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The origin of upper Precambrian diamictites, northern Norway: a case study applicable to diamictites in general

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Abstract

Upper Precambrian diamictites in Varangerfjorden (northern Norway) have been examined for evidence of origin, whether glaciogenic, gravity flow or polygenetic. Studies of geomorphology, sedimentology and surface microtextures on quartz sand grains are integrated to provide multiple pieces of evidence for the geological agents responsible for the origin of the diamictites. The documented sedimentary and erosional structures, formerly interpreted in a glaciogenic context (e.g., diamict structure, pavements and striations) have been reanalysed. Field and laboratory data demonstrate that, contrary to conclusions reached in many earlier studies, the diamictites and adjacent deposits did not originate from glaciogenic processes. Evidence from macrostructures may occasionally be equivocal or can be interpreted as representing reworked, glacially derived material. Evidence from surface microtextures, from outcrops which are believed to exhibit the most unequivocal signs for glaciation, display no imprint at all of glaciogenic processes, and a multicyclical origin of the deposits can be demonstrated. The geological context implies (and no geological data contradict this) an origin by gravity flows, possibly in a submarine fan environment. This reinterpretation of the diamictites in northern Norway may imply that the palaeoclimatological hypothesis of a deep frozen earth during parts of the Neoproterozoic has to be revised.

Key words: Surface microtexture, debris flow, diamictite, tillite, Bigganjargga, snowball Earth

1. Introduction

More or less by default, many diamictites have been regarded as tillites or at least to have originated from glaciogenic processes. This inference may be based on palaeoclimatic interpretations (see documentation in e.g., Jensen & Wulff-Pedersen, 1997; Arnaud & Eyles, 2004), and/or that the outcrops have "chaotic" appearances, with matrix-supported clasts, striated pavements and supposed dropstones nearby. If the research area is considered influenced by glaciers, geomorphological, depositional and tectonic data from nearby outcrops are often interpreted within that context.

After Schermerhorn (1974) published his classic paper on diamictites, by comparing recent glaciogenic formations, mass flow deposits and diamictites/diamictons, researchers have reinterpreted many "tillites" as alternative geological phenomena, especially mass flow deposits. The logic presented in this classic paper has been followed here. My research has been integrated with recent advances in the knowledge of geological processes in a study of diamictites in the Varangerfjord area (northern Norway; Fig. 1). The Varangerfjord diamictites are most often interpreted to have originated during more or less glacial conditions.

The best-known "glaciogenic" formation in the Varangerfjorden area, the Geađgefális (formerly

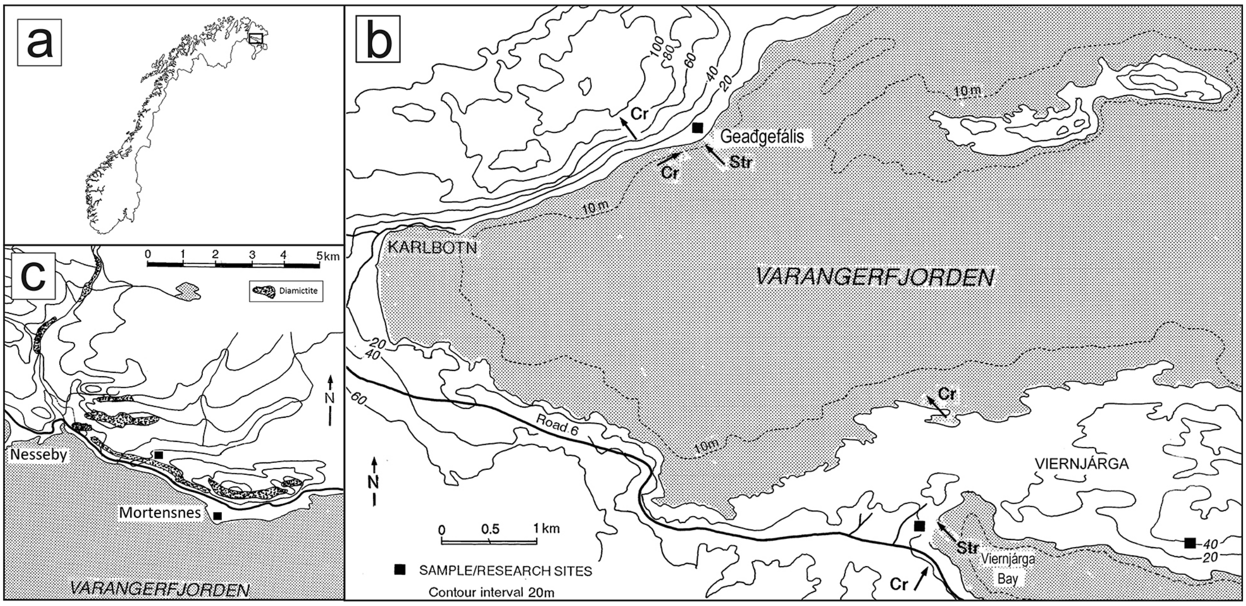

Fig. 1. Localities in the Varangerfjord area (northern Norway), from where samples have been collected or at which a more detailed analysis have been performed. Geađgefális, Viernjárga (Veines) Bay, the mid-eastern part of Viernjárga where samples were collected (right square). Mortensnes with the Mortensnes Formation (sample site marked, square between Nesseby and Mortensnes) and the Smalfjord Formation tectonic formations at Handelsneset (square east of Mortensnes) which were interpreted to be glaciotectonic by Arnaud (2008). The insert map of the Mortensnes area is situated *c*. 5 km northeast of Viernjárga, on the north coast of Varangerfjorden. Arrows – palaeodirections, Cr – cross bedding, Str – striations. Arrows directed northeasterly show the transport direction in the sandstone underlying the diamictites (after Bjørlykke, 1967).

Bigganjargga) diamictite, is difficult to differentiate from a till solely by a superficial visual inspection, as the general diamict texture is similar in both. This outcrop has been restudied in greater detail and additional techniques were used in order to reveal whether there are diagnostic geological criteria for a glaciogenic origin or whether the origin may be from mass flow.

2. Geological setting

In Finnmark Fylke at Varangerfjord, Tanafjord and Laksefjord (northern Norway), there are numerous outcrops of upper Precambrian diamictites (Rice et al., 2011). Most of these form part of the Smalfjord Formation, which occurs over an area of approximately 20,000 km². The general geology, age and geological and tectonic setting of the area have been described and discussed by many researchers (e.g., Arnaud & Eyles, 2002, 2004; Edwards, 2004; Rice et al., 2012).

No researcher has ever questioned the general diamict structure of the outcrops in the study area. There are, however, some geological structures and textures which are of special interest in interpreting the origin of the diamictites. These are documented in the present paper.

2.1. Varangerfjord diamictites

Most of the Varangerfjord diamictites have recently been interpreted to have formed by direct or indirect glacial action by most researchers (see references in Rice et al., 2012). This interpretation is so widely accepted by some researchers that non-glaciogenic interpretations of the Varangerfjord area diamictites have been noted as having "caused some confusion" (Laajoki, 2002, p. 410). The diamictites include numerous deposits in Finnmark Fylke (Edwards, 1975, 1984), inclusive of the Mortensnes Formation in the northern part of Varangerfjord (Beynon et al., 1967) and the Smalfjord Formation (Fig. 1). The best-studied of these diamictites is the classic Neoproterozoic so-called Reusch moraine, Bigganjargga tillite (Bjørlykke, 1967) or the Geađgefális, situated in the southwestern part of Varangerfjord. This outcrop has been renamed Oaibaččannjar´ga in the recent geological literature because the name change on geological maps conforms with the older Sami names (Edwards, 1984). However, according to the Sami authorities, the name of the "tillite" is Geađgefális, and it is situated on the peninsula of Oaivbáhčannjárga (Y. Johansen, project leader, pers. comm., March 2014).

The Geađgefális diamictite is a *c*. 3-m-high and approximately 70-m-wide, mound-like formation, draped by sandstone. It is one of few Precambrian alleged tillites which sits on a striated pavement, and therefore has been the focus of much geological interest. The outcrop is protected by Norwegian law as a natural preservation area (Bjørlykke, 1967). It is situated adjacent to the sea, in an area of severe climate, and the diamictite and its surroundings are slowly weathering away. Other diamictites in the area have, more or less by default, been interpreted as glaciogenic or tillites without discussing or documenting sedimentological details which could be used for genetic interpretations. For instance, no specific glaciogenic features have been documented (e.g., see Edwards, 1984; Laajoki, 2002).

On the Viernjárga (Veines peninsula), approximately 4.5 km east of Geađgefális, there are many diamictites (Fig. 1). The outcrops on Viernjárga are smaller in size, not continuous but spread over a larger area, and display affinities that are less similar to tills than the Geađgefális (compare descriptions in Edwards, 1975, 1984).

The Mortensnes Formation at the northern side of the Varangerfjord is younger than the Smalfjord Formation. It is considered, in large part, to be glaciomarine by many researchers (e.g., Edwards & Foyn, 1981), displaying many gravity-flow deposits and supposed dropstones. The formation is occasionally described as having full cycles of glaciogenic sediments. For example, Rice et al. (2011, p. 600) wrote that, "For both cycles, lodgement tillite was followed by floating ice, giving finer-grained sedimentation and dropstones".

Most workers have considered the origin of most of the Varangerfjord diamictites to be probably proglacial, or ice marginal, to a large part deposited by glacially induced debris flows and/or glaciotectonic in origin (Edwards, 2004; Arnaud, 2008, 2012; Rice et al., 2012). However, others have suggested that there possibly was no glacial influence at all (except maybe from sea ice) for deposits which are considered to display the best proof of glaciation (e.g., Jensen & Wulff-Pedersen, 1996, 1997; Arnaud & Eyles, 2002). Mainly the pavements and diamictites are taken as evidence of glacial action, and most other geological data are interpreted in that context.

2.2. Diamict macrotextures and striated clasts

Except for the general diamict texture of outcrops there are geological textures and structures in the study area which are relevant for genetic interpretation.

Soft-sediment deformation in non-tillitic sediments in the "proglacial" area of the Smalfjord Formation are interpreted as glaciotectonic or gravity flows deposits (Arnaud, 2008, 2012). Many different soft-sediment structures form during various kinds of tectonism and gravity flows (e.g., Arnaud, 2012 and references therein). Arnaud (2012, p. 52) noted that, "... no single deformation structure is diagnostic of any specific setting and trigger as they often occur in a number of different glacial and non-glacial settings ...". Combinations of structures may be of more significance. Even if many deposits in the Smalfjord Formation result from non-glaciogenic gravity flows, the combination of deformation structures in some small outcrops at Handelsneset close to Mortensnes (Fig. 1) have been interpreted to be from "spatially variable coverage of ice" that shifted on a scale of only a few kilometres (Arnaud, 2012, p. 52).

In the Mortensnes Formation there is an abundance of gravity flow and slide structures, e.g., transported rafts of soft sediment and flow structures. The largest transported blocks in the Mortensnes Formation are up to *c.* 40 m long (Edwards, 1984), but a 100-m-long and 3-m-thick raft from the Varangerfjord area was mentioned by Edwards & Foyn (1981). There are no geological structures that bear direct evidence of glaciation in the Mortensnes Formation.

Striations on clasts, which often are interpreted as evidence of glaciation, appear to be rare. They were not observed in the area by Jensen & Wulff-Pedersen (1996), Arnaud & Eyles (2002) or by myself. None are found on gneisses and sandstones, but quartzite pebbles are reported to display striations (Bjørlykke, 1967), and other striated clasts have been recorded from Viernjárga (Edwards, 1975) and the Mortensnes Formation (Edwards, 1984). However, striations on clasts are not uncommon in gravity flows, and even quartzites can be striated (e.g., Schermerhorn, 1974).

2.3. Sub-diamictite erosional forms

In the study area there are a few small striated pavements. The pavement that has been considered most often in this area is the one at Geađgefális. This is the largest one; it is visible over many square metres and continues out of sight, covered by the diamictite. It can also be seen in cross section for many metres. Striations are in two main directions. An area within six of 86 striations is described as "polished" (Rice & Hofmann, 2000). Below this "polished" area, in the upper part of the pavement, there is a very thin breccia, *c.* 0.1–2.5-mm-thick. Rice & Hofmann (2000) argued that the pavement was solidified and that the striations and breccia were glaciogenic in origin.

The diamictites in the Varangerfjord area have been interpreted to have formed in an ancient "fjord valley" (Baarli et al., 2006) and rounded landforms have been interpreted as ancient exhumed roches moutonnées (Laajoki, 2004).

2.4. Palaeogeographical setting

The palaeogeographical setting of the area is believed to have been either high polar or low to equatorial palaeolatitude, but in view of the fact that the palaeomagnetic data for the upper Proterozoic display a large scatter, it is difficult to draw any final conclusions (Schermerhorn, 1983; Chumakov, 1988; Elston et al., 1988; Perrin et al., 1988; Young, 1991; Jensen & Wulff-Pedersen, 1996, 1997; Evans & Raub, 2011; Rice at al., 2011, 2012).

Dolostone beds are present both below and between diamictites in the area (Siedlecka & Roberts, 1992; Rice et al., 2011, 2012), and these commonly indicate a warm climate (Schermerhorn, 1974; Johnson et al., 1978; Zenger et al., 1980; Schermerhorn, 1983; McKenzie, 1991; Young, 1991). These dolostone beds have either not been discussed in a palaeoclimatological context, are believed to have formed in a cold environment, or are thought to result from climatological and chemical catastrophic turnovers on a worldwide scale (Shields, 2005).

Recent dolomite precipitation linked to cold water (which would be the case if precipitation were to take place near glaciated areas), has been observed at hot springs (Pichler & Humphrey, 2001), in mounds (Pirlet et al., 2010) or in thin layers which contain much non-dolomitic sedimentary material of different sizes in the matrix and between layers of dolomite (Monien, 2010). In sedimentological appearance, this is very different from the deposits in the Varanger area, the latter being composed of more or less pure, extensive, thick dolostone beds (Bjørlykke, 1967; Roberts, 1976; see also Shields, 2005 for similar dolostone beds worldwide).

3. Material and methods

3.1. Localities

The Geađgefális outcrop displays more similarities to tills than do all the other diamictites in the study area. It has been extensively studied by geologists and is the main object for the present research as well. The diamictites closest to this outcrop, at Viernjárga, display many similarities to Geađgefális, and therefore may support and/or modify the final interpretation of the origin. Attention is also paid to the Mortensnes Formation which is commonly interpreted to have formed during a younger glaciation.

During four field seasons in the Varangerfjord area, observations were made of macrotextures and structures at the Geađgefális and Viernjárga, as well as some 10 kilometres around Mortensnes/Handelsneset close to the main road and the coast. Geological features which have a bearing on the interpretation of the origin of the diamicties were recorded.

3.2. Grain surface microtextures – preparation

Samples for SEM analysis were collected from diamictites at Geađgefális, Viernjárga (Fig. 1, eastern site) and Mortensnes (north coast of Varangerfjorden, Fig. 1). At Geađgefális legal restrictions allowed to collect only three loose (albeit *in-situ*), small pieces (a few cm^3 each) of rock at three different levels at the diamictite outcrop (permission granted by Fylkesmannen in Finnmark). Thin sections of two of these samples were made to study grain outlines and determine whether the deposits were matrix- or grain-supported. It was not possible to make a thin section from the third sample, which was too fragile and broke into pieces.

For surface microtexture analysis, samples were rinsed with water and subjected to low-energy sonification treatment for a maximum of 30 s. The procedures did not involve any kind of mechanical crushing except for slight hand squeezing to loosen grains from the matrix, nor any treatment with strong acids. This methodology is similar to that used by Molén (2014).

Twenty-five to fifty translucent quartz sand grains (≤2 mm in diameter) were randomly subsampled from each sample under a light microscope and then analysed using SEM. All grain surface microtextures have been recorded on grains magnified 35–1,000 ×, and, if necessary, verified at magnifications up to 20,000 ×.

3.3. Grain surface microtextures – interpretation

To read surface microtextures, a method has been designed which can be used as guide for tracking down the geological histories of quartz sand grains.

Table 1. The predominant processes that influence the surface of a quartz grain, and symbols/abbreviations for the different surface microtextures (details in Molén, 2014)

Mechanism	Microtexture	Environmental forces
Crushing	large-scale fractures (***F***)	glacier, tectonics, crystallisation, rock slide/fall
	small-scale fractures (***f***)	water, glacier, wind, gravity flow
Abrasion	rounded edges, rounded microtextures, grooves (***A***)	water, glacier, wind, gravity flow
Chemical	solution, precipitation (***SP***)	weathering, contact reactions, lithification
Crystal growth	embayments, nodes (***EN***)	metamorphism, crystallisation
	crystal surfaces (***C***)	precipitation, lithification, crystallisation

The method was described in detail by Molén (2014).

Surface microtexture is linked to a geological process (Table 1). Depending on a combination of processes, the geological history of a grain can be interpreted. Depending on the freshness of grains, the surface textures provide a basis for interpretation of subsequent geological histories.

Surface microtextures are ordered in a 2-History Diagram (2-HiD), for easy interpretation. Definitions and labels are according to Tables 1 and 2 (Molén, 2014). History-0 (not used in the present paper) refers to absolutely fresh surface microtextures. History-1 microtextures are "recent" – these appear to be fresh (or probably fresh) based on SEM analysis, or the last geological process which shaped the grain surface. History-2 are all weathered grain surface microtextures which do not reflect the most recent history, i.e., some geological process shaped the grain subsequent to the origination of these surface microtextures.

The geological history of quartz grains is as follows: first crystallisation (*EN, C*), then release from bedrock (*F, f*), transport (*F, f, A*) and weathering (*SP*), in different combinations. A weathered grain, released from bedrock and then abraded by ice, will probably document large fresh fractures and abrasion as the most recent geological history (History-1) and weathered surfaces and crystal surfaces from previous history (History-2) of the host bedrock, i.e., *F1, A1, EN2* or *C2*, and *SP2*. Small scale fractures (*f*) often are of lesser genetic importance, as they easily originate from small forces/collisions and may almost always be hypothesised for History-2.

Examples of quartz grains displaying different surface microtextures, from tills and glaciofluvial material, from various lithologies and from transport over different bed lithologies, are shown in Figure 2. In tills almost all grains have an appearance that is more or less similar to grains *a/b* and *d* (Fig. 2). The other grains are included to demonstrate exceptions (grain *c*) and modifications in glaciogenic grain surface microtextures originating from (glacio)fluvial transport (grains *e* and *f*).

4. Results

4.1. Diamictite formations, structure and texture

The Geađgefális diamictite has the same appearance as a high-strength cohesive debris flow (Talling et al., 2012) and is conformably draped by mass

Table 2. Summary of "2-History Diagram" (2-HiD) classification features. The numerical values are the percentage limits of a grain surface, which define the presence or absence of a certain surface microtexture (= *SM*). Percentages are approximate. The percentage of a surface microtexture is calculated in comparison to the total area of the grain surface which is possible to observe by SEM. Percentage definitions of all History-2 surface microtextures are similar to History-1 microtextures except that no microtextures are excluded with the exception of *F2* (see table for definition of *F2*). Details are from Molén (2014)

SM	Area coverage	Excludes
F1	≥ 20–25%; or sum of many 5–20% *f1* covering ≥ 50–55%	*f1* (except if many ≤ 4% covering ≥ 10–15%); and *SP1* (except if sequence of origin is unknown)
f1	5–20%; or sum of many ≤ 4% covering ≥ 10–15%	*SP1* (if single *f1* is 10–20%; or sum of many < 10% *f1* covering ≥ 20–25%) (except if sequence of origin is unknown)
A1	≥ 15–20%	
SP1	≥ 10–15%	*SP2* (except if sequence of origin is evident)
EN1	≥ 10–15%	
C1	≥ 5–10%	
F2	See definition of *F1*	*f2*

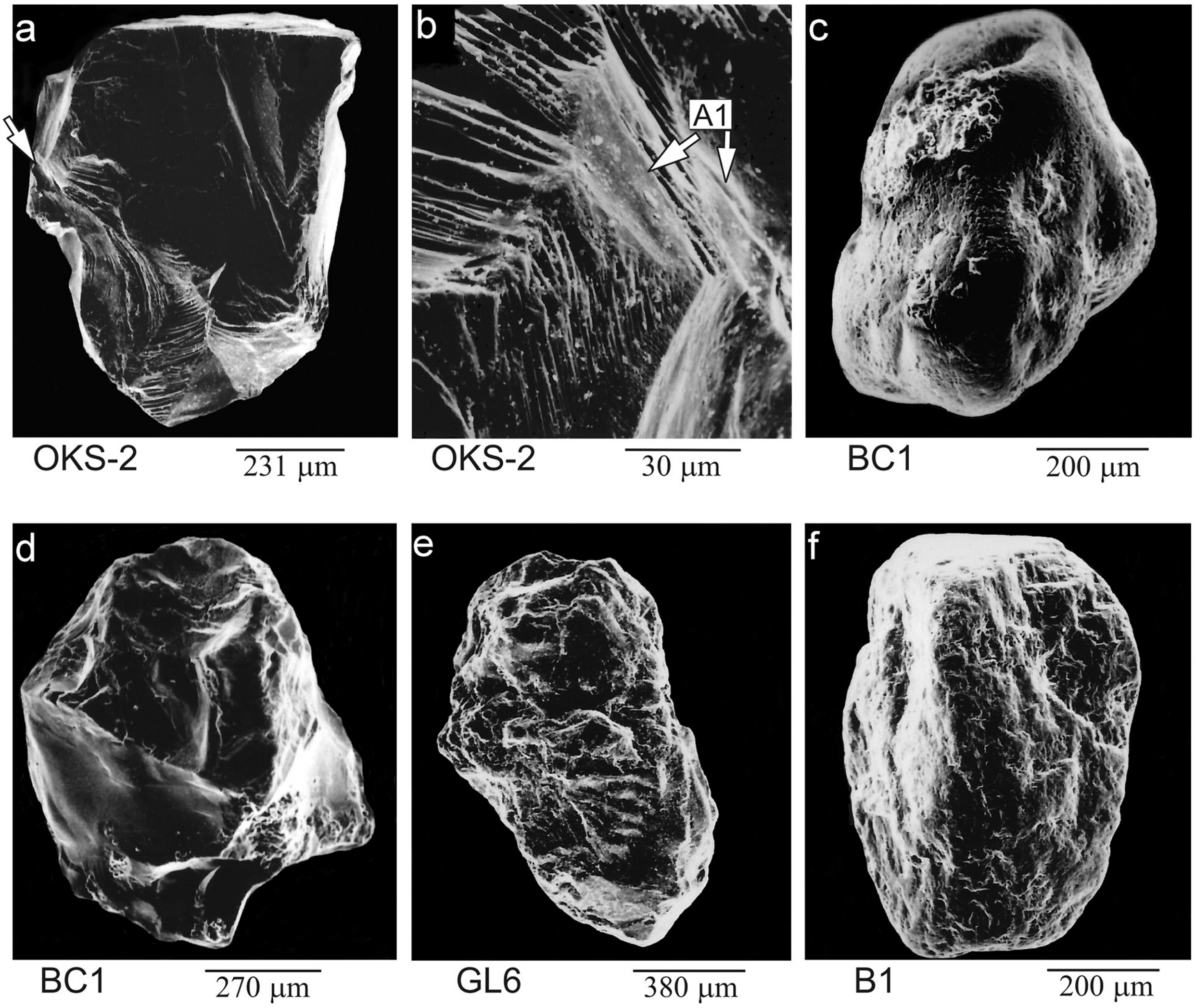

Fig. 2. Surface microtextures. **a –** grain from a small glacier, *c.* 50–250 m in thickness. The grain displays many fractures all over the surface (*F1*). Many patches and surfaces of the grain are more or less (irregularly) abraded (*A1*). This is evident because the fractures are not sharp, except on the semi-flat fracture on the top of the grain. Arrow – area enlarged in picture b; **b –** Part of grain a enlarged. Picture shows fracture steps, most of which are abraded. The most extensive abrasion is marked by arrows; **c, d –** Grains from Black Creek, York University, Toronto, deposited from a continent-sized, kilometre-thick Pleistocene ice sheet. Bubbles in upper left of c and lower right of d are contamination due to the mounting technique for SEM. Grain c is exceptional, maybe one in five hundred, a very rare find in tills, as it retains all original surface microtextures (in this case from multicyclical sediments: *A1, SP1*) and has not been fractured but possibly only slightly abraded by the ice sheet. The surface microtextures make it possible to track this grain to the source area, i.e., Palaeozoic strata; **d –** Judging from from the general grain outline, it was formerly multicyclical, a more or less spherical grain. It is probable that this grain is from the same source area as grain c, i.e., Palaeozoic sedimentary deposits (as are many grains from southern Ontario; see Molén, 2014), even though there is granitic/gneissic bedrock in the area as well. But the grain has been heavily fractured. It can be seen that most fractures are not sharp, but have been abraded. None of the original surface microtextures are untouched. The classification for this grain will therefore be *F1, A1*; **e –** Glaciofluval grain from southern Ontario. The grain exhibits *F1* and *A1* all over the grain surface, except for small patches of *SP2*, i.e., the same as grains from tills. But, the grain is so much abraded that the glacial marks will soon disappear, i.e., the large fractures will be totally obliterated, and it will change to *f1, A1*, and later maybe to *A1, SP1*; **f –** Glaciofluvial grain from Umeå, Sweden, that probably has been transported a very long distance by melt water (there are many eskers that, even if not intact today, stretch from the Scandinavian mountains to the coast), grain displays *f1, A1, SP1*. The f1 are not clearly visible on this photomicrograph, as they are small and have to be verified with larger magnification, but it is easy to see that the grain surface displays many small steps. The transformation to a multicyclical grain is almost completed, and if this grain would have been found out of geological context, the glacial impact and transport mechanism would be difficult to detect.

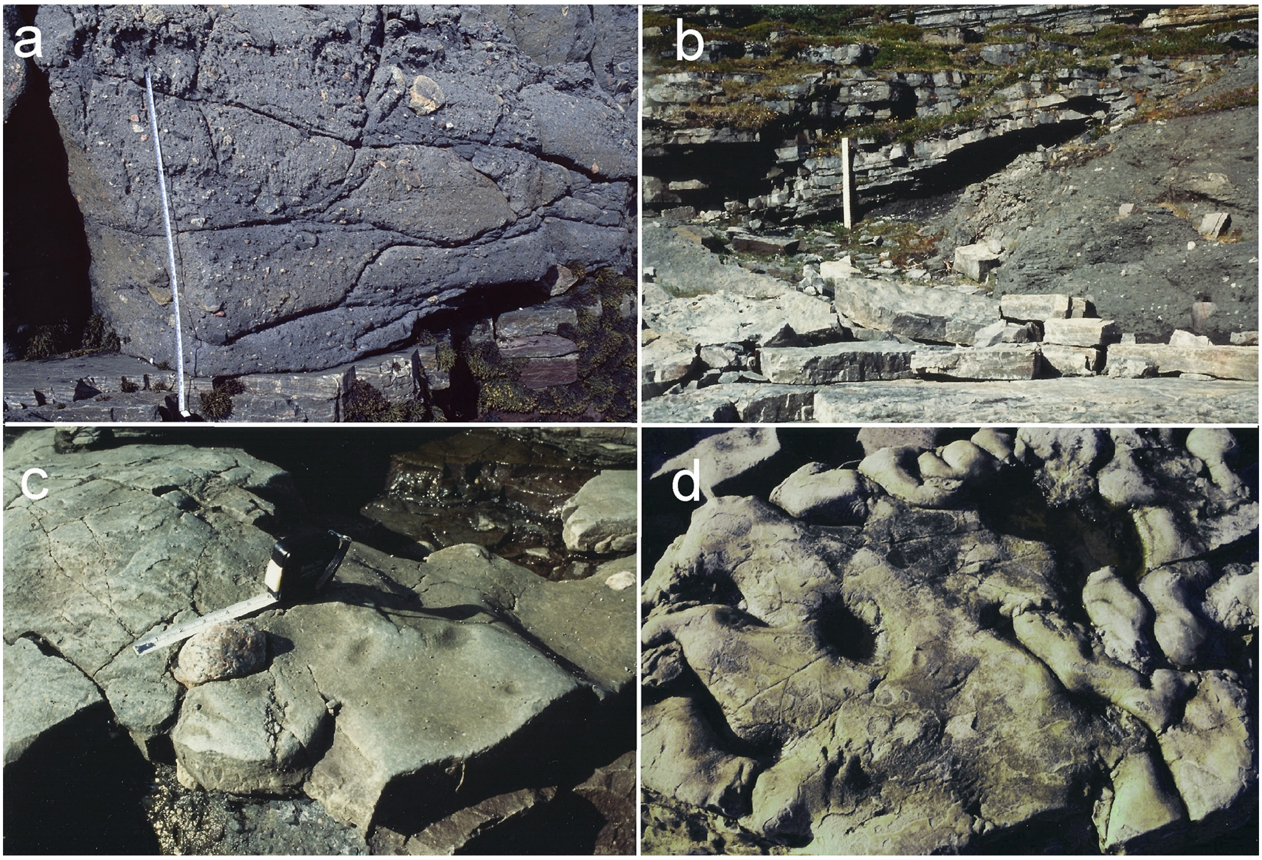

Fig. 3. The Geađgefális diamictite. **a –** exhibits superficial till structure; **b –** terminates bluntly; and **c–d –** is draped with sandy debris flow sediments displaying load casts and lonestones (occasionally interpreted as dropstones). Diamictite visible in lower left corner of photograph c. Scale in b equals 1 m.

flow beds of rapid deposition, displaying loadcasts, rhythmites and climbing ripples. It exhibits crude bedding in a few sections, sometimes displaying similarities to scour and fill structures (Fig. 3). The diamictite terminates and pinches out abruptly at the margins of the deposit and erodes underlying sediments (Laajoki, 2002). This appearance is similar to the proximal part of a cohesive debris flow (Middleton & Hampton, 1976; Talling et al., 2007, 2012). The thickness-to-width ratio of the outcrop is similar to those in debris flows, i.e. thicker than 1:50 (Shanmugam et al., 1994). One slightly contorted (and hence formerly soft), *c*. 50-cm-long and *c*. 3–10-cm (variable) thick slab of sandstone is present within the Geađgefális diamictite. Such is also common in gravity flows (e.g., Dakin et al. 2013), and enhances the interpretation of the diamictite as deposited by a debris flow with Bingham plastic movement, rather than the often more crushing and ploughing movements below a glacier.

On the Viernjárga, the diamictites show a great degree of scatter, having formed in channels or beds with diamictites and sandstones interlayered and showing scour and fill structures and load casts. Diamictites sometimes have an appearance of cross bedding (Figs. 4–5). These geological structures are typical of debris flow deposits (Shanmugam, 2016) and do not closely resemble till. These observations corroborate descriptions by Edwards (1975, 1984), even though he interpreted the formations to be glaciogenic. In addition, these observations conform well to data on e.g., Eocene submarine debris flow deposits (Dakin et al., 2013).

The diamict texture is similar in outcrops at Geađgefális and Viernjárga, as are colour, grain surface microtextures (see below) and matrix (Arnaud & Eyles, 2002). None of the deposits displays grading (except very sporadically). The directions of striae and cross bedding are the same for both areas (Fig. 1) (Bjørlykke, 1967). The gradients of individual outcrops are 4.2–5.0 degrees in the same direction as the transport direction of diamictites (Fig. 1). The gradient of the line of connection between the outcrops sampled in the present study is 0.26 degrees. Even a slope of only 0.26 degrees (or less) is possible for debris flows to occur (Mountjoy et al., 1972; Carter, 1975; Middleton & Hampton, 1976; Flood et al., 1979; Embley, 1976, 1982; Talling et al.,

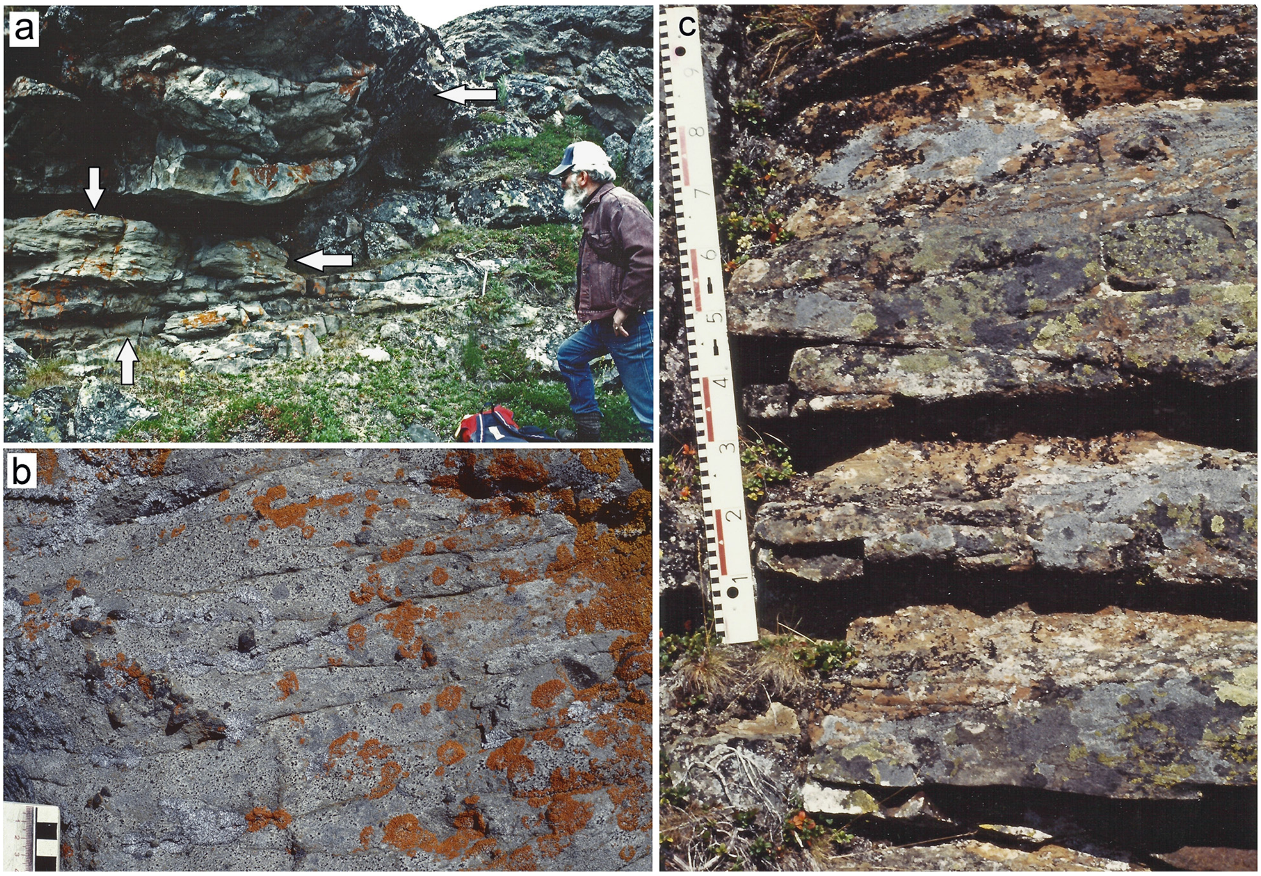

Fig. 4. Examples of sedimentary structures at Viernjárga bay (left square in Fig. 1). **a** – Erosional channel filled with different types of sedimentary rocks. Diamictite at the bottom (marked with three arrows), conglomerate at the right part of the channel (right arrow, but not easy to see in photograph) and sandstone on top; **b** – Cross bedding texture in diamictite. Scale in centimetres; **c** – Four *c.* 20–30-cm-thick diamictite beds in between beds of sandstone. The diamictite beds are softer and therefore partly weathered away at the surface of the outcrop. In the photograph, a *c.* 10-cm-thick veneer of lighter grey diamictite is seen on top of each darker sandstone bed. But parts of the diamictite beds (10–20 cm) in the photograph are hidden by the shadows from the sandstones. Scale equals 1 m.

2007, 2012). But the palaeoslope at the time of deposition of these sediments is not known. Neither do we know the altitude of the Viernjárga prior to any Pleistocene glaciation, and interpretation of older palaeogeography is hypothetical because most of the formations eroded away (see also Laajoki, 2002). The diamictites on the Viernjárga were interpreted as tillites by Bjørlykke (1967) and Edwards (1975, 1984) and correlated with the Geađgefális diamictite. The similarities displayed at these two outcrops support correlation.

The largest boulder recorded in the Geađgefális diamictite is 0.4 m (long axis). On the Viernjárga it is 0.3 m in sampled diamictites, and 1 m (Edwards, 1975) in parts of the formation which are more clearly debris flow deposits. Larger transported blocks, in parts of the Smalfjord Formation which display fewer glaciogenic and more debris-flow signatures, are from metres to tens of metres (Edwards, 1984). The appearance of the diamictites therefore conforms well with high-strength cohesive debris flows (which display most similarities to tills) which carry clasts of a maximum size of *c.* 1–3 metres (e.g., Talling et al., 2012). This often is also the maximum size of boulders which have been observed moving with recent slow (Chamberlain, 1964; Shepard & Dill, 1966; Carter, 1975; Middleton & Hampton, 1976) or rapid (Elfström, 1987) gravity flows. Clasts larger than 1–3 m in the deposits display evidence of gravity flow transport mechanisms, e.g., next to larger boulders there are flow and load structures, and in general the deposits show fewer similiarities to tills. In glaciers there is no realistic maximum size for transported clasts, as the competence of ice sheets is almost limitless.

The pavement below the Geađgefális diamictite reveals curved, parallel and semi-parallel striations, as would be expected below a highly concentrated debris flow. Rocks and soft mud-flakes were pressed down into the pavement, showing up

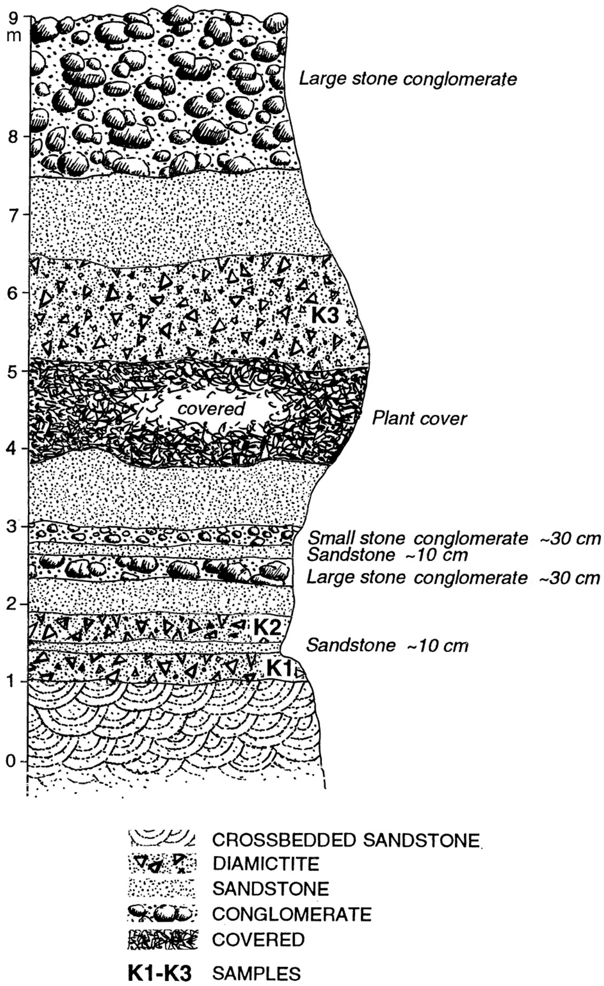

Fig. 5. Lithostratigraphic section showing the Viernjárga sample site (right square in Fig. 1). Thin diamictites are interlayered with other sediments.

Fig. 6. Pavement exhibiting striations below the Geađgefális diamictite. Note the pits, where stones or mud-flakes have been pressed down into the soft substrate.

as depressions, and there are small push-up rims around these depressions (Fig. 6; see also Jensen & Wulff-Pedersen, 1996; Rice & Hofmann, 2000). One small clast, recorded *in situ*, was recorded as pushed down into the underlying soft substrate of a poorly striated surface at Viernjárga, and other workers have made similar observations at Geađgefális

Fig. 7. Closeup of small raft (in total *c.* 1.5 m long, *c.* 40 cm tall) of soft sediment between Mortensnes and Nesseby, Mortensnes Formation.

(Jensen & Wulff-Pedersen, 1996; Rice & Hofmann, 2000), thus favouring the notion that substrate was soft and the striations formed below a debris flow.

The supposed dropstones at Geađgefális occur just above the main diamictite in the sandstone which is conformably draped around the diamictite and displays load casts (Fig. 3) and climbing ripples. No geological evidence has been presented to show that these stones may be dropstones. In their sedimentological context (i.e., in the strata above the diamictite), these outsized clasts are similar to "outrunners" or "leftovers", i.e., clasts retained by mass flows and deposited in a finer matrix, rather than dropstones (e.g., compare Crowell, 1957, 1964; Schermerhorn, 1974; Arnaud & Eyles, 2002; Rice et al., 2012).

The Mortensnes Formation is in large part homogeneous, with smaller rafts of sediment, a few metres in length, present in many places at outcrop (e.g., Fig. 7). The largest crystalline boulder recorded (foreign to indigenous sedimentary rafts) is approximately 2 m in diameter. It is difficult to document any evidence of e.g., depressions around outsized solitary clasts (i.e. supposed dropstones), because of the uniform structure and colour of the formation. One such clast in the high hills approximately 2 km east of Mortensnes, exactly at the border between lighter and darker mudstone, showed a lee-side structure formed by currents, similar to clasts deposited by gravity flows. In conclusion, there is no evidence of any "tillite" in the formation, and "dropstones" reveal no sign of having sunk down through a water column. The observed geological evidence from this unit was correctly documented by Baarli et al. (2006, p. 135), who stated that the formation had an "inferred glacial origin".

4.2. Surface microtextures and microscopic analysis

Even though the geological macrotextures and structures of diamictites in general may indicate a gravity flow origin, and few may be incompatible with such an origin, there is always the possibility of arguing that the deposits are proglacial gravity flows that derived most of their material from glaciers with little glacial influence at outcrop. This last question can be resolved by applying the results from surface microtextures on quartz sand grains.

4.2.1. Geađgefális and Viernjárga

The Geađgefális diamictite contains approximately 10–15% silt and clay, as measured in thin sections (Fig. 8; see also Bjørlykke, 1967). It is grain supported and ≤10% of the sand grains have a:b axis ratios of 2:1 or more. Most grains are subrounded to rounded and are mostly equant (see also Jensen & Wulff-Pederssen, 1996). On the Viernjárga the grains are slightly less spherical, and approximately 20% of the grains exhibit an a:b axis ratio in excess of 2:1.

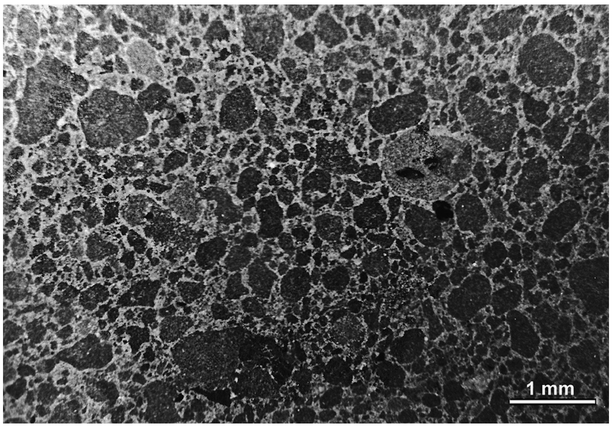

Fig. 8. Part of thin section from Geađgefális. The diamictite is grain supported and made up of rounded grains.

The grains from the Geađgefális and Viernjárga diamictites mainly exhibit full surface/continuous abrasion (*A1*) and solution/precipitation (*SP1*) surface microtextures (Fig. 9). Such surface microtextures are typical of multicyclical sediments, particularly grains from marine or fluvial environments (Fig. 10; Mahaney, 2002). None of the grains exhibit glaciogenic surface microtextures. A typical glacially crushed grain displays both large-scale fracturing (*F1*) and discontinuous (patchy) abrasion (*A1*), including abrasion on fractures (Molén, 2014). Even very small glaciers induce fracturing and abrasion of grain surfaces during release from bedrock and transport, but the extent, especially of abrasion, is usually smaller than for a large ice sheet. Hence, there are very significant differences between glaciogenic grains and those from the diamictites in the present study. Almost all surface microtextures are different when comparing these diamictites to those deposited by all glaciers, including deposits from very thin glaciers (Fig. 10), and this includes all kinds of tills that have been subglacially impacted. Available data from the surface microtextures support the interpretation that the present sand grains are from former fluvial, beach or continental shelf environments, but not from high-energy environments such as tectonic or subglacial settings (Abd-Alla, 1991, Prusak & Mazzullo, 1987; Johnsson et al., 1991; Mahaney, 2002; Molén, 2014). Even if all History-2 fractures (*F2, f2*) are reinterpreted and assumed to be primary (*F1, f1*), the grains do not display any surface microtextures that are similar to those from grains transported by glaciers of any size (Molén, 2014), i.e., there are no fractures

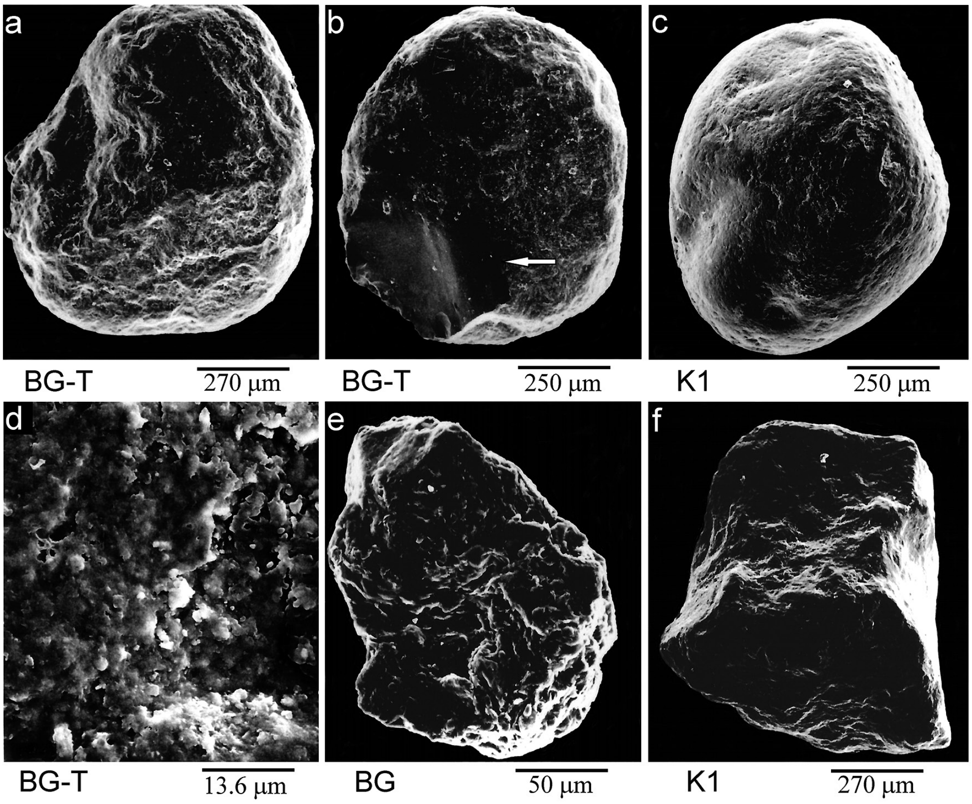

Fig. 9. Geađgefális (BG) and Viernjárga (K). **a –** One of the commonest grain shapes, displaying *A1, SP1, f2*; **b –** One of a few grains from Geađgefális displaying *F1*, but different from glaciogenic grains as *F1* has not been abraded (see arrow; surface microtextures *F1, A2, SP2*); **c –** This grain, displaying *A1* and *SP1*, is the most typical in all samples from the study area; **d –** Closeup of *SP1*, which is typical of most Geađgefális and Viernjárga grains; **e –** Rare grain with different appearance, *SP1, f2*. But as this grain is <250µm it has retained much of its original shape (Molén, 2014); **f –** One of few grains which is not much rounded (*SP1, F2*).

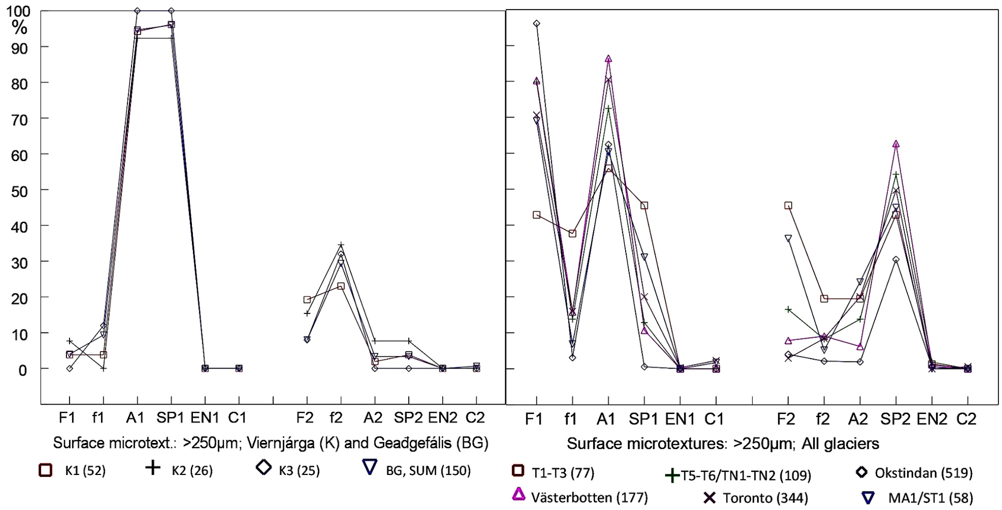

Fig. 10. Left: Surface microtexture data for the Viernjárga and Geađgefális diamictites. The grains display the typical combination of (covering/regular) *A1* and *SP1*, common of multicyclical grains. Right: Surface microtexture data for glaciogenic quartz grains. These grains display the typical combination of *F1* and (patchy/irregular) *A1*, common of glaciogenic grains. Samples are from a very thin Neoglacial glacier tongue, *c.* 10–30 m, (samples T1-T3), a *c.* 50–100-m-thick glacier (T5-T6/TN1-TN2), a *c.* 50–250-m-thick glacier (Okstindan), Pleistocene Scandinavian-Västerbotten and southern Ontario (Toronto) lowland ice caps (500+ m) and southern Ontario till grains from a very special till consisting of *c.* 95–99% limestone grains (MA1/ST1, 500+ m). Numbers of recorded grains in parentheses. Data from tills are from Molén (2014).

on grains that are irregularly abraded. In addition, there is no evidence for extensive – or even minor – chemical post-depositional transformation or obliteration of surface microtextures recorded.

The similarities in grain surface microtextures of samples in all sections (both Geađgefális and Viernjárga) corroborate the correlation between these beds.

4.2.2. The Mortensnes Formation

As demonstrated by the appearance of the sediments (as described above) it is possible to interpret the origin of the Mortensnes Formation as either entirely non-glaciogenic or partially glaciogenic only by help of macrotextures.

A study of surface microtextures from Mortensnes sand grains shows that they are almost identical to those from Geađgefális and Viernjárga. The only slight difference is that many grains from Mortensnes acquired single, simple fractures. However, these grains display no evidence of (irregular) abrasion after fracturing, which is the typical appearance of glaciogenic grains. In total, all surface microtextures are similar to those seen in multicyclical grains (Fig. 11). For instance, compare these grains to those in Figure 2, where it is possible to identify the source area, the impact from glaciers and the transformation of grain surface textures through glaciofluvial transport. Only for short distances of glaciofluvial transport, maybe hundreds of metres, is the glacial impact still clearly visible (Molén, 1992). The grains from the Mortensnes Formation do not show any surface microtextures that originate from glaciofluvial transport, i.e., there are no partly obliterated glaciogenic surface microtextures displaying regular abrasion on fractures. There are only grains similar to those from multicyclical environments, but some of these are fractured, this being the final fracturing of the grain, maybe during transport entrained in a mass flow. One grain from Mortensnes fractured after thumb squeezing while it was being mounted onto an SEM stub, which shows the vulnerability of these grains.

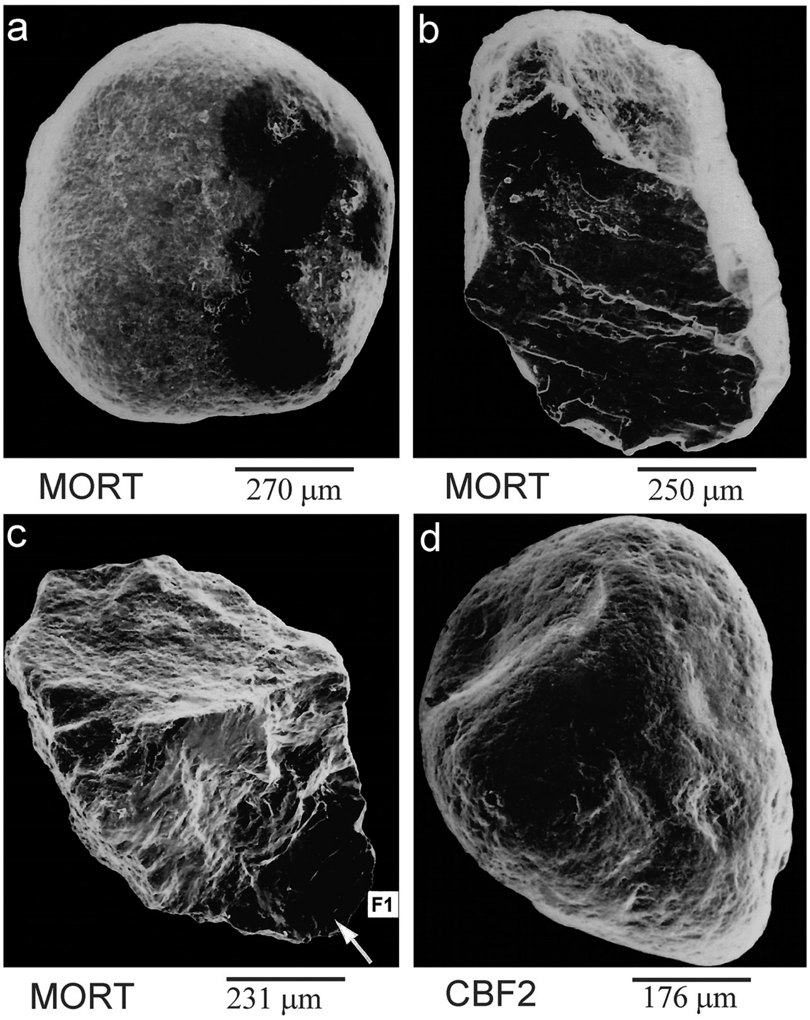

Fig. 11. Sand grains from the Mortensnes diamictite and, for comparison, a typical multicyclical grain. **a –** The commonest grain type in Mortensnes (*A1, SP1*); **b –** An abraded grain which has been fractured (*F1, A2, SP2*); **c –** Two grains of all 56 grains recorded had an appearance similar to this grain (*F1, F2, A2, SP2*); **d –** The commonest grain from Ordovician conglomerate and sandstone, Shadow Lake Formation west of Burleigh Falls, Ontario, Canada (*A1, SP1*) (Easton, 1987).

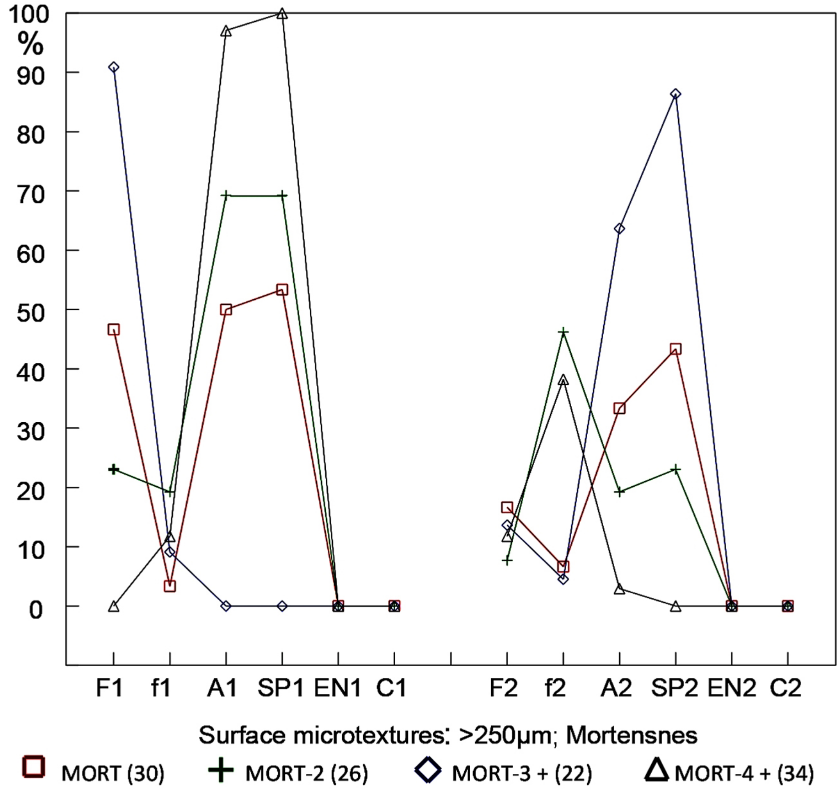

Fig. 12. Mortensnes samples, MORT and MORT-2. Most of these grains display *A1* and *SP1*. However, as many grains have been fractured during or after deposition, the diagrams are obscured. Therefore, grains with fractures have been resorted to "sample" MORT-3+ (i.e. *F1/f1, A2, SP2*) and those with no fractures to "sample" MORT-4+ (i.e. *A1, SP1*), i.e., the two dominant grain types in Mortensnes. Then it is evident that the fractures are nonglacial, as they have not been abraded after fracturing (no *A1* on *F1/f1*, but *F1/f1* on *A2*), and the abrasion (*A1* or *A2*) covers complete grains, i.e., the grains are multicyclical/fluvial.

Mixed grain populations obscure the 2-HiD (Molén, 2014). In order not to obscure the data from Mortensnes, the grains have been ordered in two ways (Fig. 12). First the samples have been ordered "as is" (i.e., MORT and MORT-2). Secondly, the samples have been separated into two groups, those exhibiting fractures in the most recent "history" (MORT-3+) and those that do not (MORT-4+). Thus, it is clearer even in the diagram that the grains display the same surface microtextures as multicyclical grains. The History-1 fractures are not abraded. This is opposite to what is shown by glaciogenic grains which exhibit many different kinds of small and large, irregularly abraded fractures (Mahaney, 2002; Molén, 2014). Instead, either a long period of weak abrasion, or final simple fracturing of some of the grains prior to or after deposition, was the most recent event that took place during deposition of the Mortensnes Formation.

5. Discussion

5.1. Interpretation of macrostructures

Striated pavements may be taken as evidence for either glaciation or debris flow (Bjørlykke, 1967; Edwards, 1975; Jensen & Wulff-Pedersen, 1996; Rice & Hofmann, 2000). Thin striations, even in two directions, are not uncommon beneath gravity flows (Allen, 1984; Jensen & Wulff-Pedersen, 1996, 1997). At least some of the "polishing" in the area within the six (of a total of 86) striations at Geađgefális are reported to be post-depositional and only chemically modified (Laajoki, 2001, 2002). At least in part, the "polishing" resembles slickensides, and there is "polishing" even on striations with rugged margins (Laajoki, 2002). Thus, this presumed evidence for glaciogenic action is equivocal at best.

As clasts and mud-flakes were pressed down into the striated pavement from above and are of a lithology similar to the overlying diamictite (Rice & Hofmann, 2000; Laajoki, 2001), any reference to the pavement as solid rock cannot be substantiated. The same observations have been made for debris flows (Dakin et al., 2013). The *c.* 2 mm push-up rims or ridges rising above the striated pavement, which surround weathered-out clast or mud-flake imprints, present unequivocal evidence for a soft substrate. Proof of a soft or semi-soft condition of the pavement has to be either dismissed or toned down so as to avoid consideration of an unlithified pavement (Jensen & Wulff-Pedersen, 1996, 1997; Rice & Hofmann, 2000; Laajoki, 2002; Bestmann et al., 2006).

Rice & Hofmann (2000) and Laajoki (2001) hypothesised that there was a long time period between glacier-induced striation and diamictite deposition. Rice & Hofmann (2000) stated that, "... a period of erosion occurred between striation formation and diamictite deposition ..." (p. 364) and "... the striated platform (...) is c. 150 Ma older than the overlying diamictite ..." (p. 355). There are no observable data for these speculations, as the diamictite and platform (including striations) are closely integrated (e.g., pressed into each other, as described above).

The "glaciogenic" breccia in the top part of the pavement (see section "Sub-diamictite erosional forms", above), may actually be non-glaciogenic. If the surface is semisoft, it may break into small angular pieces, which contrasts to that below a glacier where it would probably deform and just be smeared out. It has been documented that debris flows may brecciate the substratum ("somewhat lithified sandstones"), and a thin basal layer of debris may form below high-strength cohesive debris flows (e.g., Dakin et al., 2013). A debris flow origin of the breccia in the pavement appears to be a realistic and more plausible alternative than glaciation, as seen from the geological evidence described above.

A more "exotic" interpretation of the appearance of the pavement is super rapid melting and cooling of quartz at a temperature in excess of 1,000 ^{o}C during catastrophic movement of a 1-km-thick glacier, as suggested by Bestmann et al. (2006). No such speculation would be needed if the evidence for glaciation were clear cut. This also holds true for the interpretation of a 150 myr lag between pavement and diamictite as suggested by Rice & Hofmann (2000).

Almost 100 m above and *c.* 4 km west of Geađgefális, there is a small rounded rock surface which has been interpreted as a Neoproterozoic exhumed roche moutonée (Laajoki, 2004). This surface is a part of the underlying slightly rolling landscape. Therefore, as the outcrop is only a few square metres in extent, any interpretation of its origin is tentative. Different kinds of plucking of rounded rocks are also caused by gravity flows, even on hard granite (Dill, 1964, 1966; Shepard & Dill, 1966; Carter, 1975; Stock & Dietrich, 2006; Dakin et al., 2013).

The outcrops interpreted to display glaciotectonic deformation at Handelsneset (marked by a square east of Mortensnes in Fig. 1) are at four different elevations, all within *c.* 40 m in height, and within a few hundred metres lateral from each other (Arnaud, 2008). Arnaud (2008, p. 346) wrote that, "... the exact stratigraphic relationship of units between all sites (...) remains unclear ...". The outcrops do not expose tillite but many slices or zones of different materials, including an abundance of mud clasts of different sizes which occur regularly within mass flows deposits (Shanmugam, 2016) (Fig. 13). The appearance of the outcrops is easily explained if it is assumed that they originated from recurrent gravity flows, including slides, from former semi-consolidated/cohesive beach and/or near coast or slope sediments, pushing earlier deposits (or just within the individual flows/slides because of internal forces) and giving rise to many tectonic sedimentary structures. Hence, the interpretation of glaciation for the origin of these sediments is equivocal at best and only an inference in the worst case.

The palaeovalley in which the Varangerfjord diamictites formed has been labelled by some authors as "an open fjord" or a "fjord valley" (Baarli et al., 2006). However, the palaeovalley is very shallow and may have originated mainly by tectonism

Fig. 13. "Floating" mud clasts at the Handelsneset site of tectonic deformation, indicating a mass flow deposit.

(Røe, 2003; Arnaud & Eyles, 2004; Laajoki, 2004) prior to deposition of the diamictites (Siedlecka, 1985). There is no documented evidence to suggest that this valley originated by glacial action. There are many similar non-glaciogenic valleys (subaqueous or subaerial) all over the world. If the present valley had been similar in appearance to a Pleistocene Norwegian fjord, a glaciogenic interpretation would be relevant.

A closer study of the Geađgefális diamictite shows that its origin is compatible with a subaqueous intermediate to high-strength cohesive debris flow deposit (Talling et al., 2012) with no evidence of glacial influence, in part corresponding to the conclusion reached by Jensen & Wulff-Pedersen (1996). The largely grain-supported diamictite is more closely similar to debris flow deposits (Costa, 1984; Johnson & Rodine, 1984) than to tills, as even very thin glaciers (*c.* 10 m in thickness) fracture and comminute grains (Molén, 2014). At first sight, some of the macrotextures and structures pertinent to the deposit appear to be compatible with a glaciogenic origin, but more detailed research shows that these are better explained by a gravity flow origin. The appearance of the outcrop and surroundings compares well to e.g., Eocene submarine debris flows displaying a diamict texture, erosion of a slightly lithified basement sandstone with embedded clasts impacted downwards from the debris flow, holes below the debris flow where embedded clasts have been eroded out, striations, basement sandstone which has been rounded with a superficial appearance of roches moutonnées with evidence of plucking, and lonestones (Dakin et al., 2013).

The geology of the interbedded dolostone beds in the area adds weight against the interpretation of a "snowball earth" during the Neoproterozoic (e.g., Schermerhorn, 1974; Young, 2013). The only way out from this would be to speculate about a worldwide climatological/chemical mega-catastrophe, with rapid melting of glaciers worldwide, with consequences for ocean circulation for several thousand years, as outlined in a very speculative hypothesis by Shields (2005).

5.2. Surface microtextures

During more than 50 years of research, it has been thoroughly documented that different surface microtextures originate from different environments (e.g., Mahaney, 2002; Molén 2014, and references therein). If there is glaciogenic material which has never been processed by a glacier (not during release and not during deposition), for example supraglacial till (material that has fallen onto a glacier) and has not been below a glacier, it will of course not display any surface microtextures made by glaciers. The same holds true for flow tills, if they are supraglacial mass flows which have never been covered by a glacier. Such material is in any case difficult to differentiate from non-glaciogenic mass flows, except if they are in an environment of glaciation. But as soon as a glacier processes rock material, glaciogenic grain surface microtextures will form. Supraglacial tills and flow tills usually are a minor part of glaciogenic sediments, and they are easily removed by subsequent erosion, in contrast to basal till. The above discussion also concerns periglacial deposits (Kalińska-Nartiša et al., 2017).

The microtextures of quartz sand grain surfaces at Geađgefális are very different from glaciogenic grains. Their appearances are similar to multicyclical grains which have been abraded by low-energy processes over a long time. The Viernjárga diamictite outcrops have grain surface microtextures similar to those from Geađgefális. Quartz grains in the Mortensnes Formation display surface microtextures similar to Geađgefális and Viernjárga, hence arguing for a non-glaciogenic origin for this formation as well.

6. Conclusions

Most geologists have subscribed to a glaciogenic interpretation of the diamictites in the Varangerfjord area, even though they have documented and published inconsistences with such an explanation. Most of these inconsistences have been confirmed by my own field work. These inconsistences and problems have been compiled, documented and discussed, and the most important are tabulated in Table 3. Conjectural and less well-documented structures are not included in the table. As can be seen from Table 3, even if many structures have an equivocal origin (i.e., those not labelled in the table) the appearances of some structures are at odds with a glaciogenic origin (labelled NotG) and none can be interpreted to have originated exclusively from glaciation. The total compilation of field observations from the diamictites in the Varangerfjord area is consistent with origins by gravity flows, in a warm climate, and no observation is contradictory to such an origin.

Surface microtextures contradict any nearby glacial action during deposition of all facies. The data are at odds with a hypothesis of any glaciation in the area, even on a minor scale. In this case, grain

Table 3. Diamict origin table of macrostructures and textures, simplified and adapted for the Varangerfjord area diamictites (after Molén, in preparation). Tabulated features are only those that differ significantly between glaciogenic and non-glaciogenic deposits (in this case, mass flow), which also are present close by or within diamictons and diamictites worldwide. Even though the absolute differences are not known between different processes, relative values have been provided. For both the Smalfjord and Mortensnes formations the values are for the diamictites, and not for the complete formations. This includes the tectonic deposits at Handelsneset. Only those structures which are mainly indicating a non-glaciogenic origin are marked with NotG (= not glaciogenic). Details of the origin of these structures are discussed in the text. Conjectural or insignificant (not fully) documented differences from the study area are not tabulated but only discussed in the text. No structure demands a glaciogenic origin

Feature	Origin		Smalfjord Fm.	Mortensnes Fm.
	glaciogenic	mass flow		
Areally continuous	2	1	NotG	
Large areal extent	2	1		
Matrix-supported, fine-grained	2	1	NotG	
Warm climate sediments	1	2	NotG	NotG
Unconsol. transport. sediment	1	2	NotG	NotG
Erratics	2	2		
> 1–3 m diameter	2	1–(2)	NotG	NotG
Striated stones	1–2	1–2		
Pavement/striae/grooves	2	1		
Subparallel striae	2	1		
Parallel striae	1	2		
Crossing striae	2	1		
Soft sediment pavement	1	2		
Polished striations	2	1		
Cont. extensive areas	2	1		
Sediment pressed down		2	NotG	
Pressed up ridges		2	NotG	
Brecciation below	1	1		
Roches moutonnés/plucking	2	1		
Dropstones/lonestones	2	2		
Lee–side structures	1	2		
Large tectonic structures	2	1		

No sign in table = no example known, 1 = less common, 2 = more common, parentheses = very rare or commonly displaying a distinct appearance.

surface microtextures have resolved the difficult problem of the genetic interpretation of diamictites. The deposits do not display any indication of having originated from glaciation, either directly or indirectly by transport of material via glaciofluvial action or mass flows or any other means of transport of glaciogenic material.

These deposits conform well to the architecture of fan deposits along the continental margin, because these commonly are made up of detached lobes of debris flows. Some massive debris flows may travel 200 km without depositing any sediment (Talling et al., 2007). Debris flows commonly have sharp and irregular fronts, exhibit channels, are reworked at the top by bottom currents and are covered by sands or turbidites (Talling et al., 2007; Shanmugam, 2016). Shanmugam (2016, p. 110) noted that, "... the long-standing belief that submarine fans are composed of turbidities, in particular, of gravelly and sandy high-density turbidities, is a myth. This is because there are no empirical data ... 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." In the Varangerfjord and nearby areas, recurrent gravity flows could have been activated by small tectonic movements or any other disturbances, leading to a cover of large areas with marine fan deposits (Talling et al., 2007; Shanmugam, 2016).

The data presented here may be used in interpreting the origin of diamictites worldwide as an extension of the work by Schermerhorn (1974), especially when it comes to gravity flows and glaciogenic deposits. Also, this evidence has additional relevance for palaeoclimatological reinterpretations, raising doubts over the hypothesis of a "snowball earth".

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