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Patterns, processes and models – an analytical review of current ambiguous interpretations of the evidence for pre-Pleistocene glaciations

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Abstract

Models (paradigms) and former interpretations have often been presupposed when conducting field research. In the 19th century diamictites were for the first time interpreted to have originated from ancient glaciations. These interpretations have to a large part prevailed in the geological community, although there has been much progress in the areas of sedimentology, glaciology and physical geography. The present work is an effort to find criteria which most clearly discriminate between geological features produced by different processes, mainly glaciation and mass flow, the latter predominantly sediment gravity flows. Geological features which have been interpreted to have formed by glaciation throughout pre-Pleistocene Earth history are compared to similar-appearing geological features formed by mass flow and tectonics, so as to uncover variations in the appearance between features resulting from these different processes. The starting point for this comparison is documentation of the appearance of Quaternary products of erosion and deposition, in order to discern the origin of older formations. It is shown that the appearance and origin of pavements, dropstones, valleys, small-scale landforms, surface microtextures and most other geological features may in some cases be equivocal, but in others the details are indicative of the process which generated the feature. Detailed geological field data which have been compiled by geologists from outcrops of pre-Pleistocene strata, more often than is considered in most papers, commonly point to a mass flow origin, mainly a sediment gravity flow origin, rather than a glaciogenic origin. A process of multiple working hypotheses or interpretations is therefore advocated, based mainly on a comparison of the appearance of features formed by different geological processes documented from different research disciplines. Instead of starting with current interpretations or models, this multiple working hypothesis or methodology helps to avoid confirmation bias and jumping to conclusions.

Keywords: Diamictite, pavement, dropstone, sediment gravity flow *vs* glaciogenic characteristics, tectonics

1. Introduction

In the field of science, if formerly accepted interpretations are too easily endorsed and not thoroughly reviewed, especially if these have been built on older and not updated information or knowledge, this may have hampered which research questions have been investigated and consequently what has been documented. Lithified mixtures of non-weathered sediments of various grain sizes, displaying clasts and rock fragments of different shapes and sizes embedded in a matrix of clay, which originated from, for example, mass flow or glaciation, are labelled with the non-genetic term diamictite. Pebbly sandstone, matrix-supported conglomerates, breccias and weathered bedrock displaying core stones or less weathered rock fragments in a matrix, are (commonly) not labelled diamictites. The origin of diamictites and other geological features that are produced from erosion and deposition, which have been interpreted to be from pre-Pleistocene glaciations, is the scope of the current article.

For the present review, which is concerned only with geological features interpreted to be evidence of cold climates (not climates *per se*) throughout pre-Pleistocene Earth history, the starting point is the year 1855 when Ramsay interpreted some Permian boulder deposits in England to be of glacial origin (Hoffman, 2011). Ever since that publication there has been controversy over the interpretation of diamictites. The Gondwana Late Palaeozoic Ice Age, probably best represented by the Dwyka Group in South Africa, was first interpreted to be from an ancient glaciation in 1870, and this interpretation was generally accepted in 1898 (Sandberg, 1928; Hancox & Götz, 2014; Molén & Smit, 2022). In 1891, Reusch described a striated pavement below a diamictite, which was interpreted to be from a Neoproterozoic glaciation, in the Varanger Fjord area (northern Norway), which has since then been a very popular excursion locality (Bjørlykke, 1967; Molén, 2017). In 1908, Coleman interpreted diamictites in the Palaeoproterozoic Gowganda Formation as evidence of glaciation (Coleman, 1908; Molén 2021). These influential early papers were published before detailed documentations from studies of sediment gravity flows (SGFs) became well known amongst geologists, and these early interpretations have prevailed and often directed later interpretations and research questions of diamictites worldwide. Papers describing deposits interpreted to have been produced by former glaciations have been published for thousands of sites, from all geological periods (e.g., five episods in the Cretaceous), in the Precambrian interpreted to have covered probably the complete Earth one or many times (Snowball Earth or Slushball Earth), including major glaciations during the Hirnantian (Late Ordovician) and the Late Palaeozoic (Hambrey & Harland, 1981a; Deynoux, 1985a; Deynoux et al., 1994; Molén, 2023a).

The birth of sediment gravity flow (SGF) research can be said to have been in the year 1827, with the introduction of the term flysch (Studer, 1827). The first mention of a submarine fan dates from 1955 (Menard, 1955), and the first mention of a turbidite-fan link in ancient fans was from 1962 (Bouma, 1962; Shanmugam, 2016). Former interpretations of diamictites as glaciogenic, without taking into account the more recent understanding of the importance of SGFs in the geological record (Shanmugam, 2016, 2020, 2021), have often resulted in underestimation of SGFs in favour of glaciation, even if SGF deposits have often been documented in papers concerning diamictites. As the understanding of the geological work resulting from gravity flows is a recently growing research area (e.g., Ogata et al., 2019), more diamictites and co-occurring geological features have been interpreted as non-glacial. As a consequence of the general lack of sufficient knowledge of this research area, Shanmugam (2016) was invited to write a review concerning deposition by gravity flows in fan environments. This paper was a reaction generated because another major paper concerning global geological studies had missed 60 years of research on the importance of deposition in submarine fans. Lately, hyperpycnal flows, i.e., highly dynamic dense and often long-lived (up to months) subaqueous underflows orginating from land-derived gravity flows (including from sediments transported by rivers), have been recognised to be far-transporting agents of sediments and organic matter. These flows may 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 & Arcuri, 2016; Shanmugam, 2021; Zavala, 2019, 2020).

The transformation in the geological community to a reinterpretation of the origin of diamictites, started in the early 1970s, but could be said to have begun with an earlier paper by Crowell (1957). Out of this came recognition that many "ice-age remains" had been deposited by different kinds of SGFs, for example by turbidity currents, but more commonly by cohesive debris flows. For example, in the Cenozoic of Alaska, twelve major glaciations were reinterpreted as having formed largely by SGFs (Plafker et al., 1977; Eyles & Eyles, 1989). Schermerhorn documented similar reinterpretations shown in his classic work on Late Precambrian diamictites (Schermerhorn, 1974, 1977). 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 & Harland, 1981b; Boulton & Deynoux, 1981; Anderson, 1983; Wright et al., 1983; Eyles, 1993). The documentation in Schermerhorn´s classic paper (1974), of criteria showing differences between the appearance of features from SGFs and glaciation, has to a large part gone unnoticed, even though this article may have been referred to in passing by many geologists (e.g., mentioned by Le Heron et al., 2017).

By using multiple working hypotheses, the current analytical review documents detailed descriptions of geological features from pre-Pleistocene deposits and compares these to Quaternary geological features. However, this analytical review does not start with models or former interpretations. Literature from relevant areas of physical geography and glacial geology, including mass wasting processes and tectonics, has been reviewed. Field work combined with literature studies have been applied to reports of pre-Pleistocene sections where the geological features had been interpreted to be glaciogenic. It is evident that Quaternary erosional and depositional landforms are often dissimilar to those which are interpreted from the pre-Pleistocene when studied in detail, even if there are similarities in the more general appearances. Quaternary landforms are commonly described in great detail and have on occasions even been observed during formation. The same holds true for sediment gravity flows (SGFs) and other mass movements (e.g., Shanmugam, 2016, 2021; Ogata et al., 2019; Peakall et al., 2020; Rodrigues et al., 2020; Dufresne et al., 2021; Kennedy & Eyles, 2021).

Interpretations of the origin of diamictites and co-occurring geological features may vary widely even though an origin by mass flow or glaciation constitutes the most common interpretations (e.g., Dufresne et al., 2021; Isbell et al., 2021). However, as knowledge about geological processes has expanded, it has become more apparent which interpretation - glaciogenic or mass flow - the origin of an ancient formation is better justified. Research on diamictites and their surrounding geological features needs to be reconciled with recent scientific progress in many different research disciplines of, e.g., sedimentology, physical geography and geochemistry. In particular, research progress on Quaternary glaciations and sediment gravity flows has revealed both similarities and differences, the most important of which are easily documented in the field.

Thousands of papers have been published on diamictites and pre-Pleistocene climates, and a subsample of the most detailed of these are summarised or cited below. Older papers may contain details about geological features which are relevant to the interpretation of an outcrop, but such details may not always be documented in more recent papers which have accepted former interpretations. The classic 150-page paper by Schermerhorn (1974) provided inspiration for the present work when it was suggested that everything maybe did not appear to be what it was supposed to be. Results of the process-related studies by Shanmugam (2012, 2021) are also informative as are other papers like Peakall et al. (2020), who documented the origin of soft sediment striated and grooved surfaces/pavements and the transport of large clasts by SGFs. Furthermore, papers describing 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 & Eyles, 2021), have helped in the interpretation of ancient deposits. The work by the present author (Molén, 2017, 2021; Molén & Smit, 2022) has benefitted from the combination of studies from different research areas used in a paper by Kennedy and Eyles (2021). A summary of process-related research is similar to the Lyellian statement that, "The present is the key to the past", i.e., to study recent geological features with known origins, assumes that the natural laws have not changed over time (even though not all processes can be mathematically described), and applies documented observations to ancient deposits. However, classic uniformitarianism is scientifically dead (Romano, 2015), i.e., processes may not have operated with the same "momentum" all throughout Earth history, and different kinds of sediments have different preservational potential.

Whether or not an area should be interpreted to have formed by glaciation, is a matter for the field geologist to determine. Accepted interpretations of an ancient outcrop or area, while describing the appearance of the geological features from that area as evidence of similar interpretations of other ancient deposits, may lead to mistakes. Old interpretations and paradigms may not always be correct, and recent progress in sedimentology and glaciogenic processes needs to be acknowledged.

The geological features discussed below are those which most commonly are interpreted to be from glaciation. The different features are first described in a more general context, and then details are provided which makes it possible to interpret the origin of these features more conclusively from either glaciation or some other processes, the latter mainly SGFs.

2. Geographical extent, thickness of deposits and tectonics

It has recently been acknowledged that the main depositional areas of sediments today are submarine fans and mass transport in areas of subsiding basins (Shanmugam, 2016). Even on land the most important process of moving material is mass wasting (Shanmugam, 2020), while other processes may be dominant in confined areas (i.e., areally and/or environmentally restricted) and/or during shorter time intervals. Quaternary tills are commonly thin (2–15 m, more often on the lower end), except in confined areas with general thicker tills (e.g., 10–52 m in a 300-km-long band at the southern border of the North American inland ice sheet; Molén, 2023a), and therefore their preservation potential for deep time would be low. These observations indicate that, whatever the climate was during Earth history, there would be few preserved features originating from earlier glaciations on former higher, stable bedrock. That especially concerns subglacial sediments, as most material would have been transported into marine settings and subsiding basins. In the Neoproterozoic, diamictites are commonly preserved in thick sequences in tectonically unstable subsiding basins at the edges of cratons, and would therefore not easily qualify as subglacial sediments *in situ* (Eyles, 1993). Furthermore, geological features from the Late Paleozoic Ice Age and the Hirnantian (Ordovician) glaciation, in most places, are preserved in areas of subsiding basins and/or areas affected by transgressions (Ghienne, 2003; Buatois et al., 2010; López-Gamundí, 2010; Schatz et al., 2011; Molén & Smit, 2022; Molén, 2023a). The progress in knowledge of SGFs has changed interpretations of most ancient diamictites which had formerly been interpreted to be commonly primarily subglacial, to instead be (to a large part) reworked SGFs, especially cohesive debris flows. This reinterpretation is absolutely not controversial. A provisional older estimate is that 95 per cent of pre-Pleistocene "glaciogenic" diamictites have now been reinterpreted to be SGF deposits (Eyles 1993), even though a glacial marine interpretation displaying SGFs is not excluded.

3. Diamict structure

At first glance, diamictites formed by cohesive SGFs and till deposited by glaciers, may be difficult to distinguish (e.g., Lowe, 1982; Visser, 1983; Wright et al., 1983), and there have been many mistakes of interpretation (e.g., Dufresne et al., 2021; Molén, 2023a). Cohesive debris flow deposits may contain all particle sizes, including a large fraction of clay, similar to tills (e.g., Molén & Smit, 2022), and therefore these may be difficult to distinguish by particle size analyses, contrary to other sediments which are more easily separated, e.g., outwash, sheet flow and loess (Blott & Pye, 2012). In many cases, however, it is possible to document other patterns/properties of diamictites that are more characteristic of either SGFs or tills.

Diamictites which commonly have been interpreted to be tillites, even to this day, often display grading, bedding and amalgamation, similar to SGF deposits (Visser, 1983; Domack & Hoffman, 2011; Kennedy & Eyles, 2021; López-Gamundí et al., 2021; Shanmugam, 2021; Molén & Smit, 2022). They are often covered by laminated deposits and/or sediments with marine fossils (Sterren et al., 2021). Occasionally, there is even a gradational transition from the diamictite into the overlying (sorted) bed (Cuneo et al., 1993; Isbell, 2010), but there may be long time periods in between the deposition of diamictites and the subsequent (sorted) beds.

Glaciers process all kinds of sediments and bedrock, slowly turning these into rock flour, and do not sort out the finer material (albeit, of course, with the exception of sediments from small alpine glaciers which are processed during a very short time, and produce deposits which would be more vulnerable to erosion and would be difficult to document in the rock record). In pre-Pleistocene diamictites which are interpreted to be glaciogenic and displaying outcrops over large areas, there is often no rock flour, contrary to Quaternary tills (Frakes 1979; Le Heron et al., 2005, 2006; Yassin & Abdullatif, 2017; Molén 2017; Chen et al., 2021). Soft sediment clasts may be common (Deynoux, 1985b; Molén, 2017; Kennedy & Eyles, 2019, 2021), and sometimes clasts in diamictites have been pressed into underlying surfaces (Isbell et al., 2021), or the overlying sediment has been pressed down into the diamictite, or the diamictite has been pressed upwards into the overlying sediments (Cuneo et al., 1993; Isbell, 2010), i.e., features which frequently accompany SGF deposits (Shanmugam, 2012; Molén, 2017, 2023a; Vesely et al., 2018; Kennedy & Eyles, 2019, 2021; Rodrigues et al., 2020; Kraft & Vesely, 2023).

4. Fabrics

Fabrics in subglacial tills are less varied and azimuth constrained than those in SGF deposits. While glaciogenic fabrics may often be unimodal or bimodal, with a common updip of 10 to 20° in the direction of the ice movement (e.g., Evans et al., 2016), this can also be displayed by gravity flow deposits (including in flow tills). In gravity flow deposits the fabric also may be planar or steeper than in tills, but the main difference is that it commonly differs in vertical section (Lindsay, 1968).

5. Erratics

There has never been a systematic study of differences in size of clasts in tills and SGF deposits, even though clast size is often mentioned. In tills there

Fig. 1. A – Example of the common size of a Pleistocene erratic. Västerbotten County, Sweden; **B –** Jigsaw puzzle texture, where fine-grained sediment has been pushed in between the fractured clasts. Gowganda Formation, Canada (Molén, 2021). Marker is 20 cm.

are almost always numerous large clasts, many metre-sized (Fig. 1A). In mass movements clasts also may be large, and kilometre-sized blocks are not uncommon in slides (Nwoko et al., 2020a, 2020b; Puga Bernabéu et al., 2020; Kennedy & Eyles, 2021; Kumar et al., 2021). If clasts in SGFs are large, it is commonly easy to see evidence of soft sediment structures originating from the movement.

Calculations show how much cohesive strength is needed to transport large clasts in a mud-rich fluid, which could be a cohesive debris flow (Peakall et al., 2020). The increase in buoyancy needed for clast size is exponential, and clasts larger than 1 m in diameter would need so much yield/matrix strength that it would be suspected that such transport would be rare (Peakall et al., 2020). Thus, if >1m clasts are transported, one would suspect to see clear evidence of the flow mechanism, i.e., any kind of disturbances in the sediments. This size pattern is exactly displayed in diamictites which have been interpreted to be glaciogenic: the largest clasts are seldom more than 1 m in diameter, even though clasts in SGF and other deposits from the same area may include much larger sizes than those parts which are considered to be subglacial (Molén, 2023a). In conclusion, the presence of large clasts is almost always much rarer in pre-Pleistocene diamictites than more recent glaciogenic sediments, and they are smaller than in tills.

In many diamictites there appears to be a mix of different clast types and no/few intermediate clasts, e.g., rounded, long-transported clasts and highly irregular and sharp short-transported clasts together (Molén, 2021; Molén & Smit, 2022). This is easily explained by mixing of material from different sources, like in SGFs which have mixed material transported for distances of 2,000 km and depositing material over areas of 132,000 km^2 (Molén, 2023a), but is not implausible for tills, even though glaciers commonly quickly abrade sharp edges (Eyles & Eyles, 2000; Ortiz-Karpf et al., 2017; Ogata et al., 2019; Nugraha et al., 2020; Rodrigues et al., 2020).

In some diamictites there is a correlation between bed thickness and the diameter of the erratics (Schermerhorn, 1974; Martin et al., 1985; Eyles & Januszczak, 2007). In quite a few diamictites, clasts or bedrock are fractured into a jigsaw puzzle texture (Fig. 1B); this is common in mass wasting deposits but has never been recorded from Quaternary tills (Ui, 1989; Thompson, 2009; Ali et al., 2018; Dufresne et al., 2018, 2021; Molén, 2021). There are, of course, fractured rocks in tills, but these do not display a jigsaw puzzle texture.

Boulder pavements (i.e., flat-topped accumulations of large clasts or boulders) are produced by glaciers in a process almost like a slow gravity flow (Clark, 1991; Hicock, 1991), and therefore there may be similarities to boulder accumulations formed by SGFs, e.g., planed-off boulders displaying striations as if processed by glaciers (e.g., Scott, 1988). If the boulders are more sorted, like a train (Bussert, 2014; Kennedy & Eyles, 2019), this may be more consistent with SGFs.

6. Polished, facetted and striated clasts

Clasts can be striated in many different environments. The variety of striations, and the number of striated clasts, may be similar in SGF deposits and tills (Atkins, 2003, 2004; Molén, 2023a). Often there is no detailed systematic documentation of any pattern in the appearance of striations, neither by researchers working with mass wasted deposits or those working with diamictites which have been interpreted to be tillites. However, Kennedy & Eyles (2021) documented that there were more striated clasts in SGFs in places where more clasts were present.

Detailed documentation of different combinations of processes which produce clast form is also often inconclusive, and it may be possible that the only exclusive glaciogenic form is clasts that display double stoss-lee forms (Sharp, 1982; Krüger, 1984; Rowe & Backeberg, 2011).

7. Striated, grooved and polished surfaces/pavements

Surfaces may become striated and grooved by different kinds of movements, such as glaciation, mass wastage and tectonism, and it is not always easy to determine the origin of a striated surface.

Clasts which are transported within glacier ice are always moving slightly, vertically up and down, and laterally from side to side, more or less depending on the temperature of the ice, which is also evidenced by the appearance of Pleistocene and more recent glaciogenic striations and grooves (Chamberlin, 1888; Sugden & John, 1982; Iverson, 1991) (examples in Fig. 2). It is less well known that clasts within SGFs may be stuck in the same position for very long distances, almost like a small plough moving over the subsurface (Peakall et al., 2020), e.g., Figure 2A. In SGFs striations and grooves may also change direction and display an appearance similar to glaciogenic pavements (Enos, 1969; Kneller et al., 1991; Pickering et al., 1992; Butler & Tavarnelli, 2006; Draganits et al., 2008; Peakall et al., 2020).

Outcrops of pre-Pleistocene striated areas commonly display regularly parallel, straight striations and grooves, both in soft sediments and in sedimentary and igneous/metamorphic bedrock (Fig. 3). They are commonly dispersed and cover more restricted areas. Surfaces are often not covered by diamictite, which may indicate bypass zones as in SGFs. The striated surfaces are often vertically stacked, and may display many unique features that are not produced beneath glaciers (examples in Table 1).

One main difference between pre-Pleistocene pavements and Quaternary glacial pavements is the

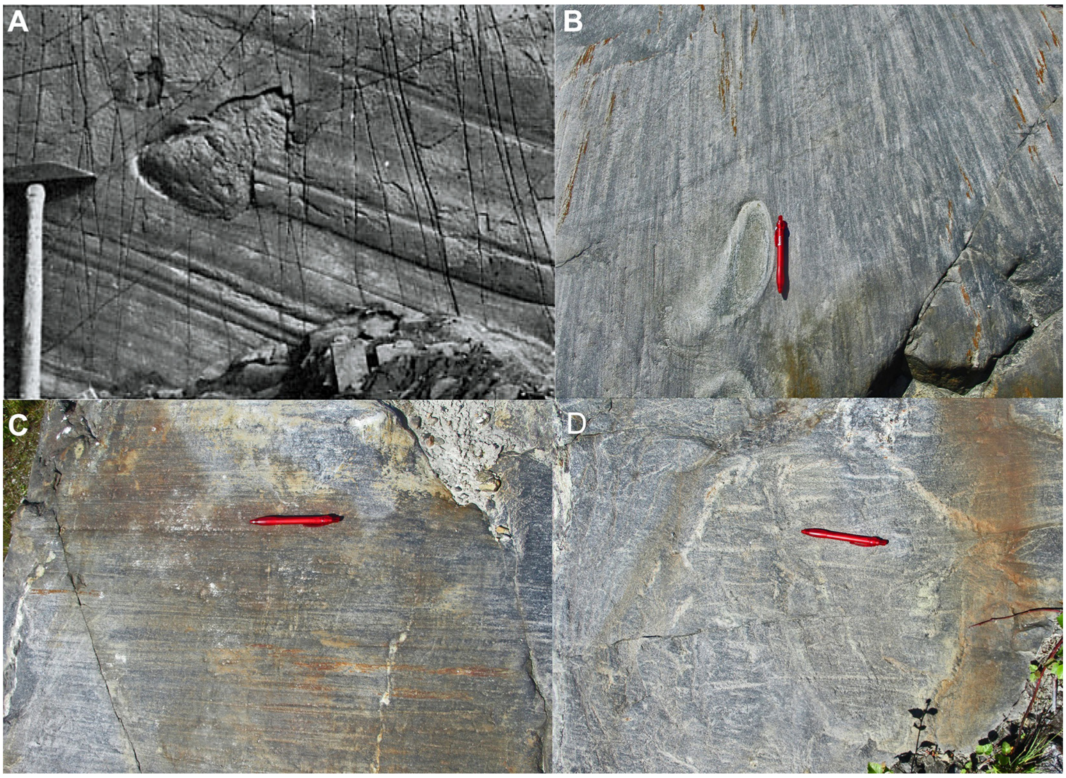

Fig. 2. A – Clast *in situ* in a SGF-deposit showing long parallel striations, similar to those in many pre-Pleistocene pavements and different from Quaternary striations and grooves. Compare with Figure 3. (Picture from: Enos, 1969. Used with permission from *Journal of Sedimentary Research*); **B–D –** Examples of Pleistocene striations on gneissic metamorphic bedrock, in the city of Umeå, Västerbotten County, Sweden. Note that the striations are semi-parallel, waxing and waning, commonly short and turning (especially on steep surfaces); **D –** This is an appearance of striations that has been well documented from Quaternary glaciers. Even if there are variations in the appearance of the striations, they are different from all documented pre-Pleistocene striations that the present author is aware of.

presence of soft sediment surfaces. Soft sediment striated and grooved surfaces are commonly very regular, recorded from SGFs soon after formation in soft sediments (Peakall et al., 2020), and they are not present with similar appearance in any Pleistocene or younger subglacial environment, except possibly very locally. Soft sediment striated or grooved surfaces may often be interpreted to be glaciogenic if

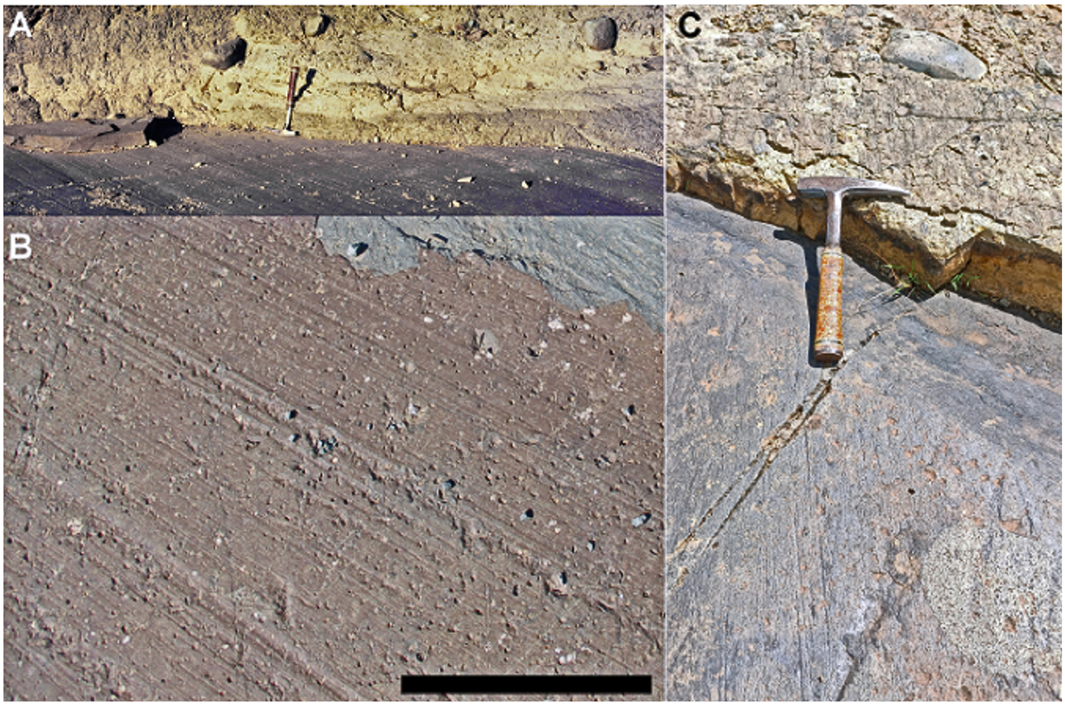

Fig. 3. Straight and parallel striations and grooves on pre-Pleistocene pavements, Dwyka Group, South Africa, commonly interpreted to be evidence from the Late Paleozoic Ice Age. **A –** Pavement on Precambrian Ghaap Formation Dolomite, close to Douglas, where striations are long and unbroken (photograph and pers. comm., Johan N.J. Visser); **B –** Pavement in Neoarchean Ventersdorp andesitic/basaltic lava, at Douglas, with similar appearance as the striations and grooves in the pavement in the Precambrian Ghaap Formation Dolomite (scale is 30 cm, pavement has been recently weathered); **C –** Striations leap over a small scarp (apparently formed by sheet jointing; Molén & Smit, 2022) between the Ventersdorp andesitic/basaltic lava and Dwyka Group diamictite, at the famous Nooitgedacht pavement. There are striations in different directions, but commonly in regular groups and not displaying the common curvilinearity of Quaternary striations (Molén & Smit, 2022). (Photograph J. Johan Smit).

Fig. 4. Examples of multiple stacked surfaces displaying striations and grooves produced from turbidities, negative view. These are reminiscent both in detail and in overview of striations or grooves in stacked soft sediment pavements that often are interpreted to be linked to pre-Pleistocene glaciations, but then the positive, rather than the negative, side is visible. Pictures are at *c.* 100 m distance from each other. Arrow is 25 cm. This outcrop was described in detail by Bischoff (2002) and in general by Hoffman (2016). Lower Saxony, Germany, Lower Carboniferus (Visean).

Table 1. Appearances of pre-Pleistocene “glaciogenic” striated surfaces/pavements, which are commonly generated by SGFs and tectonics, and are commonly not (or never) displayed by Quaternary glaciogenic pavements. Left-hand column: Examples of features of pavements which have been interpreted to be glaciogenic, but display unique appearances that have seldom or never been observed to have been produced by glaciers. Right-hand column: Presence of features produced by SGFs or tectonic movements, in comparison to formation by glaciers, approximate: 1 = may possibly and occasionally, more or less by chance, be produced by glaciers, but may be rare or commonly present on surfaces produced by SGFs or tectonics. 2 = never or almost never produced by glaciers but may be present or are common on surfaces produced by SGFs or tectonics (for field data and references, references is made to Molén & Smit, 2022; Molén, 2023a).

Straight, regular, striations and grooves	2
Perfectly parallel striations and grooves	2
Soft sediment surfaces	2
Pavements commonly without diamictite	1
Striations continue from top of “tillite” into striations on pavement below	2
Superposed/stacked striated soft sediment surfaces	2
Striated or “fluted” sediment internally in diamictite	2
Sediment between pavement and diamictite, i.e., traction carpet	2
A soft sediment striated surface is cut into ripple laminated siltstone	2
Fossil plants jammed in between “tillite” and the striated pavement	2
A soft sediment pavement is draped with mudrock displaying crustacean track ways	1
Slickensides turn into striations, tectonic and “glacial” striations on same surface	2
Sand flows cover striations	2
Striations pass from lava to soft sediment stacked striations	2
Striations in same direction as foliation in underlying bedrock	1
Overhanging walls in striations	2
Molded sediment turns into striations	2
Bifurcating striations	2
Push up rinds at striations	1

they are recorded in positive relief, but similar appearing surfaces are commonly from SGFs if they are negative (Fig. 4) (compare Molén, 2023a, Supplementary Material Table S2; Peakall et al, 2020; Baas et al., 2021).

Below SGF diamictites there are often traction carpets, i.e., thin beds of granular sediment between the diamictite and the underlying sediment or bedrock (Georgiopoulou et al., 2010; Talling et al., 2012; Dakin et al., 2013; Cardona et al., 2020; Peakall et al., 2020; Molén & Smit, 2022). Similar sediments may also be present beneath supposed tillites but are seldom documented in publications (Molén & Smit, 2022; Molén, 2023a). Soft sediment may also be moulded into strings displaying striations or grooves, by SGFs on top of hard surfaces, and the latter may become striated by the same process (Molén & Smit, 2022).

There are pre-Pleistocene soft sediment grooves and striations which have been interpreted to have been formed by iceberg keels (Vesely & Assine, 2014), but these surfaces display no definite evidence of waves, currents or tides, even if there may be occasional changes of direction even up to 180° for some features (Isbell et al., 2023). However, changes in directions up to 180° are also displayed by SGFs (Kneller et al., 1991). Surfaces interpreted to have been formed by pre-Pleistocene icebergs are rare, areally restricted, and often only isolated examples from single “icebergs”, contrary to areas of Quaternary ice-keel marks (Woodworth-Lynas & Guigné, 1990; Bennett & Bullard, 1991; Woodworth-Lynas, 1992; Woodworth-Lynas & Dowdeswell, 1994; Dowdeswell & Hogan, 2016).

8. Are outsized clasts dropstones?

Outsized clasts are defined as clasts evidently larger than the particle size in the surrounding sediments. Outsized clasts which are present in fine-grained sediments in pre-Pleistocene formations, in either stratified or unstratified sections, often are labelled dropstones and interpreted to stem from input from icebergs or lake or sea ice (Bronikowska et al., 2021; Molén 2021). This is evident from a large number of papers on the subject, in which outsized clasts are described as dropstones and advanced as evidence for a glaciogenic interpretation of a formation (Le Heron et al., 2022b; Molén, 2023a), or not glaciogenic if there are, e.g., no outsized clasts (Clapham & Corsetti, 2005). Systematic descriptions of outsized

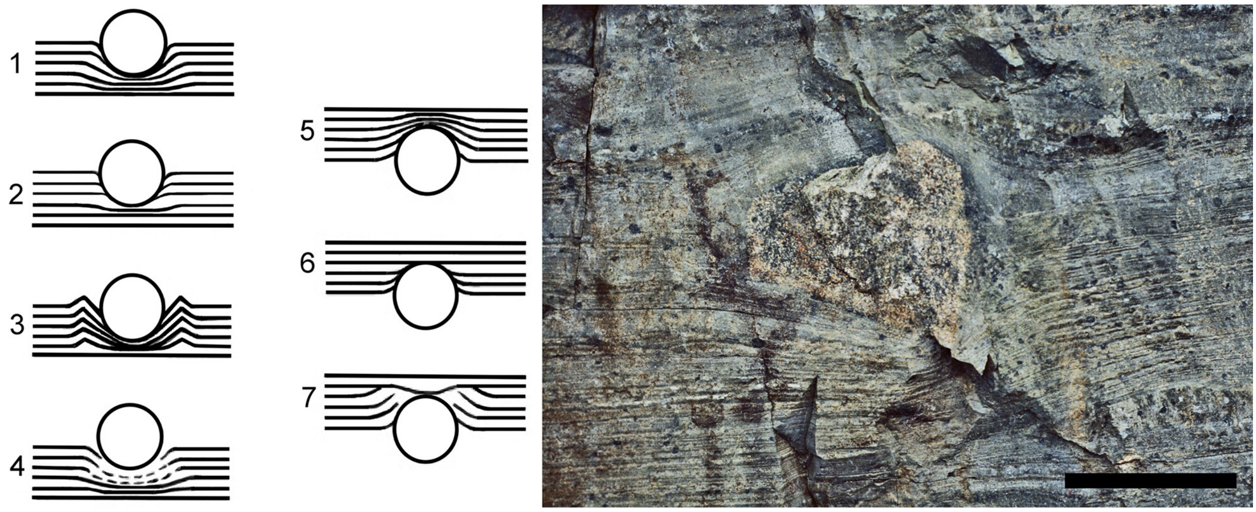

Fig. 5. Left: Schematic definition of sedimentary structures next to dropstones. 1–4 are bottom contact, 5–7 are top contact. 1 = bending. 2 = penetration. 3 = rucking. 4 = rupture. 5 = bending. 6 = on-lap. 7 = rupture (after Thomas & Connell, 1985). Right: Photograph of an outsized clast commonly interpreted as a dropstone, Gowganda Formation at Cobalt, Ontario, Canada (Molén, 2021). The appearances of the sedimentary structures next to this clast conform to the definitions of a "leftover", i.e., a clast that has been transported with a SGF, as defined in the right-hand column of Table 2 (marker is 10 cm).

clasts, formerly interpreted to be dropstones, are the studies by Kennedy & Eyles (2021) and Molén (2021). Researchers may document different disturbances in sediments close to outsized clasts, and label these disturbances after similar structures described in the much-quoted paper by Thomas & Connell (1985) describing Pleistocene dropstones, e.g., rucking structures (Fig. 5). Yet, such comparisons are seldom mentioned or fully documented.

However, clasts up to sizes of metres in diameter can be lifted and transported by agents other than ice, i.e., vegetation and macro algae, and clasts transported with such agents may display the same appearance and thus be impossible to discriminate from clasts transported by glaciers, icebergs and sea ice. Even at this moment an estimated hundreds of thousands of clasts, most small but up to metres in diameter, are lifted and transported with kelp (Waters & Craw, 2017). Marine macro algae which can transport clasts of up to a few centimetres in diameter, have been present from the Neoproterozoic and possibly even earlier (Bengtson et al., 2017; Gibson et al., 2018; Del Cortona et al., 2020). Therefore, the appearance of sedimentary structures next to outsized clasts (as documented by Thomas & Connell, 1985) are always problematic for discrimination between transport by vegetation or ice.

Outsized clast are almost always transported with SGFs, larger clasts in denser, more cohesive and stronger flows. If clasts are transported within more cohesive and denser parts of gravity flows, the resulting deposit will be a (non-glacial) diamictite. Otherwise, it may be a laminated deposit where clasts may penetrate and disturb laminae in a similar way as dropstones. Therefore, the appearance of outsized clasts has to be documented in more detail in order to determine their origin.

Outsized clasts in rhythmites or other fine-grained sediments which have been transported by SGFs are commonly smaller than glaciogenic dropstones, they are commonly smaller than clasts in nearby diamictites which are interpreted to be tillites, and they are also smaller than clasts in more clearly evident SGF deposits, i.e., deposits which are not massive but display much evidence of movement and therefore do not display freezing of the movement as is common in cohesive debris flow deposits. Many inferred dropstones are so small (<1 cm) that they would hardly make an impact on the bottom sediment (Bronikowska et al., 2021; Le Heron et al., 2022b; Molén, 2021), while such small clasts would commonly impact sediments transported with SGFs only because of flowage or later compaction (Molén, 2023a).

Non-glaciogenic outsized clasts may display a fabric similar to SGFs, they may be sorted where there is a correlation between clast size and sediment thickness, they are often draped with sediment, but they more seldom clearly penetrate laminae (Molén, 2021, 2023a). The beds or laminae where the clasts are present often display a thickening next to the clast, and occasionally there may be a pushed-up sediment bulge in front of the clast. The latter may often be labelled a rucking structure if the deposit is interpreted to be glaciogenic (Valdez Buso et al., 2021), i.e., a structure that develops when a dropstone penetrates laminae and pushes sediment to the sides of a clast. On closer inspection it may be possible to document if it is a push or current structure from lateral movement, or if it is a structure formed by vertical penetration from above. This may be deduced from the lateral length of the disturbance, the thickness of the disturbance, if laminae are moved to different heights or splits/joins at the outsized clast, or if the disturbance is only on one side. If clasts are dropped in flowing water, or if there are SGFs at the bottom, or if clasts are stuck to a piece of ice and only sink slowly to the bottom, the appearance of the structures surrounding the clasts will display similarities to those in SGF deposits.

Table 2 lists differences between the structures labelled by Thomas & Connell (1985) from dropstones (Fig. 5) compared to pre-Pleistocene "dropstones," and also special features only present in connection to diamictites (not counting those that have already been interpreted by researchers to be from SGFs, as they all fall in the same category). It is, of course, not possible to decide whether each single outsized clast is a dropstone or not, but the evidence from appearances of many outsized clasts present together in a bed or area will indicate the best interpretation of that area.

The most definite pattern of sedimentary features indicating a non-glacial origin includes comparative clast size, correlation between sediment thickness and clast size, if there is little or no penetration (i.e., the clasts are within a single lamina or group of laminae) and the length of deformation surrounding the clasts, i.e., a pattern which is much fulfilled in e.g., Late Paleozoic Ice Age outcrops in Australia that are commonly considered to be glaciogenic (see figures in Eyles et al., 1997 and Fielding et al., 2023). There should also be a correlation between clast size and impact force, but such a correlation has not been studied systematically in the field (Bronikowska et al., 2021).

A more neutral label for dropstones, except for outsized clasts, would be lonestones, which is a non-genetic label (Neuendorf et al., 2005).

9. Erosional structures, lineations, valleys, fjords and sculpted bedrock

Lineations formed by Pleistocene glaciers may cover large areas, from glaciers moving over heights and down in valleys (Eyles et al., 2018; Bukhari et al., 2021), while those present in the pre-Pleistocene are commonly few or only single and may

Table 2. Sedimentary structures next to outsized clasts. The upper seven structures were mentioned and defined by Thomas & Connell (1985) from dropstones (see Figure 5), and the data below the line are from the documentation in the main text. The differences between documented (Quaternary) dropstones, compared to outsized clasts that are commonly interpreted to be dropstones in pre-Pleistocene deposits, are described in the right-hand column.

Documented structures of glacial dropstones	Common appearance of pre-Pleistocene "glaciogenic dropstones"
Bending below	Similar, but may be less; more often like draping all around the clasts
Penetration, laminae are disrupted, commonly 1/3 to 2/3 of clast size	Possible, but commonly less penetration and more often only at sharp edges of clasts
Rucking below	Present, but more often only one sided
Rupture below	May be present if at front of a SGF in soft sediment
Bending above	Similar, but may be less; more often like draping all around the clasts
On-lap above, laminae are disrupted	Similar, but more often sediments thin out and are draped around the clast; there may be a bulge upwards too
Rupture above, laminae are disrupted	May be present, but would be more common if a clast has been dropped
Dropstones come in all sizes	Commonly small, only a few cm
Approximately similar clast size of dropstone as in till	Smaller size than in "tillite" or accepted SGF deposits
No correlation between sediment thickness and clast size	May be correlation between sediment thickness and clast size
Deformation of sediment locally and probably quite similar on both sides of clast	Deformation of sediment more extensive, including push and current structures, and different on opposite sides
Penetration common	Clast often within single beds
Fabric may be inclined or subvertical	Fabric similar to SGF deposits

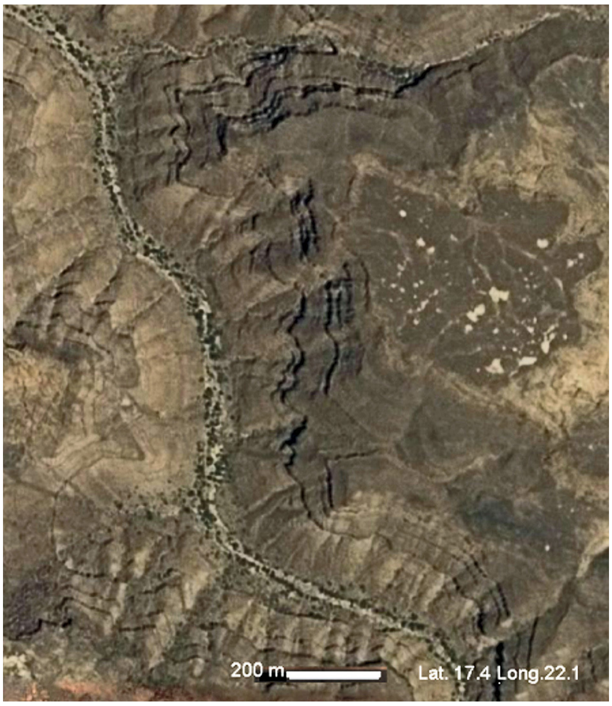

Fig. 6. In the area which is interpreted to display glacial lineations in Chad, the underlying bedrock consists of superimposed dipping sandstone beds. Erosional processes on roughly level areas may produce an appearance of lineations from these dipping beds, independent of the erosional process. The photograph shows one example of dipping sandstone beds from the area in question, but here displaying curved and not straight erosional surfaces. An intermittent creek is visible in the centre of the photograph. Other detailed photographs from the same area were published by Le Heron (2018, figs 3, 4) showing juxtaposition to the underlying dipping sandstones, including positive features labelled nunataks or drumlins by Le Heron (2018), with an appearance similar to those made by flooding, rather than deep erosion made by glaciers (photograph from Google Earth/Google Maps).

be more bevelled or downcutting. Lineations in the Ordovician of Sahara, interpreted from satellite imagery to be glaciogenic (Le Heron, 2018; Le Heron et al., 2022a), follow the structure of underlying and planed-off dipping sandstone beds (Fig. 6). On closer inspection, the lineations are irregular, meaning that they may not be lineations but surfaces exposed to non-glaciogenic erosion (detailed Google Earth study of the area which is interpreted to display lineations by Le Heron, 2018). Glacial lineations would be independent of the linearity of underlying sediments, and some lineations are probably produced from tectonics (Le Heron, 2016, 2018). Sculptured areas, including pavements, have also been shown to have originated in dipping strata probably by tectonics and recent erosion, above a palaeolandscape with an equivocal origin (Vandyk et al., 2021; Le Heron et al., 2022a). Lineations in southern Africa interpreted to be from glaciation are shorter and wider than their Pleistocene "counterpart" (Andrews et al., 2019).

SGFs and water currents have been shown to sculpture large areas, including positive landforms with an appearance of nunataks or drumlins, especially if there are catastrophic flooding events, but these commonly leave more bevelled landforms and downcutting lineations than glaciation (Burr et al., 2002; Plescia, 2003; Rodriguez et al., 2005; Major et al., 2005; Moscardelli et al., 2006; Leask et al., 2007; Gupta et al., 2007, 2017; Robinson et al., 2017; Ortiz-Karpf et al., 2017; Nwoko et al., 2020a, 2020b).

Glaciogenic (alpine) valleys are supposed to be commonly U-formed in shape, while fluvial or other valleys are supposed to be more often V-shaped. However, research on almost 900,000 transverse logs and shapes of different valleys have shown that this is a truth with modification, i.e., different shapes are possible in many environments (examples in van der Vegt et al., 2012; Coles, 2014; Gales et al., 2014; Ortiz-Karpf et al., 2017; Pehlivan, 2019; Puga Bernabéu et al., 2020). Also, thousands of different canyons and other valleys are formed by processes that are non-glacial, including tectonism and SGFs, in all kinds of bedrock, including hanging valleys (Shepard & Dill, 1966; Clapham & Corsetti, 2005; Mitchell, 2006; Lamb, 2008; Amblas et al., 2011; Normandeau et al., 2015), so there may be many different interpretations of pre-Pleistocene valleys that have been interpreted to be glaciogenic (Giddings et al., 2010; Macdonald et al., 2011; Coles, 2014; Ortiz-Karpf et al., 2017; Bechstädt et al., 2018; Pauls et al., 2019; Isbell et al., 2021; Vandyk et al., 2021). If valleys display an irregular (not polished/abraded/sculptured) basal boundary geometry, they may be more compatible with SGFs and slides than glaciation, even though this is not always the interpretation made (Dakin et al., 2013; Sobiesiak et al., 2018; Soutter et al., 2018; Dufresne et al., 2021; Molén 2021).

Recent research at Namibian basins displays areas below diamictites where the basal unconformity may be undulating, highly irregular and heterogeneous, with areas of heavy sediment injections into fractured bedrock that are interpreted to be subglacial (Le Heron et al., 2021b) and not only clastic dykes; the latter may be common subglacially (e.g., Sokołowski & Wysota, 2020). Sediment injections are regular features of SGFs, and together with the general appearance of the area, this may indicate an origin by SGFs and not glaciation (Dufresne et al., 2021; Molén, 2021, 2023a; Molén & Smit, 2022).

Fig. 7. One of the smallest (former) fjords, which is now the *c.* 2-km-long lake Ågvatnet next to the small village of Å in Lofoten, Norway. All characteristic appearances of fjords are present even in these smallest fjords. They are narrow, overdeepened and display a prominent transverse ridge at the outlet. At this former fjord the ridge has been the foundation for the road and house in the lower picture (the fjord is barely visible behind the house and ridge).

The most interesting valleys from a glaciogenic point of view are fjords. These display a very characteristic appearance, i.e., narrow, overdeepened and with a prominent transverse "sill" or ridge at the outlet into the sea (or lake) (Fig. 7). If a valley has no transverse ridge at the outlet, it is probably not a fjord, even if that may be the interpretation which is published (e.g., Dietrich et al., 2021). Overdeepening of ancient valleys may be more difficult to document, because surrounding mountains may have eroded away, but if there is evidence of deeper areas where the surroundings are higher, it may provided evidence of a fjord. No valley has ever been documented in a pre-Pleistocene formation that displays the typical appearance of a fjord. But, fjords are very common in Pleistocene and more recent glaciated areas, and it could be suspected that they should be similarly prominent in more ancient areas, as these landforms do not readily vanish.

Plucking, which is a typical glacial phenomenon, also may be induced by water currents and gravity flows (Dakin et al., 2013; Lamb et al., 2014; Hodgson et al., 2018), but these often display steep stoss sides and gentle lee sides in bedrock (Molén, 2023a), contrary to glaciogenic landforms (e.g., Krabbendam & Glasser, 2011). Tectonic forms may be moulded into sculpted glacial-apparent bedrock by fluvial action, including shapes reminiscent of roches moutonnées (Vandyk et al., 2021).

10. Channels, tunnel valleys and eskers

Channels are excavated by many non-glacial processes, including SGFs (Talling et al., 2007; Keller et al., 2011; Macdonald et al., 2011; Dakin et al., 2013; Kneller et al., 2016; Shanmugam, 2016; Baas et al., 2021). If channels are later filled with more resistant sedimentary material, and the material around erodes away, the resulting land form will appear to be a longitudinal ridge, i.e., a topographic reversal. In northern Africa and the Arabian Peninsula, there are thousands of channels which have been filled with sediment, and many of these now display an appearance that is in part similar to eskers (Zaki et al., 2018, 2020, 2021). Le Heron et al. (2018) recognised that there are no "suitable modern analogues" to channels which have been interpreted to be Ordovician tunnel valleys, which make the interpretations equivocal (Molén, 2023a).

Pleistocene and recent esker sediments are commonly sorted, with large rounded clasts in the bottom middle, and then finer on top and at the margins, even though many eskers are made up mostly from sand. There is often tectonic deformation displayed by eskers. Large clasts, which have collapsed from the overlying glacier, are often present on their tops (Frakes, 1979). There is some evidence of tectonics in longitudinal landforms which have been interpreted as eskers (Allen, 1975; Biju-Duval et al., 1981), but not so much that it has to be more than local deformation which could have occurred simply by gravitational collapse. No large clasts have been documented on top of esker-like formations from pre-Pleistocene deposits.

11. Laminated sediments

Recent experiments have shown that clay laminae can form as quickly as sand or silt laminae, not only in turbidites but also during slower deposition (Schieber et al., 2007, 2013; Sutherland et al., 2015; Yawar & Schieber, 2017). This process results from clay particles flocculating and therefore quickly sinking. Earlier settling experiments with flumes had disintegrated these floccules, and therefore clay particles did sink much more slowly. A recently described process which more clearly unfolded how laminae are quickly produced and able to cover large areas, is a combination of high fluid shear and sediment concentration (Al-Mufti & Arnott, 2023). In conclusion, there are many indications that presumed varves in pre-Pleistocene outcrops have been deposited much more quickly than on a yearly basis, which may be discovered by detailed studies (Matys Grygar, 2019; Smith, 2019, 2023 reinterpreting 60 recently published papers on this subject; Kochhann et al., 2020; Isbell et al., 2021; Molén, 2021).

12. Periglacial structures, soft sediment deformation and tectonism

Geological features which may appear to be formed by permafrost, such as patterned ground and ice wedges, also may form by desiccation, small-scale tectonics, and almost any volume change in sediments (Bryan, 1983; Eyles & Clark, 1985; Eyles, 1990; Tipper et al., 2003; Robinson et al., 2017), and they may therefore be easily misidentified (Molén, 2023c).

Large-scale soft sediment deformation may be difficult to evaluate if it is glaciogenic or SGF. So far, no clear characteristics have been identified for one or the other potential origin (Sobiesiak et al., 2018; Rodrigues et al., 2020; Molén, 2023a).

13. Glaciomarine and glaciolacustrine environments

Yearly varves only form in fresh water, but apart from that there is no great difference between sedimentation in glaciomarine and glaciolacustrine environments. In Quaternary glaciomarine and glaciolacustrine environments there is an abundance of linear, transverse and irregular geological features (Dowdeswell et al., 2016a, 2016b). In pre-Pleistocene deposits interpreted as glaciomarine or glaciolacustrine these features are generally absent, even though subaqueous depositional areas should be excellent for the preservation of such geological landforms. Single examples of geological landforms with such an appearance in ancient deposits may be intepreted to be glaciogenic, but there are no large areas demonstrating these features, even if the areas under study ought to display such landforms in large numbers (Molén, 2021). Almost the sole piece of evidence given for a glaciomarine or glaciolacustrine origin for a pre-Pleistocene outcrop is the interpretation of outsized clasts as dropstones (this includes the majority of papers mentioning outsized clasts; e.g., Freitas et al., 2011; Figueiredo & Babinski, 2014, Milana & Di Pasquo, 2019; Molén, 2023a).

14. Fossil vegetation

Plant fossils, commonly as coal but also separate fossils, are often deposited next to or occasionally even within diamictites which are interpreted to have formed from large-scale Late Paleozoic glaciations. There is evidence for more plant refugia than earlier recognised during the last continental Pleistocene glaciation (Birks & Willis, 2008; Binney et al., 2009; Westergaard et al., 2019). However, there is no evidence from large forests next to the continental glaciers during the Pleistocene, and both recent forests growing at former glaciated areas and Pleistocene refugee plants have typical cold weather species (e.g., *Picea*, *Larix*, *Betula*). The fossil plants stratigraphically and palaeogeographically next to Late Palaeozoic diamictites are considered to be near continental glaciers, or close to palaeopoles in the same sedimentary successions as geological features that have been interpreted to be glaciogenic. Therefore these plants are often considered to have been adapted to cold climate. However, these plants commonly display large, complete, non-toothed leaves which are typical of warm-weather plants, possibly subtropical or tropical, and not small, toothed leaves indicative of polar/subpolar climates (Götz et al., 2018; DeVore & Pigg, 2020; Gastaldo et al., 2020a, 2020b; Mays et al., 2020; Tripathy et al., 2021). Plants are better climate indicators than sediments, which would undermine interpretations of former cold climates in the Late Palaeozoic.

15. SEM studies

After reorganisation of patterns of data from older studies, and conducting process-oriented studies of

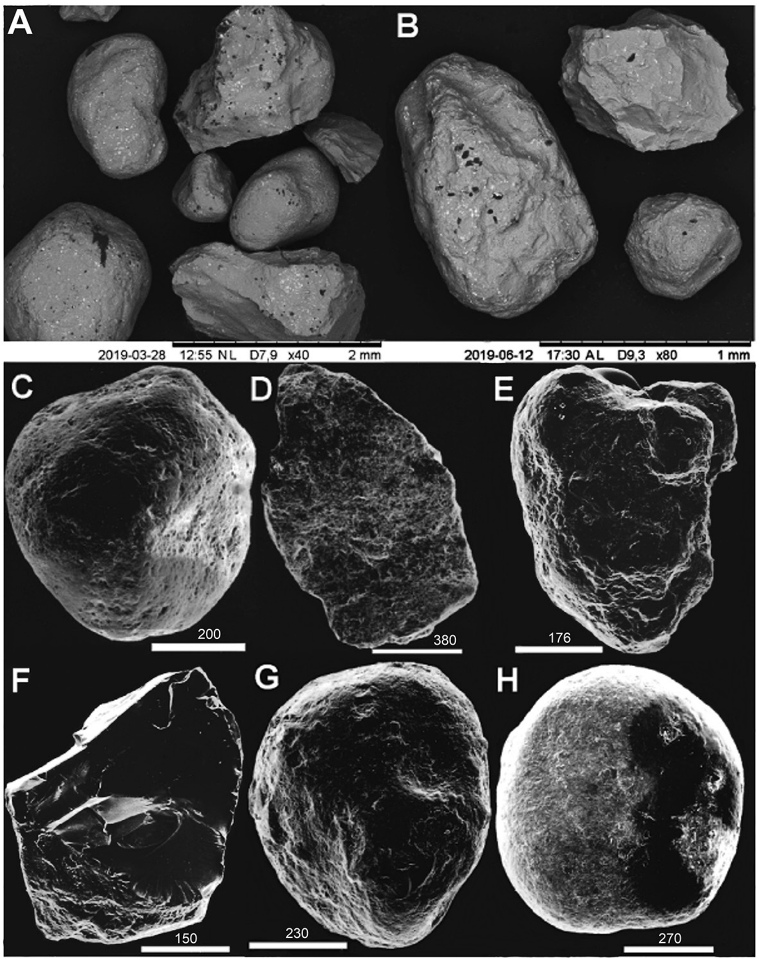

Fig. 8. SEM images of quartz sand grains from diamictites which have been interpreted to be glaciogenic; compare these to grains in Figure 9. Except for a few grains displaying fractures, these are more or less spherical and display a combination of regular abrasion all over the grain surfaces combined with weathered surfaces, i.e., surface microtextures which are typical of multicyclical grains. The grain surfaces display no evidence of glaciation, i.e., irregular abrasion and especially irregularly abraded fractures. A few grains display fractures that are either sharp or otherwise regularly abraded all over the fracture faces, i.e., these grains are still not similar to glaciogenic grains but only display fractures that are produced in any high-energy environment and no irregular abrasion. **A –** Ordovician Pakhuis Formation, South Africa; **B –** Carboniferous Dwyka Group, South Africa; **C-D –** Hirnantian Kosov Formation, Czech Republic. C is the most common appearance; D is rare; **E-H –** Neoproterozoic diamictites, Varanger, Norway. E, G and H display the most common appearances; F is rare. Notice the non-abraded sharp fractures in F, indicating only fracturing, yet no abrasion following fracturing.

how surface microtextures on quartz sand grains originate in different environments (Molén, 2014, 2017), this area of research has become a well-functioning working tool for the study of all kinds of sediments, including diamictites (e.g., Mahaney, 2002; Molén, 2014, 2017, 2023a; Molén & Smit 2022).

Minerals are fractured in many environments, and therefore solitary fresh and sharp fractures by themselves do not indicate glaciation (Molén, 2014). Glaciers simultaneously both irregularly fracture and irregularly abrade rock material (i.e., not evenly/regularly spread on rocks or grain surfaces but more or less in separate patches), so in glaciogenic sediments evidence from both these processes is present. There is often overprinting of fractured and abraded surface microstructures on glaciogenic grains, i.e., recurrent fracturing and irregular abrasion on the same grain surface. Therefore there are unique combinations of surface microtextures that have been generated by glaciers, i.e., fresh fractures that have probably at the same time become irregularly abraded during short, intense contacts with hard clasts or bedrock (Molén, 2014). In less energetic environments, e.g., transport by wind or water, regular small scale abrasion/comminution will spread over the complete grain surface, and such abrasion will round off the grain surfaces regularly because of the continual and slight abrasion/comminution, and also, at the same time, will induce physical and/or chemical weathering. Subglacially, grains are not abraded constantly, but when abrasion takes place it is commonly strong and in more confined areas. This has been documented in Pleistocene and more recent deposits and is clearly tested (Mahaney, 2002, Molén, 2014; Kalińska-Nartiša et al., 2017, Passchier et al., 2021; Kut et al., 2021; Kalińska et al., 2021).

SEM studies conducted on samples from pre-Pleistocene diamictites indicate a non-glacial origin of Neoproterozoic outcrops in northern Norway (Molén, 2017), Upper Ordovician outcrops in South Africa (Rowe & Backeberg, 2011) and in the Czech Republic (Štorch, 1990), and in Upper Palaeozoic deposits from the Dwyka Group in South Africa (Molén & Smit, 2022). From the evidence displayed by macroscopic geological features, there is no definitive evidence of glaciation displayed by these outcrops (Rowe & Backeberg, 2011; Molén, 2017; Molén & Smit, 2022) (however, the outcrops in the Czech Republic have previously only been macroscopically studied and considered to be of glaciomarine origin; Štorch, 1990). Typical examples of quartz sand grains from these areas are here shown in Figure 8 and are compared to examples of Pleis-

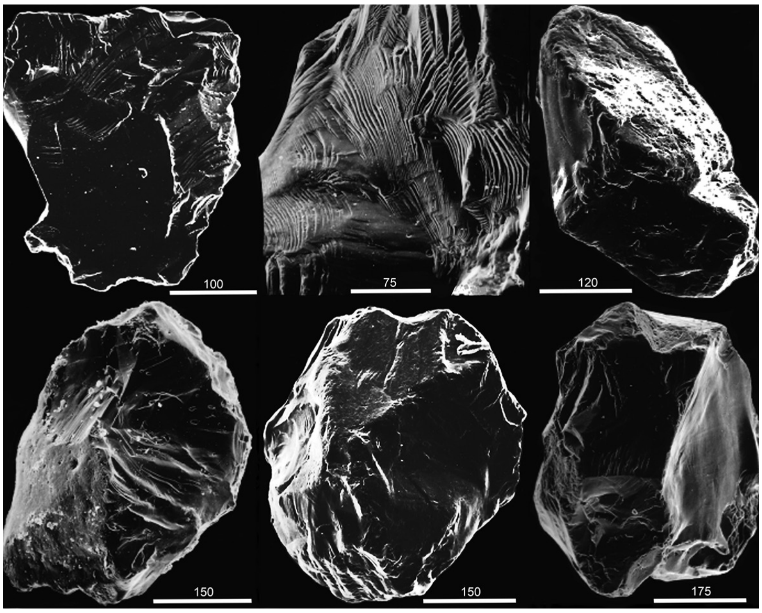

Fig. 9. Typical surface microtextures on quartz sand grains from Pleistocene glacial environments; compare these to grain surfaces in Figure 8. All these grains display a combination of multiple fractures, irregular (strong) abrasion both on many fractures and on non-fractured parts of the grains. The upper three pictures are from an area of granitic and gneissic bedrock, Västerbotten County, Sweden. The lower three pictures are from an area displaying mainly Phanerozoic sedimentary bedrock in southern Ontario, Canada. The small areas of weathered parts of the grains from southern Ontario are original quartz sand grain surface microtextures from the non-glacial Phanerozoic sedimentary bedrock, and are similar to the grain surfaces in Figure 8. More examples of glaciogenic grain surface microtextures were published in Mahaney (2002), Molén (2014, 2017, 2023a) and Molén & Smit (2022).

tocene glaciogenic quartz grains from Scandinavia and Canada in Figure 9 (Molén, 2014). The evidence is clear cut, where the glaciogenic grains display a combination of multiple fractures, irregular abrasion is present both on parts of the fractures and on non-fractured parts of the grains. The grains from (nonglacial) diamictites display a combination of more or less spherical grains, and they are regularly abraded all over the grain surfaces combined with weathered surfaces. They display a few fractures that are either sharp or otherwise regularly abraded all over the fracture faces. In view of the fact that we assume that natural laws have not changed, and the process of inducing surface microtextures of (recurrent) fracturing and (irregular) abrasion is strictly mechanical (purely chemical processes change the surfaces in different ways and artificial coatings can be easily traced; Somelar et al., 2018; Molén & Smit, 2022), these features positively indicate that the deposits are non-glacial.

16. Discussion

Studies of diamictites have often been based on models and have adhered to older interpretations as a starting point (e.g., Le Heron et al., 2022b). This is reasonable, but progress in sedimentology and other research disciplines which may be relevant for studies of ancient glaciations and diamictites, during the *c*. 50 last years, have shown that many former interpretations need to be abandoned (e.g., see: Rodrigues et al., 2020; Kennedy & Eyles, 2021; Molén, 2023a). Proxies for ancient climates based on geochemistry, including carbon and oxygen isotopes, chemical weathering index (CIA), ikaites/glendonites and cap carbonates, are not set in stone either, but may be more clearly connected to environment than to climate (Vickers et al., 2023; Molén, 2024).

If a certain area formerly has been interpreted to have been glaciated, then the appearance of geological features of that area may have been used as evidence of glaciation also in other areas, instead of searching for field evidence for possible alternative interpretations. The geological features most easily evaluated which are interpreted to be glaciogenic, are as follows:

1. **Striated surfaces**, where papers may describe these as glaciogenic even though the appearances are different from both Quaternary subglacial and iceberg-produced striations and pavements. These pre-Pleistocene surfaces are often planar, displaying straight and invariably striations and grooves (e.g., Fig. 3), displaying appearances not observed to have been produced by glaciers in the Quaternary, but commonly by SGFs (Table 1). These pavements are often soft sediment surfaces (Le Heron et al., 2020).
2. **Outsized clasts** interpreted to be dropstones, where the patterns of deposition and sedimentary structures are seldom recognised or even reported in detail or in great numbers, e.g., the often small size of these clasts (one or a few centimetres), or if large size the appearance and position may indicate SGFs, for example, in the Cryogenian deposits of Namibia (Domack & Hoffman, 2011; Hoffman et al., 2021; Le Heron et al., 2021a).
3. **Small size and number of erratics in diamictites**, compared to erratics present in parts of the outcrops interpreted by most researchers to be from SGFs, and compared to Quaternary glaciations.
4. **Surface microtextures** where researchers have to abandon or not refer to documented differences (e.g., Mahaney, 2002, Molén, 2014) to interpret the data in a glaciogenic framework. Soreghan et al. (2022, p. 3) wrote that, „More recent work has argued that only large-scale fractures that cover at least one-quarter of the grain surface can be considered glaciogenic, as smaller scale fractures can be produced in a wide variety of environments (Molen, 2014).” Those authors had to abandon the documentation in the quoted paper, of the unimportance of simple fracturing, and the mandatory presence of combined abrasion and fracturing, as is described in the conclusion as, “A glacigenic grain typically exhibits largescale fractures (F1) and irregular abrasion (A1)” (Molén, 2014, 2023b). Similarly, Le Heron et al. (2020) studied grain surfaces on small grains displaying minute surface microtextures which did not show irregularly abraded glaciogenic fractures.

Therefore, if the interpretation of an outcrop is wrong, then other areas studied with the same mindset may also have been misinterpreted. Instead, it is always more appropriate to start from recent observations and experiments and compare the outcrops with recent and Pleistocene geological features so as to arrive at a correct interpretation. Otherwise it may be as Moncrieff & Hambrey (1990) suggested, that an ancient outcrop (in this case Neoproterozoic) “... does not have a suitable modern analogue” (p. 389) and “... can aid interpretation of modern sediments ...” (p. 408), instead of the opposite.

17. Conclusions

It has been shown that many similarly appearing geological features may form in different environments. There are considerable differences in the appearance of the details of these features, which after documentation may indicate a different origin than if a study starts with a formerly accepted interpretation. Often details which are necessary to document if the study is going to discriminate if an outcrop has been generated by SGFs or glaciation are not considered, let alone documented, in cases where there is a consensus interpretation of a deposit, or where the researchers have already developed an interpretative framework. This is a hindrance to progress in the area of diamictites, mainly in the documentations of glaciogenic and SGF features. Therefore, it may be necessary to restudy many outcrops and start with multiple working hypotheses rather than with a paradigm, model or formerly long-held interpretation, e.g., not, "Our interpretation builds on a rich tradition that envisage a glacial origin ..." and "Even diamictites known to have been deposited during a major ice age may paradoxically contain little to no evidence for direct glacial processes" (Le Heron et al., 2022b, pp. 1, 8).

As has been shown earlier, evidence from patterns displayed by appearance, size and sorting of erratics, striated surfaces/pavements, outsized clasts/dropstones and surface microtextures, is easily documented and evaluated if an area/outcrop/formation is glaciogenic or not (see Table 3). For more extensive documentation of the geological features mentioned here, and also of other geological features which discriminate between glaciation and other processes, reference is made to the discussion, tables and Appendix in Molén (2023a).

Table 3. Diamict Origin Table of geological features formed in environments of glaciation, mass wasting and tectonics. Columns display how common a feature may be, and whether it is glaciogenic or non-glaciogenic. 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. In the column for glaciogenic processes, structures that form by non-glaciogenic processes in a glacial environment are not included, e.g., not debris flows in a glacial environment. However, if clasts in debris flow deposits are glacially striated, this may be evidence of glaciation. By contrast, debris flow deposits with no other evidence of a glacial environment than clasts displaying striations that may form in debris flows, is not helpful in interpreting a former glaciation.

Feature	Origin	
	Glacial	Non–glacial
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
Fine grained and matrix supported	2	1–2
Clast diameter/bed thickness correlation	0–1	2
Sorting and/or grading	0–1	2
Streaks of different deposits/diamictites	1	2
Entrenched contorted slabs of unconsolidated soft sediments	1	2
Fabrics		
strong	2	1
weak	1	2
bimodal	2	1
planar	1	2
variable in sections	1	2
Erratics	2	2
low-inclination transport, slopes close to 0.001°	2	1–(2)
> 1–3 m diameter	2	1–(2)
smaller in "tillites" than in accepted concomitant SGF deposits	0	2
jigsaw fractures	–	1
Striated clasts	1–2	1–2
subparallel striations	2	1
parallel striations	1	2

Feature	Origin	
	Glacial	Non–glacial
curved and/or random striations	1	2
crossing striations	2	1
soft, angular, not striated co-occurring with hard, rounded, striated	1	2
Faceted and/or polished clasts	1–2	1–(2)
Pavement/striations/grooves	2	1
subparallel striations	2	1
parallel striations	1	2
crossing striations	2	1
polished striations	2	1
soft-sediment pavements	0–1	2
sediment pressed down	–	2
pressed-up ridges	–	2
stacked pavements	0–1	1–2
irregular horizontally and vertically	2	1–2
regular striations	0–1	1–2
continue over extensive areas	2	1
interlaminated sediments/traction carpet	–	1
ripples, laminae	–	1
brecciation	1	1
overhanging walls	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 striations/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	0–1
Boulder pavements	2	1–2
Roches moutonnés/plucking	2	(0–1)
uneven surfaces	0–1	1
Fjords, overdeepened, regular, ridged outlet	2	(0–1)
Eskers (or otherwise not eskers)	2	(0–1)
sorted deposits	2	1
large clasts on top	2	(?)
Glaciofluvial restricted by ice, kames	2	–
Dropstones/lonestones	2	2
random fabric	2	1
weak fabric	1	2
varied size of clasts	2	1
small grain size	1	2
obvious small size compared to other sediments which are interpreted to be glaciogenic	–	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 clasts penetrate	2	1
sediment thickness changes around clast	1	2
lee side structures/movement/wake eddies	1	2

Feature	Origin	
	Glacial	Non–glacial
rip-up clasts	0–1	1
“Varves” (with lonestones/dropstones) drape diamcitite	1	2
Rythmites, thick „winter layer”	0–1	2
Small tectonics/deformations, e.g., clastic dikes or water escape tructures, especially within rhythmites	1	2
“Glaciomarine” deposits drape diamcitite	1	2
Submarine glacial features, e.g., linear, transverse and irregular bedforms	2	1
Features not formed by frost but resembling periglacial features	1	2
Surface microtextures only fractured, or both weathered and regularly abraded	–	2
Surface microtextures synchronously fractured and irregularly abraded	2	–
Geologic features which display few criteria to easily interpret their origin		
Geochemistry	Too many exceptions and interpretations	
Lineations of landforms	Too few criteria	
Glacial valleys	Too much variation	
Channels/tunnel valleys	Too few criteria	
Large soft-sediment tectonic structures	Too much variation	

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 Diamict Origin Table reproduced here, present the conclusions from the Journal of Palaeogeography (Molén, 2023a), and has been in part published earlier by the present author in articles in Geologos (Molén, 2017, 2021; Molén & Smit 2022). The Diamict Origin Table is used by permission.

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