineations, but such forms may be labeled striations by marine geologists (e.g., de Blasio, 2006; Gee et al., 2007; Nwoko et al., 2020a). Smaller lineations, e.g., only 0.4-1.5 m high and spaced at 5-7 m, may also be formed by SGFs (Piper et al., 1999).

In the Quaternary, there are megalineations that excessively outnumber those that are interpreted from the Paleozoic, both in areal size and evidence of large-scale energy impact during geological processing. These cover extensive areas, both subaqueously and subaerially, with both soft (drumlinised sediment) and hard (rock drumlinoid) forms (Margold et al., 2015; Dowdeswell et al., 2016a, 2016b; Eyles et al., 2018; Stokes, 2018;

Bukhari et al., 2021), contrasting with Paleozoic surfaces which are interpreted to be megalineations. In some areas there are also numerous, up to kilometers long and wide, transverse ridges (Stokes, 2018; Batchelor et al., 2020). The present author knows of no transverse ridges on lineations interpreted from the pre-Pleistocene. Pre-Pleistocene ice streams and lineations appear to be more sinuous, partly anastomosing or amalgamated, follow an outline similar to a SGF where they also change direction, are often parallel to the strike of the underlying bedrock, and are shorter and wider (see figures and descriptions in Andrews et al., 2019). Similar structures form by SGFs and slides, but may be labeled striations (Gee et al., 2005, 2007; Macdonald et al., 2011). Other areas displaying megalineations interpreted from Google Earth from sandstone plateaus in Chad (Le Heron, 2018), display many different surface structures when investigated at greater detail including an underlying "dipping substrate" (Le Heron, 2018), rather than ice streams.

Single linear landforms, including those which are drop formed, which display similarities to landforms that are interpreted to be glaciogenic (Assine et al., 2018), form by catastrophic outbursts of water which may or may not have any connection to glaciation (Burr et al., 2002; Plescia, 2003; Gupta, 2007; Gupta et al., 2007, 2017; Robinson et al., 2017), and also from SGFs (Dufresne and Davies, 2009), and may be labeled "whaleback bars" (Scott, 1988a) or "shadow remnants" (Moscardelli et al., 2006).

Pre-Pleistocene roches moutonnées have often been reported, but these often display steep stoss sides and gentle lee sides (e.g., Frakes and Crowell, 1970; Visser and Loock, 1988; Bussert, 2010; Assine et al., 2018), as opposed to Pleistocene roches moutonnées. They may therefore be interpreted to be whalebacks or rock drumlins. Some "roches moutonnées" seem to have their stoss side undercut by erosion (Frakes and Crowell, 1970, their Fig. 6C) – a more likely phenomenon to take place below a SGF or in running water than below a glacier. Others have been shown to be a product of tectonics and fluvial erosion on structurally controlled bedrock features (Vandyk et al., 2021). There is a large difference between the number of “roches moutonnées” and other small scale erosional landforms in pre-Pleistocene formations compared to younger formations, as they are almost all-present in Pleistocene and Holocene glaciogenic formations.

Bedrock forms, especially those in magmatic rocks, should be better preserved than sediments in the rock record, but there is no extensive record evident from ancient “tillites.”

2.10. Erosional landforms – plucking

A process similar to glacial plucking may be caused by SGFs and fluvial action, including on the surface of magmatic bedrock (Dill, 1964, 1966; Shepard and Dill, 1966; Carter, 1975; Tinkler, 1993; Whipple et al., 2000; Stock and Dietrich, 2006; Dakin et al., 2013; Lamb et al., 2014; Hodgson et al., 2018; Vandyk et al., 2021). So-called p-forms (or s-forms) may be formed by non-glacial fluvial currents (Tinkler, 1993, Vandyk et al., 2021), even though they often are interpreted to be formed subglacially (Le Heron et al., 2019a; Chen et al., 2020; Vandyk et al., 2021). Additionally, there is a debate whether fluvial landforms which are similar to glaciofluvial landforms, have been produced by tsunamis or storm waves (Bryant and Young 1996; Burgeois, 2009; Shanmugam, 2012; Lascelles and Lowe, 2021). Cavitation may be one process responsible for plucking (Falvey, 1990). Another process that display slight similarities to glacial plucking is more like delamination, i.e. detachment of soft sediments or clasts and entrainment into SGFs (e.g., Butler and Tavarnelli, 2006; Clark and Stanbrook, 2009; Butler and McCaffrey, 2010; Dykstra et al., 2011; Fonnesu et al., 2016; Sobiesiak et al., 2016; Eggenhuisen et al., 2011; Hodgson et al., 2018; Ogata et al., 2019; Cardona et al., 2020; Kennedy and Eyles, 2021), and where the delaminated sediments have later been lithified (which is what commonly takes place, as can be seen almost everywhere in the complete geologic rock record). If plucking leaves a jagged and uneven surface, and no later polishing (Miall, 1985), this indicate plucking by SGFs and not by glaciers (Molén, 2021).

2.11. Glacial and non-glacial valleys and fjords

2.11.1. Glacial and non-glacial valleys – general appearance

Many processes create valleys. Steep incisions hundreds of meters deep may be consistent both with glacial action and fluvial erosion driven by pure tectonic rift uplift (Vandyk et al., 2021). Hanging valleys are surprisingly common in non-glaciated areas, including in magmatic and metamorphic rocks, both subaqueously and subaerially (Dill, 1964; Sheppard and Dill, 1966; Erginal and Ertek, 2002; Mitchell, 2006; Wobus et al., 2006; Crosby et al., 2007; Lamb, 2008; Amblas et al., 2011; Harris et al., 2014; Normandeau et al., 2015). Such valleys could be the equivalent of "glacial" hanging valleys that have been interpreted from the Dwyka Group in South Africa (Visser, 1982; Hancox and Götz, 2014). "Glacial valleys" an basins in the LPIA of Namibia and Brazil, are "pre-glacial" in places including with examples of streamlined and striated landforms that are interpreted to be e.g. roches moutonnées (Martin, 1981b, Santos et al., 1996; Dietrich et al., 2021; Rosa et al., 2021).

Submarine canyons are preferentially eroded in "resistant bedrock" (i.e., metamorphic, igneous and lithified sedimentary bedrock; Moosdorf et al., 2018) and next to the coast, and c. 1000 canyons are present at the Last Glacial Maxium and later shorelines (Bernhardt and Schwanghart, 2021). Isostatic movements could have elevated pre-Pleistocene submarine canyons above the present sea surface, giving these an appearance of having been carved by glaciers.

Approximately a thousand non-glacial channels or scours, on slopes as low as 0.02°, which are up to kilometers in depth and many kilometers in width and length, have been documented, and this is only from the northeast Atlantic margin (Macdonald et al., 2011). Channels are common in mass transport deposits (Kneller et al., 2016; sections 2.2.8, 2.7.-2.9.). Smaller channels are common on fan deposits (Shanmugam, 2016). Initial V-shaped grooves or "megalineaments" up to tens of kilometers long, 6-8 km wide and 600 m deep, formed by mass flow transport, may turn into larger U-shaped valleys during movement (pictures in Ortiz-Karpf et al., 2017). Megascours, up to 1 km wide, 150 m deep and 70 km in length, some with a basal slide surface of 7000 km^2 and moving down slopes of c. 1.1° for 290 km, some formerly interpreted as submarine channels, some with extremely irregular basal boundary geometry, had originated by erosion from debris flows and slides (Dakin et al., 2013; Sobiesiak et al., 2018; Soutter et al., 2018).

All this variation and similarities need to acknowledged when the origin of ancient valleys is the question for study.

2.11.2. Glacial and non-glacial valleys – shape

Glaciated valleys are commonly U-shaped, and fluvial valleys are commonly V-shaped (Montgomery, 2002; Prasicek et al., 2014). But glaciogenic tunnel valleys may be both V-shaped and U-shaped (van der Vegt et al., 2012). And U-shaped valleys are produced by many non-glacial processes and in different environments, i.e. in pull-apart basins (Gürbüz, 2010; Fedorchuk et al., 2019), by slides, rivers and SGFs (Woolfe, 1994; Ebert, 1996; Lamb, 2008; Giddings et al., 2010; Amblas et al., 2011; Macdonald et al., 2011; Clarke et al, 2012; He et al., 2013; Vachtman et al., 2013; Coles, 2014; Ortiz-Karpf et al., 2017; Pauls et al., 2019; Isbell et al., 2021), in submarine canyons (Imbo et al., 2003; He et al., 2013; Gales et al., 2014; Pehlivan, 2019; Puga Bernabéu et al., 2020; see also Kumar et al., 2021), and by lowering of the sea level (compare descriptions in Germs and Gaucher, 2012 to Sial et al., 2015; and also Giddings et al., 2010 to Bechstädt et al., 2018). Coles (2014) wrote: “In fact fluvial valleys occupied a wide range of valley shapes, not simply the V-shape referred to in previous, particularly glacial orientated, literature. This means these idealized forms cannot be solely used to distinguish between glacial and fluvial valleys.”

2.11.3. Glacial and non-glacial valleys – fjords

Fjords are distinctive overdeepened narrow valleys. They are most shallow at the outlet where there is a “sill” or ridge of any material, but commonly bedrock (Fig. 4), which can be more than 1 km higher than the deepest parts of the fjords (Mangerud et al., 2019). Fjords are very common in the Pleistocene and Holocene, almost 1800 are recorded (Syvitski and Shaw, 1995), and these would easily be preserved in the rock record. However, there is a very poor record of ancient fjords. The few examples reported in the literature mainly document sedimentary infill of valleys, they do not display the typical fjord appearance with e.g., a ridge at the outlet, and may display uneven and irregular floors (Bowen, 1969; Visser, 1987; Kneller et al., 2004; Bussert, 2010; Alonso-Muruaga et al., 2018; Bechstädt et al., 2018; Moxness et al., 2018; Fedorchuk et al., 2019; Dietrich et al., 2021; Vesely et al., 2021). Landforms interpreted as fjords/glaciated valleys, including documented striated and abraded landforms, may have been formed by tectonics combined with SGFs and fluvial erosion (sections 2.5, 2.9-2.11.1).

Fig. 4. The smallest fjord observed by the present author, Vassdalsvatnet, Lofoten Peninsula, Norway. The length of this fjord is around 400 m, but it has the same appearance as all other fjords, i.e. it is deepest in the middle and displays a ridge at the outlet. There are actually two ridges in this fjord, similar to what may be present in some larger fjords. One is next to the road and another one is sticking up through the ice as a small island (in the middle of the picture). In the same area there are more small fjords with slightly greater lengths and depths.

2.12. Glaciofluvial deposits

Any strong water currents produce similar features, e.g., compare González and Glasser (2008) to Lamb et al. (2014). Lang et al. (2020) described bedforms in glaciogenic settings generated by “supercritical” currents and wrote: “individual bedform types are generally not indicative of any specific depositional environment.“ Further, they stated that glaciogenic “upper-flow regime bedforms” are rare in pre-Pleistocene deposits, and provided only five examples from pre-Pleistocene environments and all from Upper Ordovician “glaciogenic” sandstone areas (Lang et al., 2020).

Only when water flow is restricted by ice, and no other obstacles are present, there may be differences. All kinds of glaciofluvial deposits where ice restricted the flow of water, e.g., in kames (Fig. 5B), englacial and supraglacial eskers, lateral channels, crevasse fillings, etc., are missing from ancient deposits. These structures ought to be the more diagnostic features, as opposed to the often documented “glaciofluvial” or fluvial outwash and channel sandstones which can form in a wide variety of environments.

2.12.1. Eskers

Pleistocene eskers are commonly well sorted, often large boulders at the bottom center, then followed by finer clasts and sand (Fig. 5A). Their appearance is like linear conglomerates, but mostly sand higher up in the stratigraphic sequence. This general and most important structural configuration of eskers is the most significant difference compared to pre-Pleistocene linear landforms which are interpreted to be eskers. Furthermore, there are no reports of erratics on top of or close to the top of pre-Pleistocene “eskers,” which is a common phenomenon for Pleistocene eskers (Frakes, 1979). Only a few reports mention “glacial” tectonic disturbances in pre-Pleistocene “eskers” or “tunnel valleys,” similar to ice-push structures, ice-block load structures and lateral slump and slide structures displayed by Pleistocene eskers (Allen, 1975; Biju-Duval et al., 1981).

Sediments which are interpreted to be pre-Pleistocene eskers are rarely reported (Vesely et al., 2021). There are, however, sandstone channels in many places which show superficial similarities to eskers. These are mainly present in the Upper Ordovician and many may have been reinterpreted to be tunnel valleys (see below). LPIA linear sandstone bodies in South America which had been interpreted to be eskers are commonly short but may be up to 100 m long and display about the same width (1.5-2 m) as height (1-2.5 m) (González and Glasser, 2008), while common width/depth ratios for eskers lie between 2 and 20 (Vesely et al., 2021). These “eskers” display occasional thin layers of pebbles, and are covered by “tillite” (González and Glasser, 2008). There are also debris-filled (e.g., conglomerates) channels in the same area which earlier had been interpreted to be eskers (González and Glasser, 2008).

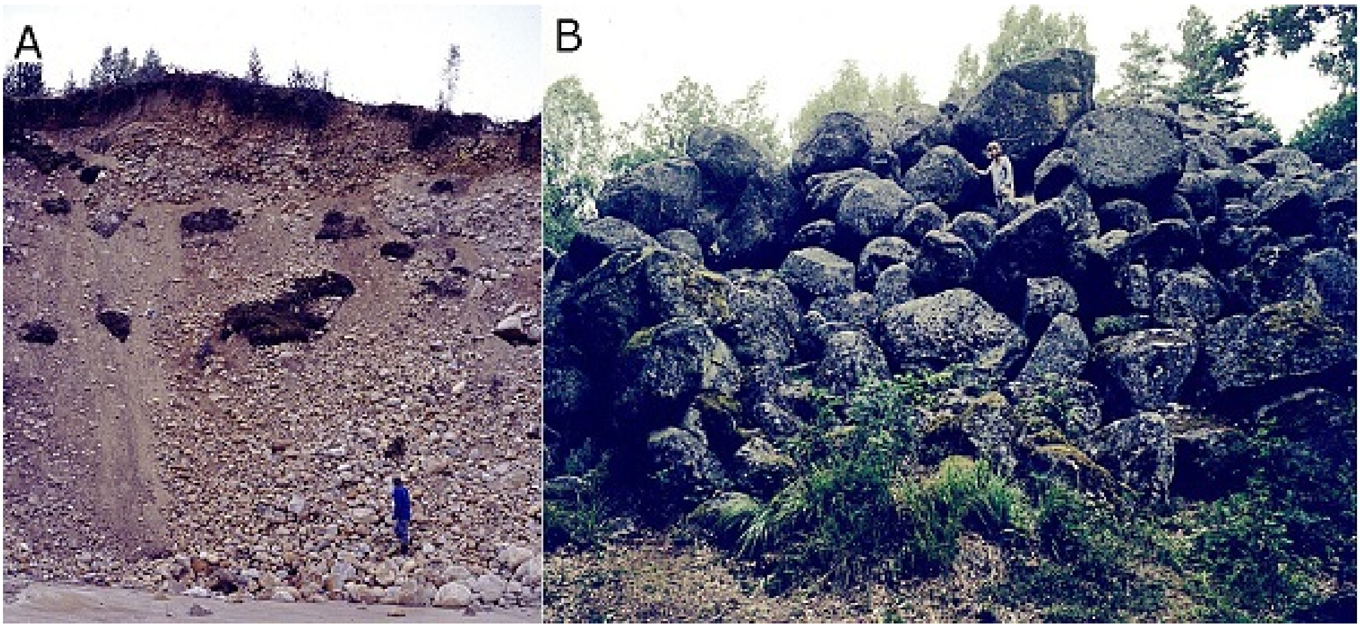

Fig. 5. A. Esker in Västerbotten county, Sweden. Boulders of different sizes and sand are sorted into different zones. Upper zone is winnowed out (below highest coastline). Commonly eskers consist of more sand and smaller boulders than the esker in the picture. B. A kame, i.e. a “short esker hill.” This one is exceptional as it mainly consists of very large boulders. Antamåla rör, Småland county, Sweden (Lundqvist, 1979).

2.12.2. Tunnel valleys

Ordovician and LPIA geologic features which have been interpreted as tunnel valleys (but sometimes may be interpreted as ice stream valleys) are commonly made up of sandstone.

These may be tens of kilometers long, tens of meters to occasionally more than 300 m deep, more than 1 km wide, linear or slightly sinuous, and may display amalgamation or an anastomosing network (Le Heron et al., 2004; Le Heron. 2010; Vesely et al., 2021). These tunnel valleys display many similarities to other types of valleys with which they can be confused. They are in many respects similar to fluvially eroded valleys (e.g., Baker and Milton, 1974; Gupta et al., 2017; Zaki et al., 2018, 2020, 2021). In some ways, they are similar to quickly formed slump-generated recent megachannels, but the sedimentary material is almost only sand in the Paleozoic valleys but richer in clay in recent valleys which may explain structural differences in appearance (Eyles and Lagoe, 1998). Tunnel valleys also resemble tidal channels (except for depth, up to 60 km long, 3 km wide and 22 m deep; Aliotta and Perillo, 1987), non-glacial sandstone channels (lacustrine or marine, tens of kilometers long, tens of meters deep, more than 1 km wide, linear or slightly sinuous and often amalgamated, but if exhumed may show up as positive landforms; e.g., Bell et al., 2020; Dou et al., 2021), and submarine channels and canyons (e.g., compare to Covault and Romans, 2009; Covault et al., 2016; Shanmugam, 2016). Some researchers have interpreted tunnel valleys to be fluvial even if glaciers have been close by (Keller et al., 2011).

Pleistocene tunnel valleys are somewhat more outstanding than more ancient “tunnel valleys,” up to 100 km long, 400 m deep and 5 km wide, but most common is c. 10 km, 100 m and 1.5 km, respectively, displaying a typical width/depth ratio around 10 (Vesely et al., 2021). While van der Vegt et al. (2012) mix descriptions of Ordovician “tunnel valleys” and Pleistocene tunnel valleys, cross-sections indicate that the Ordovician examples commonly are wider and not as deep. Furthermore, there are no intra-formal striated pavements in the Pleistocene, but these are common in the Ordovician tunnel valley sediments. Pleistocene tunnel valleys are better preserved but also display more of an appearance of a valley than pre-Pleistocene examples (Vesely et al., 2021, their Fig. 13).

The control of the distribution of Ordovician tunnel valleys may partly be from the existence of older crustal lineaments, and the valleys are bounded by faulted and/or folded zones (Ghienne et al., 2003; Le Heron et al., 2006), which may add a tectonic component to their origin. Keller et al. (2011) wrote: “The genesis of these tunnel (?) valleys is still a matter of debate.” Le Heron et al. (2018a) wrote that there is an absence “of suitable modern analogues” to these tunnel valleys, even though they tried to solve the problem.

2.12.3. Raised channels, eskers and tunnel valleys

Except for the linear non-glacial landforms described in previous sections, there are more than 100 areas displaying inverted stream channels, i.e. wadis or other fluvial channels, which have been exhumed and stand out as long positive ridges (Zaki et al., 2021). These are present on almost all continents, from the Silurian until the Holocene, and these may be compared to Ordovician raised channels/eskers/tunnel valleys which are interpreted to be glaciogenic (Maizels, 1990a, 1990b; Zaki and Giegengack, 2016; Zaki et al. 2018, 2020, 2021). In Egypt, there are more than 7000 sinuous ridges, across ~40 000 km^2, up to 18 km in length, up to a few hundred meters in width and up to 33 m high, which are commonly interpreted to be inverted wadis (Zaki and Giegengack, 2016; Giegengack and Zaki, 2017; Zaki et al., 2018, 2020). In different areas, ridges may be up to approximately 500 km long, the heights may be more than 40 m and the widths up to 4 km (Zaki et al., 2021). Such raised channels could easily be mistaken for eskers or tunnel valleys, especially if they would not show up clearly in stratigraphic sections. In the Plio-Pleistocene sediments of Oman, there is a complicated network of many generations of raised channel systems, but also many deeply buried, some of which have been labeled with the term “pseudo-esker” (Maizels, 1990a, 1990b). These are up to 250 km long, in some places more than 2 km wide, but commonly <30 m in height, and they display similarities to the Ordovician “tunnel valleys” in shape, length and composition (compare Maizels, 1990a, 1990b, to e.g., Vesely et al., 2021).

In conclusion, there is a suggested similarity of pre-Pleistocene tunnel valleys and eskers to non-glacial channels, and a suggested difference to Pleistocene tunnel valleys and eskers.

2.13. Dropstones

2.13.1. Dropstones, similarities

Dropstones are often assumed as prime evidence for glaciation, with the consequence that cold climates have been interpreted for many areas. For example, Rodríguez-López et al. (2016) interpreted lonestones in Cretaceous sediments as dropstones, even though there is no other demanding evidence for glaciation. Similarly, Frakes and Krassay (1992) interpreted lonestones in Jurassic and Cretaceous fine grained sediments as probably glaciogenic dropstones, because there was a shortage of fossil driftwood in the strata. However, Donovan and Pickerill (1997, 2008) considered lonestones in the early Cenozoic of Jamaica as non-glaciogenic, as there was no evidence or possibility for glaciation at that place and time. And Doublet and Garcia (2004) interpreted dropstones from Mesozoic sediments in Spain as dropped from floating trees. LPIA dropstones in Argentina had dropped as rock fall from steep valley walls (Moxness et al., 2018).

Many different parameters are important for the appearance of clast penetration and sediment disturbance during impact. These parameters include water depth, properties of the bottom sediment, clast size and shape (Bronikowska et al., 2021), whether clasts are frozen to ice during sinking, simultaneous deposition of sediment by flowing water, and if the sediments are reworked by SGFs. Small dropstones, approximately a cm in size or smaller, may not produce much structures in bottom sediments (Bronikowska et al., 2021). Even if there are many unknowns, there are criteria which may help to determine if a lonestone has been dropped or has been transported by a SGF (see below).

Any violent disturbance of the environment, like glaciation, earthquakes, mass movements, tsunamis, and even larger storms, may induce scenarios that transport clasts which may display an appearance of dropstones (Tachibana, 2013; see also Shanmugam, 2012). Recent tsunamis have documented runups up to 524 meter above sea level, i.e. in 1958 in Alaska (Paris et al., 2018). Clasts can also be transported in water by biological rafting, as projectiles, and occasionally by floatation or strong whirlwinds (Liu and Gastaldo, 1992; Oberbeck et al., 1993a; Bennett et al., 1994, 1996; de Lange et al., 2008; Bronikowska et al., 2021). Deposition of all these clasts may display an appearance similar to glaciogenic dropstones, like compaction of sediment both during deposition and later because of dewatering and/or compression from superimposed sediments.

Iceberg dump mounds are accumulations of clasts dropped when icebergs overturn and release lots of material at once. These may be sorted, from the sinking of the sediments through the water column, may be conical or display different patterns of irregular outlines and different penetration of the underlying sediment (Thomas and Connell, 1985; Pisarska-Jamroży et al., 2018; Bronikowska et al., 2021). However, Aitken (1993) showed the mounds documented by Thomas and Connell (1985) to be small subaqueous fans and debris flows, even if they are in an area where there is deposition from icebergs. Another accumulation of sediments, labeled “till pellets,” can be found smeared out as if they have been molded by the overlying sediment (Miall, 1983; Visser, 1983a). Clast accumulations may be produced in any flowing media.

2.13.1.1. Transport by sediment gravity flows

Clasts transported with SGFs are often embedded in a clayey matrix (Bouma, 1964; Embley, 1982). Single clasts, up to 20 meter in diameter (Shanmugam, 2016, 2021b), or clusters of clasts can be dragged along, slide on top of a sedimentary mass flow sequence, move upwards through the flow, or be winnowed out, and be deposited at different depths of a sedimentary sequence during single events (Postma et al., 1988; Scott, 1988b; Best, 1992; Pickering and Hiscott, 2015; Shanmugam, 2020, 2021b; Kennedy and Eyles, 2021). These clasts may display an appearance similar to clasts transported by icebergs, i.e. these are "left-overs" or lonestones, or "dumps" (Crowell, 1957, 1964; Schermerhorn, 1974a; Kim et al., 1995). Transport of lonestones by SGF deposits can be determined by fabric analyses (section 2.2.9).

In lahar deposits in Utah the clasts are often locally concentrated in clots high up in the sedimentary beds (Walton and Palmer, 1988), thus showing similarities with "iceberg roll dumps" (e.g., in the LPIA of Tasmania; Powell, 1990). Clasts with diameters of up to 15 cm had been transported more than 400 km, probably by water currents and/or SGFs. After deposition, the clasts became incorporated in SGFs. These clasts were earlier thought to have been transported with icebergs (Jansa and Carozzi, 1970).

2.13.1.2. Transport by vegetation, animals and floatation

Especially during a catastrophe (e.g., a tsunami) much material can be transported with up-rooted trees. In Carboniferous coal seams, boulders with weights up to 70 kg are present (Price, 1932; Woolfe, 1994). Boulders in Cretaceous and Carboniferous sediments have been transported up to 100 km or more, by floating with plants (Hawkes, 1943; Liu and Gastaldo, 1992). Boulders transported with contemporary tree roots have sizes up to 3 m (Bennett et al, 1996). Fossils of land-living plants are present from the Ordovician, even if their affinities are largely unknown (Servais et al., 2019).

Clasts dropped from kelp or vegetation may not display any differences to those dropped from icebergs (Doublet and Garcia, 2004). Probably hundreds of thousands of kelp rafts are transporting attached clasts of "dropstones-to-be" today in the Southern Ocean alone (Waters and Craw, 2017), and ancient transport with kelp or other algae is documented (Bennett et al., 1994; Zalasiewicz and Taylor, 2001). Species of green and red algae may float on the water surface (Thiel and Gutow, 2005). Red algae are present in the Precambrian (1.6 billion years, Bengtson et al., 2017; 1.0 billion years, Gibson et al., 2018) and in Ordovician sediments (Fry, 1983), but these are commonly smaller species which could not transport larger clasts than maybe a few centimeters. Unspecified macroalgae (incomplete specimens >2 cm in length which are small parts of much larger algae) are present in close connection to "glacial" diamictites in the Neoproterozoic (Ye et al., 2015; Chen et al., 2015). Green algae are known from the Cambrian (Servais et al., 2019), but their origin may be placed in the Meso- or Neoproterozoic (Del Cortona et al., 2020). Kelp, which commonly refers to brown algae, are considered to have diverged some 100 million years ago (Silberfeld et al., 2010), and most larger forms maybe not until 25 million years ago (Rothman et al., 2017), even if some Precambrian to Jurassic fossils are classified as possible brown algae (Hollick, 1930; Fry, 1983; Zalasiewicz and Taylor, 2001; Silberfeld et al., 2010). Kelp transports much sediment onto beaches, including veneers of clasts, over distances of 5000 km, in sizes commonly up to 83 kg, and a record estimated weight of a large clast of 365 kg (Emery and Tschudy, 1941; Garden and Smith, 2011).

Microbial mats occasionally are lifted from the bottom surface and may transport clasts, sand clusters and clay fragments which are up to several cm long (Schieber, 1999; Thiel and Gutow, 2005). Pebbles up to 25 mm in length, can in rare instances float directly on the surface of the sea surface (Hume, 1963; Bennett et al., 1996). Gastroliths with weights up to 2.5 kg, and clusters of gastroliths up to 70 kg. had been recorded from sedimentary sequences (Bennett et al., 1996). However, the appearance of gastroliths, commonly displaying a "polished" rounded form, in most cases would be easy to sort out from dropstones.

2.13.3. Dropstones, differences

The amount of material which has been dropped by ice in Quaternary sedimentary deposits may be "astounding" over extensive areas and can even create "pathways"of dropstones (Korstgärd and Nielsen, 1989; Dionne, 1993; Pisarska-Jamroży et al., 2018), but pre-Pleistocene rafted material commonly is dispersed. Marine sedimentation from a large glacier would be more uniform over wider areas than deposition from SGFs (Clark and Hanson, 1983; Boulton, 1990).

Ancient dropstone-bearing strata often are deposited as blanketing layers on top of "tillites," similar to turbidity deposits (compare, e.g., Talling et al., 2007; Shanmugam, 2016; Molén, 2017, 2021; Rampino, 2017). The sediments commonly are not present close to the outermost border of diamictites, or in bowls in the upper surface of the "tillite," where marine, brackish and lake sediments usually are deposited (Deynoux, 1985b).

Thomas and Connell (1985) documented data and developed criteria for recognition of dropstones from a Pleistocene lake in Scotland, and these were further developed mainly by theoretical numerical process modeling by Bronikowska et al. (2021). The list below describes the most common features, and these are also those that are not commonly present in SGF deposits. The difference between the appearance of dropstones documented by Thomas and Connell (1985), in SGF deposits, and those in pre-Pleistocene strata, are mentioned in the comments.

a) Penetration of dropstones 5-20 cm in diameter is commonly about 1/3 of the clast size, but 2/3 if clasts display close to vertical orientation and are thin. Larger clasts penetrate more (Bronikowska et al., 2021). However, it is difficult to state anything conclusively concerning the magnitude of crushing and depressions in underlying laminae, because the firmness of the bottom sediments vary from hard to soft (Bronikowska et al., 2021).

Comment 1: Clasts transported by SGFs may not penetrate laminae. Laminae below clasts are almost always bent just by the compaction of the sediments, but sharp rocks commonly penetrate. Single penetrations of laminae are always to be expected for SGFs. Some reef blocks transported by mass flows are interpreted to have sunk down >1 m into underlying soft sediments (Rigby, 1958).

Comment 2: Dropstones in ancient diamictites do not usually cut through underlying laminae (Fig. 6), although a few authors report evidence of penetration (Binda and van Eden, 1972; Smith and Eriksson, 1979; Mustard and Donaldson, 1987a), and laminae that are not penetrated are not diagnostic of a dropstone origin (Thomas and Connell, 1985). Published photos and descriptions of ancient dropstones generally show that laminae have been bent around the clasts or slightly pressed down, not commonly cut or crushed (even if photos of such features are often chosen for publication, e.g., Molén, 2021), even though the clasts may be c. 0.6 m in diameter (Schenk, 1965; Visser and Kingsley, 1982; Gravenor et al., 1984; Kim et al., 1995; Craddock et al., 2019; Isbell et al., 2021; Table S3). The sediments thin out around clasts, both above and below, and the sediments are actually draping the clasts, which is what could be expected from SGFs (Dey et al., 2020; Molén, 2021). In some areas clast are “locally very abundant along bedding planes” (Kneller et al., 2004).

b) Variable clast size.

Comment 1: Clasts may be sorted in SGF deposits. In the Gowganda Formation dropstones are more common in coarse grained than in fine grained rhythmites (Mustard and Donaldson, 1987a).

Comment 2: Dropstones which have been transported by sea ice or vegetation will usually have a smaller size and better sorting and roundness than those which have been transported by glacier ice, the latter which may be up to 10 m in diameter (Gilbert, 1990). Diameters of Quaternary glaciogenic dropstones of diameters 0.5 m and larger are not uncommon (Dionne, 1993; Meyer et al., 2016; Pisarska-Jamroży et al., 2018; Bronikowska et al., 2021). The maximum size of “left-overs” in SGFs should in general be smaller than dropstones (Clark and Hanson, 1983; Peakall et al., 2020), but as already documented (section 2.3.) the "erratics" in "tillites" are smaller than those in tills, and it is therefore necessary to compare relative sizes (Molén, 2021). While single supposed dropstones in pre-Pleistocene sediments may be up to 3 m in diameter (Rodríguez-López et al., 2016), and clasts many meters in size that are interpreted to be dropstones are present in massive debris flows or slides (Domack and Hoffman, 2011), pre-Pleistocene dropstones commonly are much smaller. As examples, dropstones in the Neoproterozoic outcrops are mostly pebble-sized (Schermerhorn, 1977) as opposed to common meter-sized dropstones of Precambrian affinity in Pleistocene and Holocene deposits (Dionne, 1993). In the Dwyka Group in South Africa dropstones are often only 2-5 cm, but may rarely be up to one meter across (Visser, 1982, 1983b), and in massive "glaciomarine" diamictites they may be a few meters (Haldorsen et al., 2001). Le Heron et al. (2017) mentioned "unequivocal" evidence for ice rafting, from the Neoproterozoic of Death Valley, but pictured dropstones were solely 2-3 cm in diameter and displaying only limited penetration, as would also be expected from lonestones. Maslov (2010) mentioned dropstones of sizes "up to 2 cm" in Paleoproterozoic sediments. It may be suspected that very small dropstones, with a diameter of only a few cm or smaller, will not penetrate much into sediments (Bronikowska et al. 2021), but in SGFs even the smallest clasts likely will disturb the laminations.

c) Most clasts are oversized.

Comment: In SGF deposits it is common that the clasts have a similar size or are smaller than the sediment beds within where they are buried. (Fig. 6, Table S3.)

d) No correlation between the size of clasts and thicknesses of beds.

Comment: SGF deposits may display correlation. (Fig. 6, Table S3.) In ancient "glaciogenic" deposits larger dropstones are often present in thicker layers, which suggest that they have been transported by SGFs (McCann and Kennedy, 1974, plate 2; Martin et al., 1985; Mustard and Donaldson, 1987a; Moncrieff and Hambrey, 1990, their Fig. 6C; Molén, 2021).

e) Fabrics – only measured on 50 clasts (Thomas and Connell, 1985). Clast orientation seldom subparallel to stratification (4%), more often inclined (46%), but most are subvertical (50%).

Comment: Fabrics variable in SGF deposits, but planar fabrics and vertical clasts are not uncommon. (Section 2.2.9. Also, see planar fabrics for outsized clasts and “dropstones” in Lindsay et al., 1970; Kim et al., 1995.)

f) No current indicators.

Comment 1: In a laminated or rhythmic sediment section, any horizontal movement in the bottom sediments may result in disturbances around clasts. Evidence of movements may indicate that the deposition was not slow, i.e. not within an environment displaying more or less stagnant bottom water. Clasts which are transported within SGFs, whether the sediments will be deposited as laminations or not, may show both external and internal (within the sediment) structures indicating horizontal movement. (Fig. 6.)

Comment 2: There are often lee side structures connected with pre-Pleistocene “dropstones” (Lindsey, 1969; Ovenshine, 1970; Visser, 1983a; Aitken, 1991; Molén, 2017, 2021). In the Middle Permian of Australia brachiopod fossils are present on the lee sides of oversized clasts which are interpreted to be dropstones (Yang et al., 2018). In places the sediment has been pushed up in front of a dropstone, without any evidence of penetration of underlying beds, as if the clast has been moved along in a SGF (Mustard and Donaldson, 1987a, their Fig. 6G; Molén, 2017, 2021).

g) Sediment around clasts are commonly rucked (pushed up on both sides, commonly sharp folds), ruptured (lamination in sediment next to, below and/or above clast is broken and mixed) and/or onlapped (covering sediment next to clasts not draped around the clast, but stops at the clast, except for those laminae that cover the clast).

Comment: Draping is prevalent if clasts are transported by SGFs. Draping of clast may display laminae that commonly are covering the clasts on all sides, but the thickness of the sediments may change next to the clast. Some laminae may thicken next to the clasts, others may thin out. Some may only stop at the clast. Commonly there are not many sharp sedimentary structures around clasts transported by SGFs. Laminae may become diffuse or split into more laminae, reflecting wake eddies (compare to Kim et al., 1995). (Fig. 6.)

Table S3 (Supplementary material) document dropstones which display features which are more compatible with transport by SGFs than to dropping from ice.

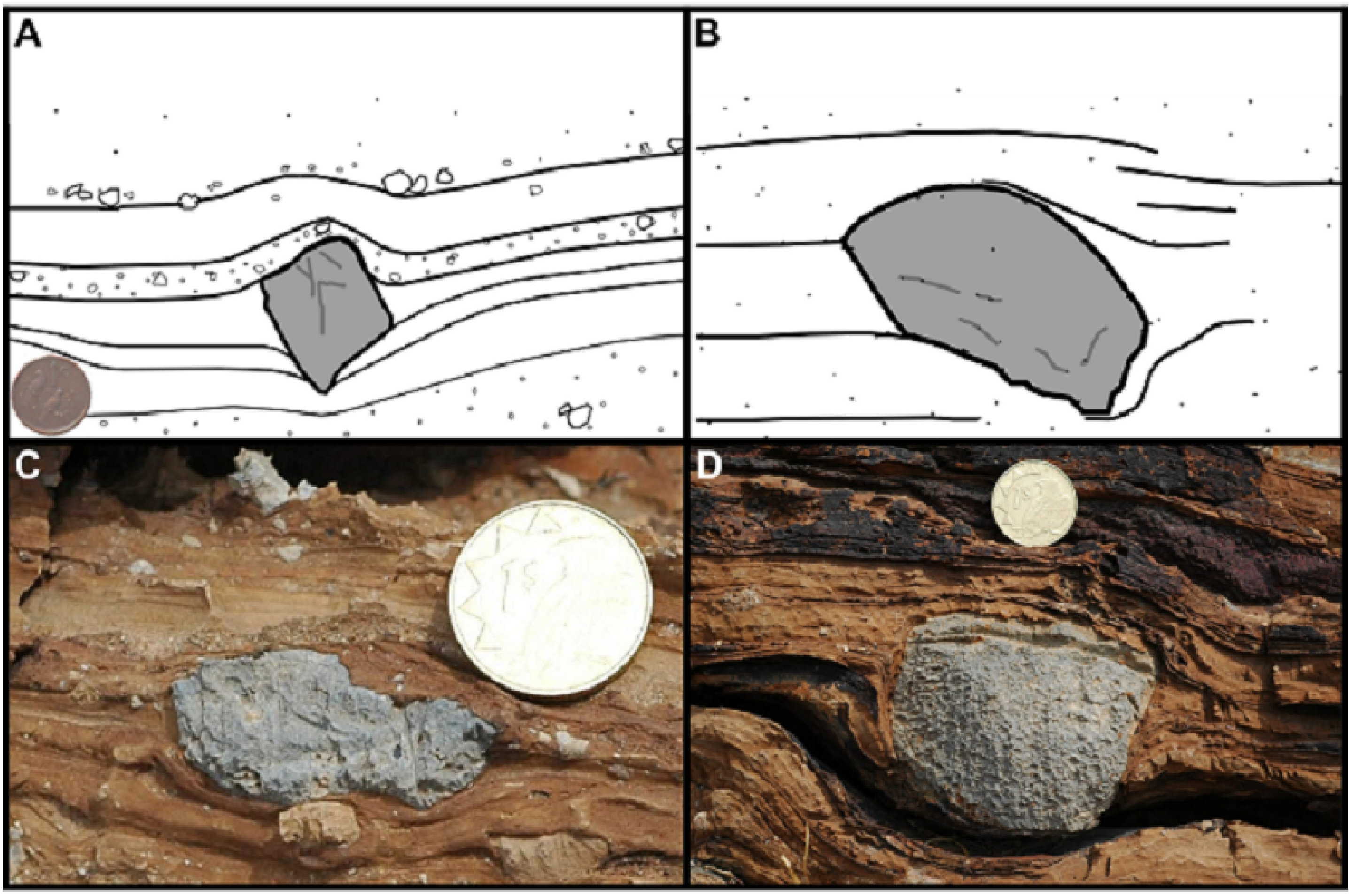

Fig. 6. Clasts which have been interpreted as dropstones from the Ghaub and Chuos Formations of Namibia. The irregularities and appearances displayed in the beds next to the clasts indicate currents and a SGF origin. If clasts as small as these would have been dropped from ice, they may not have disturbed the sediment much at all (Bronikowska et al., 2021). In general, the appearances displayed in these pictures are common in ancient "glaciogenic" sediments, but different from Quaternary dropstone bearing sections. A. The bed containing the clast becomes thicker next to the clast on both sides. There may be penetration of strata, but even if the clast is pointy it appears more that the sediment is slightly bent because of

compression during transport and therefore thins out beneath the clast. (Drawing after Hoffman www.geol.umd.edu/~jmerck/geol342/lectures/06.html). B. There is a small "impact" structure to right of the clast, but nothing on the left side. Laminae on the left are straight. To the right, the beds above the clast bend down over the clast. The appearance is one of diffuse wake eddies on the right side of the clast. Clast is c. 1.5 cm in length. (Drawing after Le Heron et al., 2021a.) C. The sediment bed becomes thicker next to the clast. The clast is regularly enclosed by sediment above and below. This is the most common appearance of pre-Pleistocene clasts interpreted to be dropstones. D. This clast is inside a thicker sediment bed. The bed thickens next to the clast, which is especially evident on the right side of the clast where the sediment surface enclosing the clast is at a lower level than on the left side. To the left, both the bedding and the underlying sediment are bent, as would be the case if the clast was transported in that direction enclosed in a SGF. It can be discussed if there is much evidence of penetration, or if the sediments mostly thin out beneath the clast. (Photographs by T. Bechstädt; Bechstädt et al., 2018.)

2.14. Laminated sediments

"Varved sediments" (laminated beds) which may be interpreted as deposited on a yearly basis can form instantaneously by SGFs, including hyperpycnal flows, and also from contour currents (the latter commonly move with speeds up to 3 m/s, and including cyclone driven bottom flows with velocities of up to 70 m/s), in many different environments (Kuenen, 1964; Pettijohn and Potter, 1964; Winterer, 1964; McKee et al., 1967; Lowe, 1982, 1988; Gravenor and Rocha-Campos, 1983; Domack, 1990; Dykstra, 2012; Zavala and Arcuri, 2016; Yawar and Schieber, 2017; Shanmugam, 2017a, 2021a; Tedesco et al., 2020; Isbell et al., 2021; Tian et al., 2021). There are criteria for distinguishing yearly varves from surge laminae, and also other rhythms, even though these criteria are not clear cut (Smith and Ashley, 1985), and there is a vigorous debate in this area (e.g., Andrews et al., 2018; Smith and Bailey, 2018a, 2018b; Da Silva et al., 2019; Matys Grygar, 2019; Smith, 2019). Marine couplets, with affinities to annual lacustrine varves, often form in response to tidal water if there is an abundance of suspended sediment available, and may display double mud layers (Cowan and Powell, 1990; Smith et al., 1990; Shanmugam, 2016, 2017a, 2021a, 2021b). A recorded maximum of 1000 couplets have been deposited in three to four years time (Molnia, 1983b). In connection to the variation in differences in sedimentation in general, Shanmugam (2017a) concluded that “the grand ingrained principle of 'one deposit for one flow type' is nothing more than a misplaced optimism.”

In pre-Pleistocene “glacial” deposits many rhythmites with an appearance of yearly varves occur in what must have been marine settings (Schermerhorn, 1977). Annual varves can only form in fresh water, for example in a lake or perhaps sometimes on a shallow shelf where an abundance of meltwater is constantly draining from a large glacier. Experiments show that clay flocculates and will deposit as quickly as sand, if there is no stirring (Schieber et al., 2007, 2013; Sutherland et al., 2015), and thin silt/clay laminae which are often interpreted to be yearly varves are deposited simultaneously in both fresh and salt water (Yawar and Schieber, 2017). The only known marine rhythmites form in response to tidal water (Cowan and Powell, 1990), or originate by turbidity currents.

Pre-Pleistocene rhythmite sequences may exhibit features not shown by yearly varves. “Varves” in the Gowganda Formation may be very finely laminated as opposite to more thickly laminated Pleistocene yearly varves (Molén, 2021). They have been reinterpreted as non-annual (because of the rhythmite pattern) “distal” turbidites and may contain ripple marks (Jackson, 1965; Miall, 1983, 1985; Eyles et al., 1985; Smith and Bailey, 2018b). Rhythmites next to Precambrian “tillites” in the Appalachian mountains, and in the Gowganda Formation, have been put into question because the “winter layers” are thicker than the “summer layers” (Schwab, 1981; Molén, 2021), as this appearance is the opposite of normal varve deposition, but may be possible in rare instances if produced during glaciation. In the LPIA Dwyka Group of South Africa this is a common appearance (Tavener-Smith and Mason, 1983). Rhythmites in the Dwyka Group have been reinterpreted to be deposited from turbidites or tidal activity (Isbell et al., 2008), and LPIA “varves” in Brazil are no longer considered to be annual (Kochhann et al., 2020)..

2.15. Glaciomarine (and lake) diamictites

There is an astounding number and a great diversity of submarine glacial features, linear, transverse and irregular, covering large areas, which have been produced by glaciers, from the Pleistocene until today (Dowdeswell et al., 2016a, 2016b). In glaciomarine sediments there would be grounding zones displaying pushed up transverse till and sea-bottom mud ridges, as well as different kinds of subglacial, englacial and supraglacial submarine fans where the upflow part of the deposits shows evidence of having been bordered by an ice-shelf or a glacier (Boulton, 1990; Powell, 1990; Zecchin et al., 2015). There is nothing remotely similar to this in the pre-Pleistocene record. There is either no record at all of similar features, the features are different than those in the Quaternary record, or there are only single examples where it would be expected to be large areas covered by similar features (Molén, 2021). And, there are no reports of observational evidence of removal of material by erosion of large areas of former subaqueous glaciogenic features, i.e. erosion of areas which would be more protected than terrestrial environments.

In pre-Pleistocene glaciomarine deposits, almost the only evidence given for glaciation is dropstones, especially if the clasts are found in rhythmites (Frakes et al., 1969; Binda and Eden, 1972; McCann and Kennedy, 1974; Anderson, 1983; Miall, 1983, 1985; Visser 1989a). But, if there are marine or lacustrine fossils close to or within sediments that are interpreted to be glaciogenic, interpretations should be regarded as tentative. As mentioned earlier c. 95%

of ancient “glaciogenic” deposits are interpreted to be marine (section 1.3.), and there are often marine fossils close to or even (autochthonously) within such diamictites (e.g., Allen, 1975; Bryan, 1983; González and Glasser, 2008; Caputo and Santos, 2020, Sterren et al., 2021; López-Gamundí et al., 2021). Marine fossils also are common in cyclone and tsunami deposits, which may trigger mass flows (Shanmugam, 2012).

Neoproterozoic “tillites” usually are not bordered by marine till and a wide zone of ice-rafted material (Schermerhorn, 1977). Diamictites in general are draped with shale or rhythmites with lonestones (e.g., Rampino, 2017; Molén, 2017, 2021; López-Gamundí et al., 2021). A submarine subglacial fan has been inferred from the Carboniferous of Tasmania, but with no diagnostic ice-contact features present (Powell, 1990). None of the other geological features have been clearly identified with diagnostic geologic features from any ancient deposit, but some features may be interpreted from commonly more restricted sedimentary assemblages to try to integrate the data into a glaciogenic framework (e.g., Aquino et al., 2016; Rosa et el., 2019; Dietrich and Hofmann, 2019).

2.16. Periglacial structures

Periglacial look-alike structures, with the appearance of e.g. ice-wedges, can form by processes other than freezing and thawing, for example, wetting and drying, thermal contraction, sedimentary compaction, gravitational loading, small scale tectonics, flexure over an uneven surface, and almost any volume change in sediments (Yehle, 1954; Flint, 1961; Schermerhorn, 1974a; Black, 1976; Walters, 1978; Eyles and Clark, 1985; Shanmugam, 2012; Robinson et al., 2017). In tropical waters, polygons originate by infilling of sediment from above, in fractures that form during cementation (SEPM, 2021). Sheeting joints in sandstones may display polygonal structures over large areas (Loope and Burberry, 2018).

Ice-wedges are normally filled with material from above and polygons frequently show stony margins (Frakes, 1979). This is not shown by pre-Pleistocene “permafrost” deposits. In Pleistocene to Holocene polygonal ice-wedge networks (or casts), polygon diameters may be between 1-46 m, wedge depth 0.25-50 m, and wedge width 0.1-10 m, while the same structures in the Neoproterozoic Port Askaig Formation were 0.35-1.5 m, 0.09-1.12 m and 0.05-0.3 m, respectively (Eyles and Clark, 1985). The latter was explained as non-glacial and interpreted to have been generated by gravitational downfolding, and similar structures are widely reported in shallow marine sequences (Fig. 7).

Clastic dykes have been documented in, for example, the Gowganda Formation in Canada (Young, 1981b) and the Dwyka Group in South Africa (Visser and Loock, 1982; Visser et al., 1987). “Ice wedges” from the Ordovician “glacial” in the Sahara likely are sandstone dykes radiating from sand volcanoes (Fairbridge, 1970; Bryan, 1983), and some sandstone dykes have been documented to cross each other with an appearance of polygons (Allen, 1975; Deynoux, 1985a). There are sandstone dykes also in, for example, the Neoproterozoic Port Askaig “tillites” in Scotland (Eyles and Clark, 1985) and the probable non-glacial diamictites in France (Eyles, 1990), and these have been interpreted as ice-wedges (Hambrey, 1983).

In the Ordovician of Sahara there are up to 1 km long domes which had been interpreted as pingos (Bryan, 1983). Further research showed that these structures are tectonically uplifted diapiric structures in soft sediments, from vertical loading or maybe from upwelling basalts (Fairbridge, 1971, 1979; Le Blanc Smith and Eriksson, 1979; Le Heron et al., 2005).

Other features which are present in periglacial sedimentary sequences are solifluction debris, loess, cover sands, ventifacted clasts, slope wash accumulations, frost shattered clasts, vertically aligned clasts, and size-sorting (Eyles and Clark, 1985), which are commonly not reported from the pre-Pleistocene.

On the whole it seems that “periglacial” structures are quite rare in pre-Pleistocene “tillites.” Instead, structures that mimic periglacial structures seem to be common, for example clastic or sandstone dykes formed by loading (Eyles and Clark, 1985). Dykes may be present below Quaternary tills but are not very common.

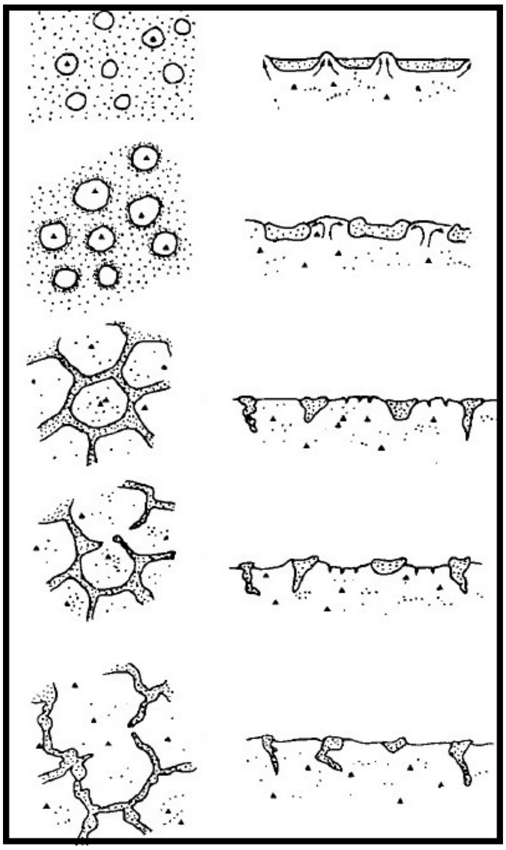

Fig. 7. The figure shows how loading and diapirism in sand have created polygonal patterns, superficially similar to permafrost polygons. Uppermost two pictures show diapirism and the lower three show the appearance after erosion. (Figure from: Eyles and Clark, B.M., 1985. Gravity induced soft sediment deformation in glaciomarine sequences of the Upper Proterozoic Port Askaig Formation, Scotland. Sedimentology 32, 789-814.)

2.17. Soft sediment deformation, tectonism

In both glaciogenic and mass flow environments there are soft sediment tectonic deformation, both compressional and tensional (Sobiesiak et al., 2018). There are no simple specified criteria used to distinguish different environments from each other. Ancient deposits have commonly not been compared to data from Quaternary proved non-glaciogenic and glaciogenic sediments (Visser et al., 1984; Hart and Roberts, 1994; McCarroll and Rijsdijk, 2003), and the structures may be present in different sedimentary environments (Arnaud, 2012). Dreimanis (1993) listed eight glaciotectonic structures, and wrote that most of them may be found in mass flow deposits. He concluded that it would be best to use multiple stress-related criteria, including e.g., glacial abrasion marks over an area of several hundred meters, to track down the origin of the deposit. Only conjugate sets of steep-dipping fractures are stated to be more common in glaciotectonic deposits (Dreimanis, 1993).

A SGF origin may be more probable if there are (Visser et al., 1984; Dreimanis, 1993; Sobiesiak et al., 2018):

a) tensional and compressional stress regimes in one single horizon,

b) presence of dewatering structures,

c) restriction of deformation to specific lithologies (even leaving other beds above and below intact and without deformation),

d) intimate association with mass flow deposits,

e) random orientation of microfold axes,

f) sheared sediment lenses that usually are curved or bent in different ways,

g) overturned recumbent flows which usually do not have their anticlines sheared off, and/or are occasionally flattened at their base, and/or have a bulbous terminus often pointing in the downflow direction,

h) extension fractures which are filled by dykes that are localized on the distal side of the deposit and are accompanied by normal faults.

Some of the structures tabulated above are also present in tills and are interpreted as evidence of glaciotectonic deformation, e.g., dewatering structures (Dreimanis, 1993).

Any mass flow which loses its velocity and comes to a stop will display both compressional and tensional regimes, except if it all stops as one large slab. If it is glaciotectonic there should commonly be more similar tectonism all through the sediments (e.g., Bennett et al., 2003), but occasionally more at the top parts of the deposits compared to the bottom.

Soft sediment deformation in diamictites in the LPIA of Brazil were interpreted to be glaciotectonically formed (Rosa et al., 2019), but there was no unequivocal evidence of glaciotectonics compared to tectonics formed by mass flows. Other soft sediment tectonics in the LPIA of Brazil is interpreted to be from mass flows, even if there are postulated glaciers nearby (Mottin et al., 2018), and some glaciotectonic features had been reinterpreted as non-glacial (Rodrigues et al., 2020).

2.18. SEM studies

SEM studies of surface microtextures on quartz sand grains is a quick method to easily distinguish glaciogenic sediments from other sediments (Mahaney, 2002; Molén, 2014, 2017). Glaciogenic quartz sand grains are characterized by fresh fractures which have been irregularly abraded all over the grain surface (Molén, 2014). The processes of fracturing and abrasion may take place at the same instant, as it is grinding rather than impacting that creates the fractures. It is possible to follow how a glaciogenic grain, which later will be transported glaciofluvially, will be abraded so that the typical glaciogenic surface microtextures will slowly first change to microtextures similar to those present in rivers (Molén, 2014; Kalińska et al., 2022), and after that will continue to change depending on the environment of deposition.

Single surface microtextures produced by glaciers, like different varieties of fractures, may form in any environment (Mahaney, 2002; Molén, 2014, 2017). This is basic physics, as there is no difference from the impact of similar forces from different environments. Therefore, there needs to be a systematic combination of surface microtextures if the origin of a sediment is to be revealed. Subglacial transport is necessary if surface microtextures typical for a glacial environment shall be acquired. Supraglacial till and flow tills (if they never have been transported subglacially), and to a large part englacial till, will not acquire any or only very few surface microtextures typical for a subglacial environment (Kalińska et al., 2022). But as soon as a glacier processes rock material subglacially, glaciogenic surface microtextures form quickly. Supraglacial till, englacial till, and supraglacial flow till, are usually a minor part of glaciogenic sediments, and these sediments are often loosely packed and surficial and therefore easily removed by later erosion. This is in contrast to basal till. Periglacial environments also do not imprint glaciogenic surface microtextures on quartz sand grains (Kalińska-Nartiša et al., 2017).

Surface microtextures often stand out more on sand grains >250 µm. Smaller grains retain older surface microtextures more easily which may therefore be preserved from the original environment, instead of the grain displaying more evidence of the latest environment or transport history (Molén, 2014).

A method of sorting surface microtextures based on the appearance of the complete grain surfaces, and not a multitude of small scale surface microtextures which may originate in different environments, has been shown to be simple and quick (Molén 2014). The data is easily visualized in a “2-History-Diagram” (Fig. 8). This diagram shows both the last geological history and the former. The former may be e.g., the origin before release from bedrock, or glaciation followed by fluvial or eolian transport. The method is described in detail in Molén (2014) and is applied in Molén (2017) and Molén and Smit (2022).

Soreghan et al. (2014) and Keiser et al. (2015), by referring to occurrences of single small-scale surface microtextures, misidentified grains that commonly originate from release from bedrock (compare to Mahaney, 2002; Molén, 2014), and interpreted these grains to be glaciogenic. This led them to suggest a glaciation at the Upper Paleozoic paleoequator. Immonen (2013) did not show any glacially abraded grains but only regular abrasion originating from movement by water, on e.g., fractures. Hore et al. (2020) and Alley et al. (2020) only showed unabraded fractures (some with regular rounding made from fluvial action) as evidence for glaciation in the Cretaceous of Australia. Le Heron et al. (2020) showed small fractures from Ordovician and LPIA sediments, which have no relevance to glaciation. Kalińska-Nartiša et al. (2017), Passchier et al. (2021) and Kut et al. (2021) correctly identified surface microtextures as not glaciogenic, in periglacial/permafrost climate. Reahl et al. (2021) could differentiate out non-glaciogenic grains.

Some typical glaciogenic grains, and a few multicyclical grains, are displayed in Fig. 9. No other environment except the subglacial environment displays the combination of fresh irregularly abraded fractures. Based on more than 50 years of research (but commonly described in a more complicated, not so straightforward way), if the combination of fresh irregularly abraded fractures is not present, then the sediment is not glaciogenic. This combination of surface microtextures is displayed even by processing from a very thin probable only c. 10 m thick glacier (Molén, 2014). Multicyclical, beach and river sand grains display fewer and smaller fractures, regular abrasion and more weathering, when compared to glaciogenic quartz grains (Mahaney, 2002; Molén, 2014, 2017). Grains in high energy environments, where there is no grinding similar to that occurring at the bottom of glaciers, like in a rockfall, a conglomerate or a SGF, may acquire many fractures but not much abrasion, at least not irregular abrasion (Mahaney, 2002; Molén and Smit, 2022).

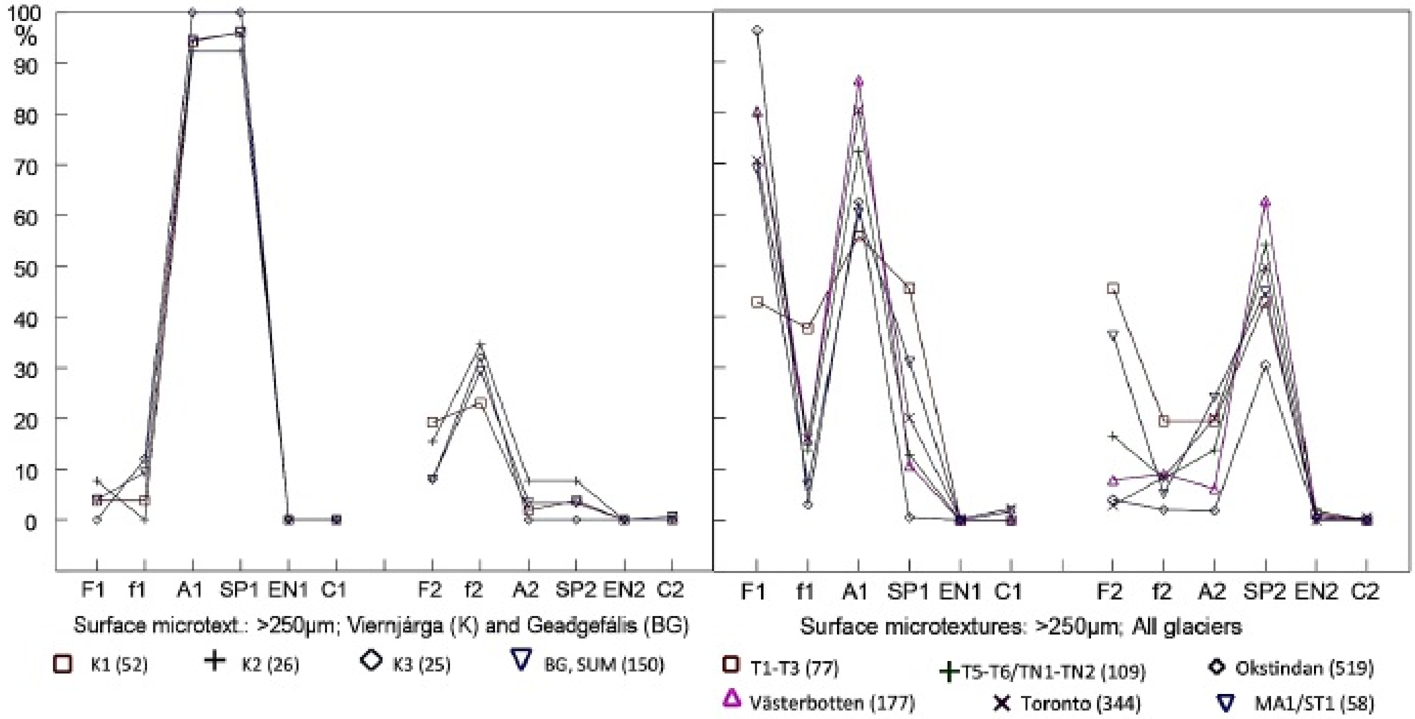

Fig. 8. A 2-History-Diagram displays a "geological signature" from the appearance of surface microtextures of quartz sand grains. The data is easily visualized, and the diagram is easy to construct. The left diagram show surface microtextures from multicyclical grains from a diamictite which commonly is interpreted to be glaciogenic (Neoproterozoic, northern Norway; Molén, 2017). Grains from this area display regular abrasion (similar all over the grain, whether the grain is round or angular in general shape) and weathering (A1 + SP1), and a few fractures, but no glacial surface microtextures (F1+A1) (Molén, 2017). The right diagram show data from Pleistocene and Neoglacial tills from Scandinavia and Ontario. T1-T3, T5-T6/TN1-TN2 and Okstindan are samples from small Neoglacial glaciers. Västerbotten (Sweden) and Toronto (Ontario) are samples from Pleistocene glaciers. MA1/ST1 are samples from Pleistocene tills in Ontario which were composed of >95% crushed limestone. The glaciogenic grains are easily identified by displaying fresh fractures which are irregularly abraded (F1+A1) (Molén, 2014).

F/f are large and small fractures, A is abrasion, EN are embayments/nodes where the grains were in contact with other bedrock material during cooling and crystallization, and C is chemically precipitated crystal surfaces. The number 1 displays the most recent surface microtextures, from the most recent geological process, and number 2 are older overlapped surface microtextures. Percentages are numbers of grains displaying the documented surface microtexture compared to the total number of grains in the samples.

The connecting lines in the diagrams are drawn only to enhance visibility, as described in Molén (2014). These lines are important, as they visually indicate the general trend of the different surface microtextures, up or down, and therefore also display an easily distinguishable "geological signature" of the appearance of each sample. Number of studied quartz sand grains are within parentheses. (Figure from: Molén, M.O., 2017.)

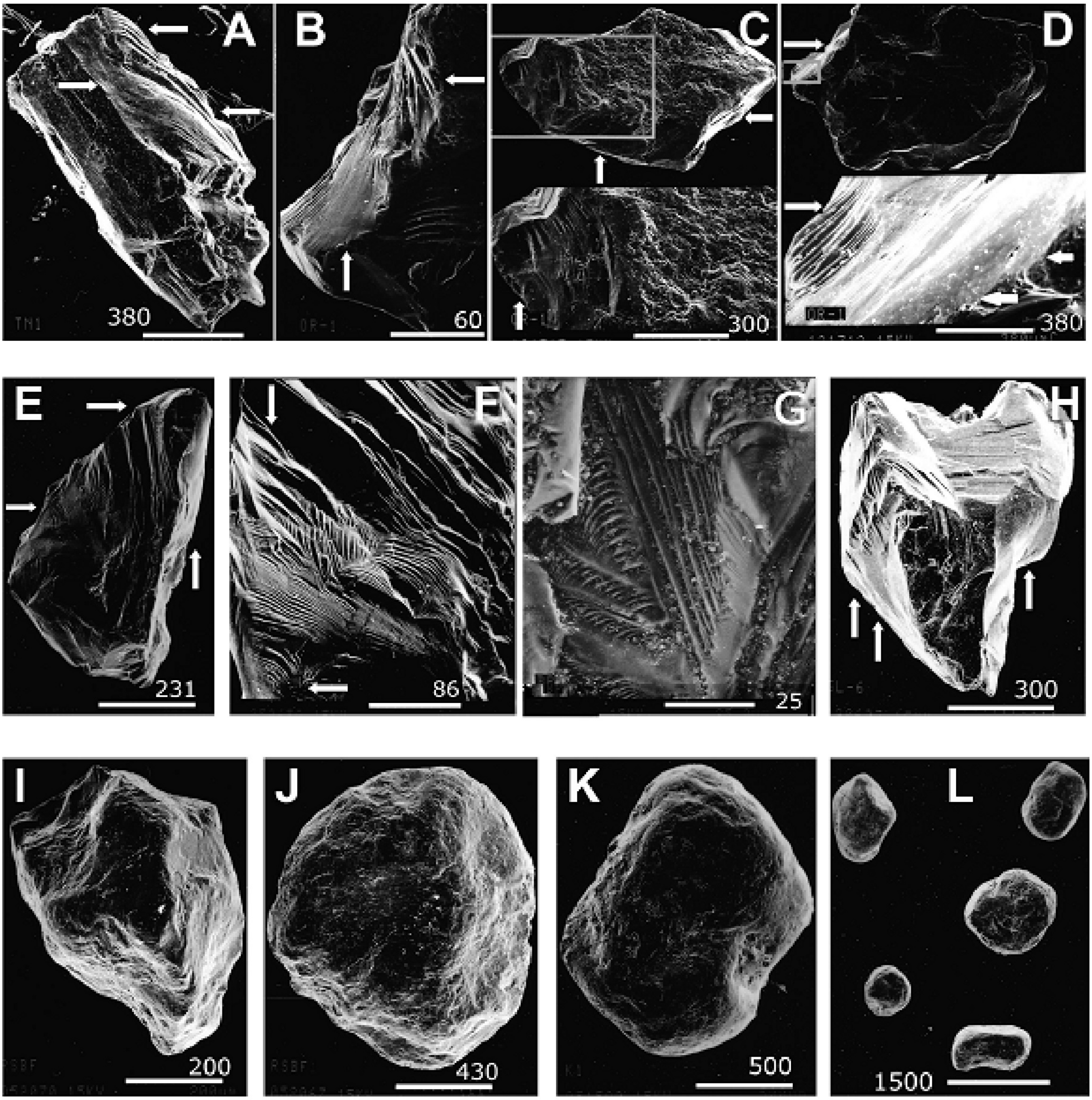

Fig. 9. SEM microphotographs of quartz sand grains from different environments. A is Neoglacial till and B-F are Pleistocene tills, Västerbotten county, Sweden. G-H are Pleistocene, Southern Ontario, Canada. I-L are multicyclical grains. Arrows point to fractures that have been irregularly abraded, i.e. typical for glaciogenic grains. A. Large fractures all over grain. On the upper surface all the fracture steps have been heavily abraded. B. Heavily fractured and abraded grain. The fracture steps on the light left surface have been abraded. C. Abrasion visible on fracture steps and in different parts of the grain surface. D. Large

fractures. Most abrasion shown in the insert, i.e. uneven abraded surface all over and fracture steps have been abraded. E. Multiple fractured grain. Many fractures are sharp, but irregular abrasion is present in many places all over the grain. F. Closeup of fracture faces displaying steps on grain E. Abrasion is best visible in lower left corner, but most other rounded surfaces are probably curved fractures. G. Closeup of spectacular fractures showing linear and curved steps. As this grain from a till is much magnified, only small areas displaying possible abrasion are visible. H. Multiple fractured grain. Many fractures are still sharp, but some have been heavily irregularly abraded. This is a short transported glaciofluvial quartz grain, and therefore the grain has not yet acquired regular abrasion typical for transport with running water. I-J. Grains displaying weathering and regular abrasion. Ordovician sandstone, Canada. K-L. Rounded grains displaying weathering and regular abrasion. These grains are from diamictites, formerly interpreted to be tillites, but the surface microtextures display the same appearance as multicyclical grains similar to e.g., the sandstone in Figs. 9 I-J. Neoproterozoic, Norway (Molén, 2017). (Scale bars are in µm.)

3. Discussion

A feature of dubious origin present in a “tillite” may be interpreted as evidence for a glaciogenic origin. This feature may later be used as evidence for a glacial origin for similar features in other deposits. Maybe it was a slip of the tongue when Deynoux and Trompette (1981a) wrote the following about some Upper Ordovician sandstones in Guinea that were correlated with the “glacial” sediments in the Sahara: “There is no evidence for the glacial origin of these sandstones.” Similarly, Moncrieff and Hambrey (1990) acknowledged Schermerhorn´s (1974a) criticism of the glaciogenic interpretation of Neoproterozoic diamictites, but wrote that the glacial origin of many of the deposits has since then been confirmed, referring to Hambrey and Harland (1981). What they did not observe was the differences between what was reported in this extensive review volume of pre-Pleistocene “glaciogenic” deposits and Pleistocene glaciogenic deposits, as reported here. Their own work (Moncrieff and Hambrey, 1990), concerning Neoproterozoic “glaciomarine” deposits in Greenland, showed that these outcrops did “... not have a suitable modern analogue.” They also suggested that ancient glaciomarine deposits, including from the Neoproterozoic in Greenland, should be used to aid the interpretation of recent sediments instead of the opposite. More bluntly, Dey et al. (2020) wrote concerning the Neoproterozoic Blaini Formation in India “... that the idea of its glacial origin is more a belief than a scientific interpretation.”

All this might end up as a philosophical problem. Actualism may be defined as the notion that physical natural laws do not change over time or space, or, uniformity of process (Gould 1987). Uniformitarianism (classical) is the notion that the rates and intensities of all processes have always been the same as today, or the same as during non-catastrophic conditions, and this concept is definitively falsified (Gould, 1987; Romano, 2015).

Instead of believing in uniformity of climatic changes (uniformitarianism), one should put stronger confidence in uniformity of physical natural laws and per se sedimentary processes (actualism). There is no natural law which states that the climate must have been cold and humid over large areas at many different occasions during earth history, just because there has been an ice-age quite recently. There is no evidence of uniformity of climatic change from the geological record even if it would be assumed that all “tillites” are glaciogenic or from theoretical considerations (the Milankovitch astronomical theory not withstanding, e.g., compare to Haldorsen et al., 2001). Bickert and Heinrich (2011) wrote “ ... we are far away from understanding the dynamics and processes of the Earth´s climatic change.” However, if the geological processes have changed during the ages (not only the rates or intensities), then also the natural laws must have changed.

The “exceptional” features which are frequently documented from ancient “glacial” periods and have been “pushed” into a glacial framework, indicate a need for a change of interpretations. The research which describe and explain processes from Quaternary glaciers and glaciations are invaluable, but they need to be accompanied by similar rigorous research of “tillites” and compare these to deposits resulting from SGFs and other non-glacial processes. Although some of the processes discussed in this paper have only been studied either in restricted areas or very rarely, we cannot reject explanations only on the basis of uniformitarianism. Many kinds of “catastrophes” have occurred, and the processes we have seen only on a local scale might on a number of occasions have been more widespread (Ager, 1981). But, there is no need for large catastrophes to explain the origin of diamictites, but only recent common processes and time.

It is essential to hold on to the basic concept that the recent is the key to the past, i.e. that the framework for scientific research should be actualism and not uniformitarianism. In the current paper the discussion has been concerning diamictites, glaciation and mass flows. In this context it is informative to quote researchers who have documented “missing” sediments:
a) By comparing ancient slides to Quaternary slides, Woodcock (1979) wrote “... where are the analogues of the larger continental margin slides in the ancient record?” (...) and “... submarine slides described from present day continental margins are on average several orders of magnitude larger in cross-sectional area than submarine slides described from ancient on-land sequences.” There are marine sediments covering large areas of recent cratonic land surfaces, and there is no reason that there should have been large differences in the appearance of submarine slides during ancient transgressions.
b) Concerning the similarities of geological features which may originate by impacts followed by earthquakes and tsunamis and those in “tillites” (even if the interpretation of impacts was overstated initially) Oberbeck et al. (1993a) wrote: “How do ancient glacial deposits become preserved, while expected impact crater deposits equal to the thickest of the ancient tillites

(and with the same appearance as tillites) become removed without a trace?”
c) Shanmugam (2016) noted that “... the long-standing belief that submarine fans are composed of turbidites, in particular, of gravelly and sandy high-density turbidites, is a myth. This is because there are no empirical data ...” (from observations in the world´s oceans nor from experiments to validate this). “Mass-transport processes, which include slides, slumps, and debris flows (but no turbidity currents), are the most viable mechanisms for transporting gravels and sands into the deep sea.” He also noted that the “geologic reality is that frequent short-term events that lasts for only a few minutes to hours or days (e.g., earthquakes, meteorite impacts, tsunamis, tropical cyclones, etc.)” are the more important processes of transporting and depositing sediments. Or, as Kneller et al. (2016) stated: “Mass failures thus include the largest sedimentation events on earth.”
d) And why, as the final and most important question, should it be that: “The dominant 'glacial' facies in the rock record are subaqueous debris flow diamictites and turbidites recording the selective preservation of poorly-sorted glaciclastic sediment deposited in deep water basins by SGFs” (Eyles, 1993). Of course, the preservation potential is greatest in deeper basins, and therefore the question is if ancient glaciogenic material really has been preserved in any large abundance. It also appears that most “glaciations” can be correlated with tectonic movements (Eyles, 1993; Eyles and Januszczak, 2007; Kennedy and Eyles, 2021; Molén, 2021; Molén and Smit, 2022), which would trigger SGFs but not per se long term cold climate, even though long term climatic changes connected to magmatism and tectonism were suggested by Youbi et al. (2021).

Documented geological data indicate that many more diamictites than suspected may be mass flow deposits. SGF is the most abundant process of moving sediment today, both on land and in water, and would have been so even in ancient times (Moore et al., 1994; Moscardelli et al., 2006; Talling et al., 2015; Shanmugam, 2016, 2020; Ventra and Clarke, 2018).

One can conclude with the words of Johan N. J. Visser, formerly of the University of the Orange Free State in South Africa, that: "... ancient deposits do not always correspond with Cenozoic glaciation models" (Visser, 1989a), or, as stated by Grotzinger et al. (2011) "... geology is about what happened – not what should have happened."

4. Conclusion

Many geologic features which are assumed to originate only during a cold climate or by the action of ice, also form in many other environments and by non-glacial processes, especially by SGFs. Furthermore, many features which are present in deposits from the pre-Pleistocene "glacial" record are not present in the Pleistocene glacial record (and vice versa). These missing features commonly indicate an origin by different kinds of SGFs, combined with tectonic uplift or subsidence (e.g., Maxwell, 1959; Wilson, 1969; Eyles and Eyles, 1989; Eyles 1990, 1993; Kennedy and Eyles, 2021), rather than glacial or periglacial erosion and deposition. "Ancient ice-ages" may be mainly deposits from different kinds of SGFs, instead of glaciogenic deposits.

However, a glacial component can often not be excluded only on the basis of sedimentary and erosional structures. Glacial environments are often complex and it is therefore possible to argue for a glacial origin for many features present in an outcrop. But if all geological data from a formation are considered, even if nine out of ten features are consistent with glaciation but may also be formed by SGFs, a non-glaciogenic interpretation of many "tillites" may become a clear possibility.

Thus, many researchers have become aware that sediments from SGFs form a large number of recent and ancient sedimentary deposits. Furthermore, even if there may still be debates, many "glaciations" have been reinterpreted completely or in part as SGF deposits or other non-glacial phenomena (e.g., Newell, 1957; van Houten, 1957; Dott, 1961; Schwarzbach, 1961; Winterer, 1964; Lindsay, 1966; Scott, 1966; Condie, 1967; Frakes et al., 1969; Volkheimer, 1969; Frakes, 1979; Schermerhorn, 1974a, 1974b, 1981; Cecioni, 1981; Vellutini and Vicat, 1983; Martin et al., 1985; Mahaney, 1987; Eyles and Eyles, 1989; Eyles, 1990, 1993; Bailey et al., 1990; Rampino, 1994, 2017; Eyles and Januszczak, 2007; Thompson, 2009; Carto and Eyles, 2012a, 2012b; Delpomdor et al., 2016; Isbell et al., 2016; Molén, 2017, 2021; Bechstädt et al., 2018; Moxness et al., 2018; Fedorchuk et al., 2019; Kennedy et al., 2019; Le Heron and Vandyk, 2019; Pauls et al., 2019; Dey et al., 2020; Kennedy and Eyles, 2019, 2021; Dufresne et al., 2021; Isbell et al., 2021; Vandyk et al., 2021; Molén and Smit, 2022). It appears that many diamictites which have been interpreted as "tillites" have been formed in a similar geological environment, but not in a similar climate.

The documentation of features from the current paper is summed up in the Appendix, a Diamict Origin Table. This table may be used as a working tool, and also as a reference in publications (Molén 2017, 2021). The documentation in the current paper has sorted out unequivocal criteria. Even if the current paper have reviewed most recent literature, because of a general lack of work in some research areas that have been discussed, a few of the similarities and differences between deposits with a different origin are provisional, requiring further documentation. Many of the features described need both better qualification and quantification before they can be used more conclusively. The evidence from surface microtextures may be the quickest way to interpret the origin of deposits, as the evidence from different surface microtextures from Pleistocene and Holocene deposits are not equivocal (Mahaney, 2002; Molén, 2014, 2017).

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5. Appendix Diamict Origin Table

FEATURE	ORIGIN		
	Glaciog.	Mass flow. Tect.	Diamict
Areally continuous	2	1	
Areally dispersed	1	2	
Large areal extent	2	1	
Warm climate sediments	0-1	2	
Warm climate fossils	0-1	2	
Matrix supported/fine grained	2	1-2	
Clast/bed thickness correlation	0-1	2	
Sorting/grading	0-1	2	
Streaks of different sediments/diamictites	1	2	
Unconsol. transport. sediment	1	2	
Soft substrate	1-2	2	
Fabrics	2	2	
Strong	2	1	
Weak	1	2	
Bimodal	2	1	
Planar	1	2	
Variable in sections	1	2	
Erratics	2	2	
>1-3 m diameter	2	1-(2)	
Smaller in “tillite” than in mass flow	0	2	
Jigsaw fractures	-	1	
Striated clasts	1-2	1-2	
Subparallel striae	2	1	
Parallel striae	1	2	
Curved/random striae	1	2	
Crossing striae	2	1	
Soft angular not striated, hard rounded striated	1	2	
Faceted/polished clasts	1-2	1-(2)	
Pavement/striae/grooves	2	1	
Subparallel striae	2	1	
Parallel striae	1	2	
Crossing striae	2	1	
Polished striae	2	1	
Soft sediment pavement	1	2	
Sediment pressed down	-	2	

Pressed up ridges	-	2
Stacked	0-1	1-2
Irregular horizontally and vertically	2	1-2
Regular striations	0-1	1-2
Continue over extensive areas	2	1
Interlaminated sediment/traction carpet	-	1
Ripples, laminae (etc.)	-	1
Brecciation	1	1
Overhanging walls (etc.)	0-1	1
Rock polish chemical	(?)	1
Iceberg keel scour marks and mimics	2	0-1
Abundant where present	2	-
Changing directions	2	0-1
Superposed/stacked in same direction	-	1
Parallel strations/grooves	1	2
Undulous in cross-section	2	0-1
Evidence of tides, wind and waves	2	0-1
Grounding pits	2	(?)
Glacier grounding-zone wedges	2	(1)
Boulder pavements	2	1-2
Roches moutonnés/plucking	2	(0-1)
Uneven surface	0-1	1
Fjords, overdeepened, regular, ridged outlet	2	(0-1)
Eskers	2	(0-1)
Sorting	2	1
Large clasts on top	2	(?)
Glaciofluvial restricted by ice, kames, etc.	2	-
Dropstones/lonestones	2	2
No fabric	2	1
Weak fabric	1	2
Varied size of clasts	2	1
Small size	1	2
Small size compared to other sediments	-	2
Correlation: clast size and sediment thickness	-	2
Larger clasts in thicker sediments	1	2
Sorted	0-1	1-2
Differently compressed laminae	1	2
No/little penetration	1	2
1/3 of clast penetrate	2	1
Sediment thickness changes around clast	1	2
Lee side structures/movement/wake eddies	1	2
Rip-up clasts	0-1	1
"Varves" (with dropstones) drape diamcitite	1	2
Rythmites, thick "winter layer"	0-1	2
Small tectonics, e.g., clastic dikes/water escape structures, especially within rhythmites	1	2
"Glaciomarine" deposits drape diamcitite	1	2
Submarine glacial features	2	1
"Periglacial" features not formed by frost	1	2
Surface microtextures a) only fractured, or b) both weathered and regularly abraded	-	2

Surface microtextures synchronously fractured and irregularly abraded	2	-

GEOLOGICAL FEATURES WHICH DISPLAY NO CRITERIA TO EASILY INTERPRET THE ORIGIN OF THESE FEATURES

Geochemistry	Too many exceptions and interpretations
Transverse/irregular landforms	Critera not fully documented
Mass flows	Difficult to see evidence of glaciation
Channels below “tillites”	Difficult to know the origin
Flutes	Critera not fully documented
Impact structures	Irrelevant, except if misinterpreted
Lineations	Too few criteria
Glacial valleys	Too much variation
Channels/tunnel valleys	Too few criteria
Large soft sediment tectonic structures	Too much variation

Diamict Origin Table of geologic features formed in environments of glaciation, mass flows and tectonics. Columns display how common a feature may be, and if it has a glaciogenic origin or a non-glacogenic origin (mass flows etc).

Tabulated features in the upper part of the table differ substantially between glaciogenic and non-glaciogenic deposits, and the more provisionally documented features are in the lower part. Even though the absolute differences are not known between different processes, relative values have been provided. Details of the origin of these structures are discussed in the text. Included in the SGF/tectonic column are also other non-glacial processes which have been discussed. Not all data discussed in the text are listed, but only those that more clearly help in interpreting the origin of a diamictite. Hence, provisional or insignificant (not fully) documented differences, and those that may be easily interpreted to have formed in different environments, are not tabulated but only discussed in the text.

In the column for glaciogenic origin, structures that form by non-glaciogenic processes in a glacial environment are not included, e.g., debris flows. However, if clasts in debrites are glacially striated, this may be evidence for glaciation. On the other hand, debrites, with no other evidence for a glacial environmen than striations that may form by debris flows, is not a very helpful evidence for interpreting presence of a glacial climate.

2 = more common, 1 = less common, 0 = very rare, - = no example known, parentheses = rare or commonly displaying a distinct appearance, ? = no well documented research known.

The complete, or parts of this table may be copied and used directly in publications (e.g. Molén, 2017, 2021). (Last column is left open for the area/outcrop studied.)

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Supplementary material: Tables

Place and/or environment	Percentage striated clasts	Interpretation or comment	Reference
Sediment gravity flow	19 of 19 clasts were striated.	One chert and the rest softer sedimentary clasts.	Winterer, 1964.
Sediment gravity flow	Almost 50%.	Ca. 1% of the grains were larger than sand, so one would not expect to find many striated clasts, even if all the striated clasts were sedimentary.	Winterer and von der Borch, 1968.
Tills and "tillites"	1-5% or 10-20%.		Anderson, 1983; Schermerhorn, 1974a.
Carboniferous "glacial" conglomerate	15-20% striated.		Anderson, 1983.
Late Paleozoic, "glaciogenic"	48% striated.	Mostly sub-parallel but also scattered.	Rocha-Campos and Santos, 1981.
Paleoproterozoic "glaciogenic"	Rare striations, and a few clasts that display facets.	Conglomerate above grooved soft sand surfaces.	Williams, 2005.
Carboniferous, "glaciogenic"	5-20% and up to 80%.		Visser, 1982; Hall and Visser, 1984; Visser et al., 1987.

East Antarctica, continental shelf	12% striated.		Anderson, 1983.
Ross Sea shelf area	60% striated or faceted; in redeposited conglomerate 21% were striated and 4% faceted.		Hall, 1989.
Antarctic shelf, McMurdo Sound	57% striated, 80% faceted.		Hall, 1989.
Many different Quaternary	0.1% - 80%, mostly 10-40%.		Atkins, 2003, 2004.

Table S1. Striations on clasts from different environments.

Location in ancient “glacial” environments	Structure, comment	Reference
Very common in pre-Pleistocene diamictites from all ages, worldwide (a, b and c from the list, and these are all displayed by most of these striated surfaces that is referred to).	Soft sediment striations and surfaces, within or on top of sediments, including within “tillites.” Striations/grooves on all bedrock surfaces are commonly perfectly parallel.	Bigarella et al., 1967; Lindsay, 1970a; Schermerhorn, 1970, 1971; Fairbridge, 1971; Deynoux and Trompette, 1976; Frakes, 1979; Visser and Loock, 1982; Visser, 1983b; Visser et al., 1987, Deynoux and Ghienne, 2004; Le Heron et al., 2005, 2010, 2018a, 2018b, 2019b, 2020; Keller et al., 2011; Vesely and Assine, 2014, list of 17 places; Rosa et al., 2016, 2019; Molén, 2017; Alonso-Muruaga et al., 2018; Assine et al., 2018; Dietrich and Hofmann, 2019; Caputo and Santos, 2020; Isbell et al., 2021; López-Gamundí et al., 2021; Molén and Smit, 2022.
Common (as described in list, letter d).	Striations and grooves superimposed, stacked, on many beds above each other, commonly in soft sand.	Frakes and Crowell, 1969, 1970; Lindsay, 1970a; Flint, 1975; Deynoux and Trompette, 1976; Von Brunn, 1977; Biju-Duval et al., 1981; Moncrieff and Hambrey, 1988; Visser and Loock, 1988; Visser, 1988, 1989b; Deynoux and Ghienne, 2004; Le Heron et al., 2004, 2005, 2006, 2010, 2018b, 2020; Keller et al., 2011; Vesely and Assine, 2014; Assine et al., 2018; Caputo and Santos, 2020; Molén and Smit, 2022.

South Africa, LPIA (a, b, c, d and e in list.)	Sediment strings turn into grooves or striations. Three of four studied striated surfaces did not display any diamictites in the surrounding areas.	Molén and Smit, 2022.
Brazil, LPIA (a, b, c and f).	Many striated surfaces, the largest covers 2500 m^2. Displaying soft sediment slickensides from sliding (similar to Isbell et al., 2001), flutes and grooved tops of diamictites, sand slumps (interpreted to be from “icebergs”; but compare to Molén and Smit, 2022) and “anastomosing shear planes,” inside diamictite or at surfaces.	Rosa et al., 2019.
Brazil, LPIA (a, b, c, d and e).	In one or more triple stacked striated surfaces: Straight, parallel, bypass zones, stacked, small sand flows cover striations, ripples next to striations. Interpreted to be a tidal water glacier.	Trosdtorf et al., 2005a, 2005b.
China (a, b, c, d.)	Bifurcating striae	Le Heron et al., 2018b, 2019a; Chen et al., 2020; compare to Molén and Smit, 2022.
Botswana, LPIA (c in list).	The “original ground moraine” is interpreted to have been “stripped off” from striated surface before mudflows were deposited.	Frakes and Crowell, 1970.
Antarctica, Permian (b, d, e in list).	Soft sediment surfaces are grooved or striated only if a thin veneer of sorted sediment is lying directly on top of the surfaces. At places where the sorted sediment disappear the striations also disappear.	Lindsay, 1970a.

South Africa, LPIA and Sahara, Ordovician (a, b, c, d and e in list).	1) Striations continued unbroken from the top of a "tillite" into the striations on the surface below. 2) Striations passed from lava to a triple stacked soft sediment surface. 3) Thin beds of sand, mud or laminated sediment directly overlying striated surface. 4) Stratigraphy is: Grooved "tillite" surface, mudstone, "tillite." 5) Soft sediment surface cut in ripple laminated siltstone. 6) Fossil plants between striated surface and "tillite." 7) A soft sediment surface, draped with mudrock displaying crustacean track ways, which transforms upwards to diamictite. Comment: All these structures may form by SGFs, but not below glaciers.	1) Flint, 1961. 2) Visser, 1988. 3) Visser, 1988; Visser and Loock, 1988; Deynoux and Ghienne, 2004 (Sahara, Ordovician). 4) Von Brunn, 1977. 5) Visser, 1983b. 6) du Toit, 1926; Sandberg, 1928. 7) Von Brunn, 1996.
Ethiopia, LPIA (b, c and e).	Traction carpet on a polished surface, stacked striated surfaces (but this was not recognized in article, their Fig. 6A.)	Bussert, 2010.
Argentina (b, d).	Intertill and intratill soft sediment surfaces, occasionally tectonic and glacial striations on the same surfaces.	González and Glasser, 2008.
South America in 1-2) LPIA and 3) Upper Precambrian (a, c, g).	1) Striations display the same direction as foliation in underlying gneiss. 2) Slickensides pass straight into the striations on a surface. 3) A 180 000 m^2 surface show parallel "glacial" grooves which occasionally exhibit "overhanging" walls. Comment: Appear to be at least partly tectonic.	1-2) Frakes and Crowell, 1969. 3) Isotta et al., 1969; Frakes, 1979.

Cameroon, Neoproterozoic (a, b, c, d).	Stacked ("staircase"), no glaciogenic deposits, on siltstone and limestone.	Caron et al., 2011.
Sahara, Saudi Arabia, Ordovician (a, b, c, d).	1) Abundance of striations and grooves in spite of the fact that there are very few clasts in the "tillite." 2) At right angles or oblique to grooves; there are in places minor ripples. 3) Striations within current rippled and laminated sandstone. Comment: Would be possible if the origin is by SGF.	1) Schermerhorn, 1970, 1971. 2) Fairbridge, 1971, 1979. 3) Le Heron et al., 2004.
Saudi Arabia, Ordovician.	One picture shows striations that are very irregular. Comment: These display similarities to striations made by volcanic flows or tectonic movements (e.g., Pierson et al., 1990, Rainbird 1993, Glicken 1996, Eyles and Boyce 1998, Atkins 2003).	Keller et al., 2011, their Fig 12e.
West Africa, Late Precambrian (e).	One 1 cm layer of sandstone with ripple-marks is interposed in between the "tillite" and the striated surface. Comment: This can be suspected from deposition of debris flows in water.	Trompette, 1981.
Canada, Gowganda Fm, Paleoproterozoic (g).	Striated surfaces and boulders are probably of tectonic origin.	Bielenstein and Eisbacher, 1969; Harker and Giegengack, 1989; Miall, 1985.
Canada and South America, Precambrian.	Occasionally the "tillite" is stratified immediately above the surfaces. Comment: This indicates deposition from SGFs.	Schenk, 1965; Isotta et al., 1969.

Australia, Paleoproterozoic.	Comment: Some believe that these surfaces are tectonic, others that they are partially tectonic and partially glacial.	Daily et al., 1973; Coats and Preiss, 1987.
Australia, Late Proterozoic (c).	Grooves etc. in soft sediment sand are interpreted to be formed by meltwater or glaciers. Conglomerate deposited on top of the sand display the same transport direction as the grooves. No evidence of any other glaciogenic proxies. Comment: Except for a few examples, similar grooves do not form by meltwater and glaciers, but all may be from SGFs.	Williams, 2005.
Chile, Cretaceous.	Surface/contact zone exhibit both striations and ripple-marks. Comment: Has been reinterpreted as formed by turbidity currents or mudflows.	Cecioni, 1957, 1981; Sanders and Cecioni, 1957; Scott, 1966.
Norway, Late Proterozoic.	2 mm push up rinds around striations, recently weathered out clasts, mud-flake imprints. Comment: 1) The evidence suggests a soft surface. Point 2-4 below are explanations based on a glaciogenic interpretation. 2). "... the striated platform (...) is c. 150 Ma older than the overlying diamictite." 3) Quick melting and "instantaneous" lithification at a temperature > 1000°C. 4) A piece of till dropped from an iceberg and landed on top of the striations.	1) Molén, 2017. 2) Rice and Hofmann, 2000. 3) Bestmann et al., 2006. 4) Mentioned by Bjørlykke, 1967; as interpreted by von Gaertner, 1943.
Worldwide.	Glaciogenic striations. Displaying changing vertically and horizontally movement directions.	Not clearly documented before the Pleistocene.

Table S2. Striated surfaces/pavements which are all commonly interpreted to be from glaciation. All these surfaces conform well with an origin from mass transport, mainly from cohesive SGFs, but not with a glaciogenic origin. The table is not documenting every single occurrence of any surface structure from all mentioned areas, because then it would be very extensive. Some striated surfaces are referred to in more than one row, if many features are documented. The letters, a-g, are the criteria described in the list in section 2.5.

Place	Age	1/3-2/3 penetration	Small size of dropstones (cm)	Small compared to other sediments size of dropst	Clasts within single bed	Correlation between clast on and sediment thickness es	Fabrics transport in	d indication feature horizontal movements of sediments size	Push structures next to clast of currents or	Sediment thickens next to clasts	Draped thins out much penetrated	Reference aroun and/or lasts but not
		a	b	b	c	d	e	f	f, g	f, g	f, g	
Brazil	LPIA	N	<1 to 40	Y	Y					Y	Y	1
Argen-tina	LPIA	N			Y			Y		Y	Y	2
Ethiopia	LPIA	N	Often cm		Y					Y	Y	3
Malaysia	LPIA	N	0.5-20							Y	Y	4
S-Africa, Namibia	LPIA	N	>2-5, but > meter	Y	Y					Y	Y	5
Brazil	Dev	N	2							Y		6
China	Cam	N	Few cm				Y		Y	Y	Y	7
China	Neo	N	Y	Y							Y	8
Namibia	Neo	N	Y (N)	Y (N)	Y	Y		Y		Y	Y	9
Namibia	Neo	N			Y			Y	Y	Y	Y	10
Namibia	Neo	N	Y		Y					Y	Y	11
Namibia	Neo	N	< 2	Y	Y			Y		Y	Y	12
Scotland	Neo	N	3.5-9		Y		Y			Y	Y	13
Canada	Neo	N	most 1-4	Y	Y	Y		Y	Y	Y	Y	14

Tasma-nia	Neo	N	most cm	Y							Y	15
India	Pal	N	Few cm			Y						16

Table S3. The table document examples of areas displaying clasts from pre-Pleistocene formations which had been interpreted as glaciogenic dropstones in the papers which are referred to, or in the majority of published papers describing the same formation. Lonestones from sedimentary sequences which have been fully explained as from SGFs, even if there may be some different opinions, are not in the table. Often reports of dropstones only mention just that word. In other reports only superficial similarities between dropstones and observed clast are mentioned, and commonly there are no detailed descriptions of the clasts which are interpreted to be dropstones. Therefore, it is difficult to find extensive data for this table, and some interpretations may be conjectural, only because too little data have been documented in the original reports. In the table appearances of dropstones which may not be mentioned in the original publication, but which are evident from published photographs, are tabulated.

Examples of appearances of dropstones and sedimentary structures displayed around these clasts, from each research area, are documented in the different columns of the table. Not all lonestones from each area display all the apperances documented (which would be impossible), but may be predominant examples. The letters a-g in the columns refers to the descriptions in the list of features, with comments (section 2.13.3.). There may be clasts in the research areas which may display appearances that are compatible with any kind of transport, but the tabulated structures are those better compatible with transport by SGFs but less common or highly implausible from simple rafting in slowly moving or standing water. The data in the table do not show examples of exceptions of single or a few clasts which may have been deposited by any agent, if there is an abundance of clasts. Instead, the documented clasts display the structures which may be in majority, or are otherwise reported in the referred articles, or possible only are photographed as typical for the area or formation. Therefore the table is partly conjectural and does not display definite documentation from each area. And further, the documentation from the different research areas does not include all data which may be of relevance, e.g., not the difference between the clast size of dropstones compared to clast size in other sediments, or other features which could be documented in the table, because such data is seldom published.

Despite the shortcomings in the documentation from different research areas, the sedimentary structures in the table are more or less incompatible with an interpretation of simple rafting by ice or any other rafting agent. It is possible to draw the conclusion that too many clasts have been reported as dropstones even if the full evidence for this interpretation is not available. In conclusion, the data in the table are as well documented as the descriptions provided in the original reports and therefore may be possible to use in evaluation of different interpretations.

Dev = Devonian.
Cam = Cambrian.
Neo = Neoproterozoic.
Pal = Paleoproterozoic.

N = Not documented as present. (Within paranthesis = exceptions.)
Y = Documented, present.
No sign = not mentioned or shown in the original publications.

References: 1. Aquino et al, 2016; Vesley et al., 2018, 2021; Tedesco et al., 2020. 2. Schatz et al., 2011; Valdez Buso et al., 2021. 3. Bussert, 2014. 4. Baioumy, et al., 2020. 5. Commonly 2-5 cm, rarely up to one meter, but in massive "glaciomarine" diamictites they may be a few meters. Visser, 1982, 1983b; Visser and Kingsley, 1982; Tavener-Smith and Mason, 1983; Haldorsen et al., 2001; Isbell et al., 2021. 6. Caputo and Santos, 2020. 7. Le Heron et al., 2018b. 8. Chen et al., 2021. 9. Hoffman and Halversen, 2008; Hoffman et al., 2021 (Ghaub). 10. Domack and Hoffman, 2011 (Ghaub). 11. Bechstädt et al., 2018 (Ghaub). 12. Hoffman and Halversen, 2008; Le Heron et al., 2021a (Chuos); see also Martin et al., 1985. 13. Hartley et al., 2020. 14. Molén, 2021. 15. Hoffman et al., 2009. 16. Rodríguez-López et al., 2021.