Diagenesis and weathering of quartzite at the palaeic surface on the Varanger Peninsula, northern Norway

Jakob Fjellanger & Johan Petter Nystuen

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Weathered zones in quartzitic bedrock on the Hakŋalančearru Mountain on the Varanger Peninsula, northern Norway, have been examined, as has the timing of their development. The weathered zones are mainly associated with fractures formed by tectonic shear. SEM, microprobe and thin section studies reveal features belonging to the diagenesis and weathering history of the rock. Flakes of phyllosilicate minerals were originally deposited together with the quartz sand and became attached as coatings to the surface of individual quartz grains as well as forming an intergranular fill. Some of the detrital clay minerals turned into kaolinite during an early stage of the burial diagenesis. Kaolinite was later partly transformed to dickite. Quartz dissolution with concomitant quartz cementation and illite formation took place during later burial diagenesis. The kaolinite occurs in intergranular voids where it was partly transformed to pyrophyllite at a peak temperature of about 300 °C. As the overlying rocks were eroded the previously formed tectonic joints and small faults enhanced the circulation of ground water. This facilitated chemical weathering along joints and nearby grain contacts where slight dissolution of quartz significantly weakened inter-granular bonds. The resulting increase in permeability facilitated recent disintegration of the quartzite by mechanical processes. The chemical weathering is interpreted to be older than the Quaternary, possibly much older, and has implications for blockfield development and quantification of glacial erosion. It is speculated that the weathered zones may represent the lower parts of a previous deeply weathered crustal layer which may be coupled to the formation of the quartzitic inselbergs, e.g. the Hakŋalančearru Mountain, on the palaeic surface. The study shows the importance of combining geological and geomorphological methods to unravel complex geomorphic processes.

Jakob Fjellanger & Johan Petter Nystuen, Department of Geosciences, University of Oslo, P.O Bok 1047 Blindern, 0316 Oslo, Norway. E-mail jakob.fjellanger@geo.uio.no

Introduction

Palaeo-weathering may yield information on palaeo-climate, the formation of palaeo-landforms and serve as a background for evaluating Pleistocene glacial erosion (Lidmar-Bergström et al. 1999; Turkington et al. 2005). At the beginning of the 20th century Reusch (1901) introduced the term *Palaic surface* for the gentle, undulating elevated landscape in contrast to the sharply incised and clearly younger glacial valleys and fiords of Varanger. Inspired by Davis (1899) and his cycle of erosion with a peneplain as the end product, Reusch focused on the role of tectonic uplift and denudation down to an erosional base level (sea level). Later workers have focused more on the formational processes, usually including deep weathering as one important process.

Preservation of palaeo surfaces in Norway (Reusch 1901; Gjessing 1967; Schipull 1974; Peulvast 1985; Lidmar-Bergström et al. 1999; Lidmar-Bergström et al. 2000; Lidmar-Bergström & Näslund 2002; Bonow et al. 2003; Fjellanger & Etzelmuller 2003) and evidence of subglacial survival of superficial material (Rea et al. 1996; Fabel et al. 2002; Ebert & Kleman 2004; Whalley et al. 2004; Fjellanger et al. 2006) affect our understanding of ice sheet dynamics and highlight concepts like non-erosive, cold-based ice (Sollid & Sørbel 1982, 1984, 1988; Kleman & Borgström 1990; Kleman 1994; Sollid & Sørbel 1994). However, it is a fact that the Fennoscandian ice sheets have removed much of the preglacial superficial material (Mangerud 2004), leaving the bedrock exposed and ice-scoured. Some preglacial weathering products can be found in sheltered positions like fissure zones (Lidmar-Bergström 1995; Olesen 2004), and some have been covered by till (Roaldset et al. 1982; Tynni 1982; Olsen 1993; Olsen et al. 1996; Lidmar-Bergström et al. 1999) or disguised by the signatures of later processes (Roaldset 1973). Thus, convincing evidence of preglacial weathering remnants has only been demonstrated in a few places in Norway, see for example Roaldset (1982), Gjelsvik (1956) and an overview in Lidmar-Bergström (1999).

In this paper we present a study of weathered zones in Precambrian quartzites occurring in the palaeic landscape of the Varanger Peninsula in northern Norway. The study focuses on mechanisms of weathering of quartzite and textural and mineralogical products of the weathering compared to the pre-weathering nature of the rock. This is an integrated part of a study in which palaeo-landforms, autochthonous blockfields and denudation by Pleistocene ice-sheets have been investigated (Fjellanger et al. 2006, Fjellanger 2006, Fjellanger & Sørbel 2006).

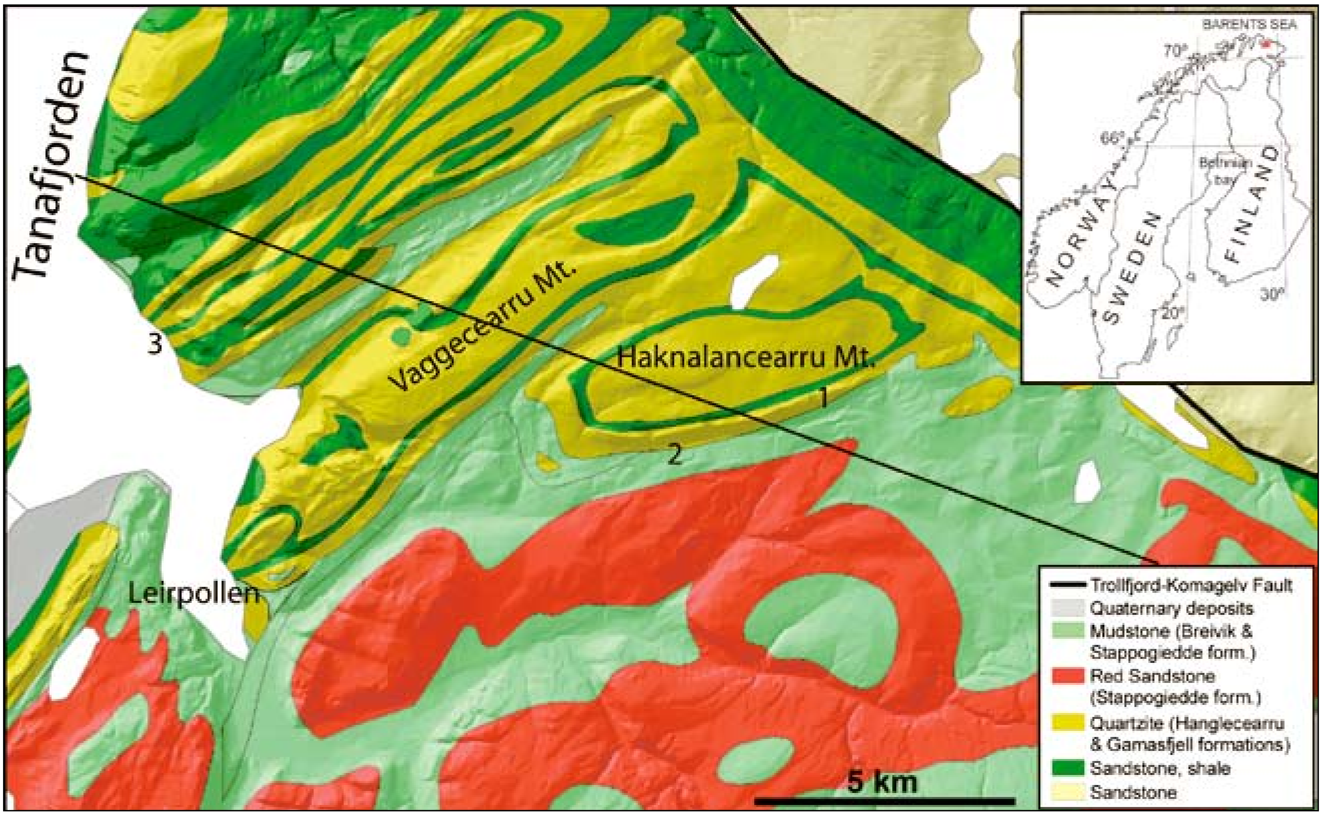

Fig. 1. Simplified geological map draped over topography (hill-shade map) showing western central part of the Varanger Peninsula, northern Norway. Black line is profile shown in Fig. 2. Sample locations of Hanglecærro Fm. quartzite: 1 and 2 are on top of and at the foot of Hakŋalančearru ridge rock wall, respectively, and 3 is by Tanafjorden.

The palaeic surface of the Varanger Peninsula: physiographic setting

The Varanger Peninsula is situated at 28-31° E and 70-71° N and is bordered by the Barents Sea to the north and east, by Tanafjorden to the west and Varangerfjorden to the south (Fig.1). The bedrock mainly consists of Neoproterozoic to early Palaeozoic shales, mudstones, sandstones and conglomerates (Siedlecki 1980; Siedlecka & Roberts 1992) with limited degrees of metamorphism, specifically south of the Trollfjord-Komagelv Fault Zone (TKFZ). The most northwesterly part of the peninsula belongs to the Caledonian Kalak nappe region (Levell & Roberts 1977).

The roughly WNW to ESE trending TKFZ divides the peninsula into two, separating the southern Tanafjord-Varangerfjord region from the northern Barents Sea region. These two regions have different sedimentary and tectonic developments (Siedlecka & Siedlecki 1967; Roberts 1972; Johnson et al. 1978). The fault zone has a complicated history with periods of normal, reverse and strike-slip movements, ranging from the Proterozoic to Tertiary times (Siedlecka 1985; Karpuz et al. 1993; Karpuz et al. 1995), the last period possibly lasting even into the Quaternary (Siedlecka & Roberts 1992). A folded and faulted zone between Geatnjajávri, Trollfjorden and Leirpollen (Fig. 1) is due to thrusting during the Caledonian orogeny (Siedlecka & Roberts 1992). Part of this area has developed as a lithologically controlled inselberg (see below).

The Varanger Peninsula is essentially an undulating plateau which represents a well preserved part of the palaeic surface as defined by Reusch (1901). Gently undulating surfaces at different altitudinal levels are often separated by escarpments in the palaeic landscape. The most extensive surfaces have been identified in summit areas over

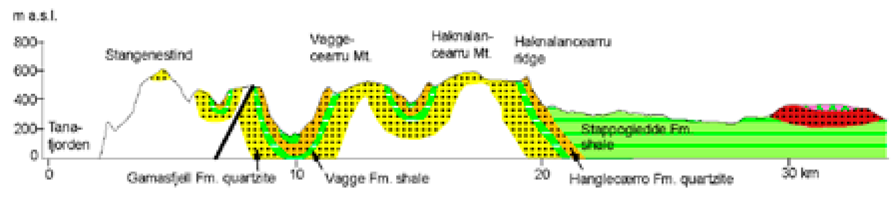

Fig. 2. Topographic profile (vertical exaggeration is about 13) with bedrock structures from Tanafjorden and past the Hakŋalancˇearru Mountain. Except for the fjord the topography mainly reflects the Paleic surface. See Fig. 1 for location of profile, but note that the Gamasfjell Fm. is given a separate colour in the profile.

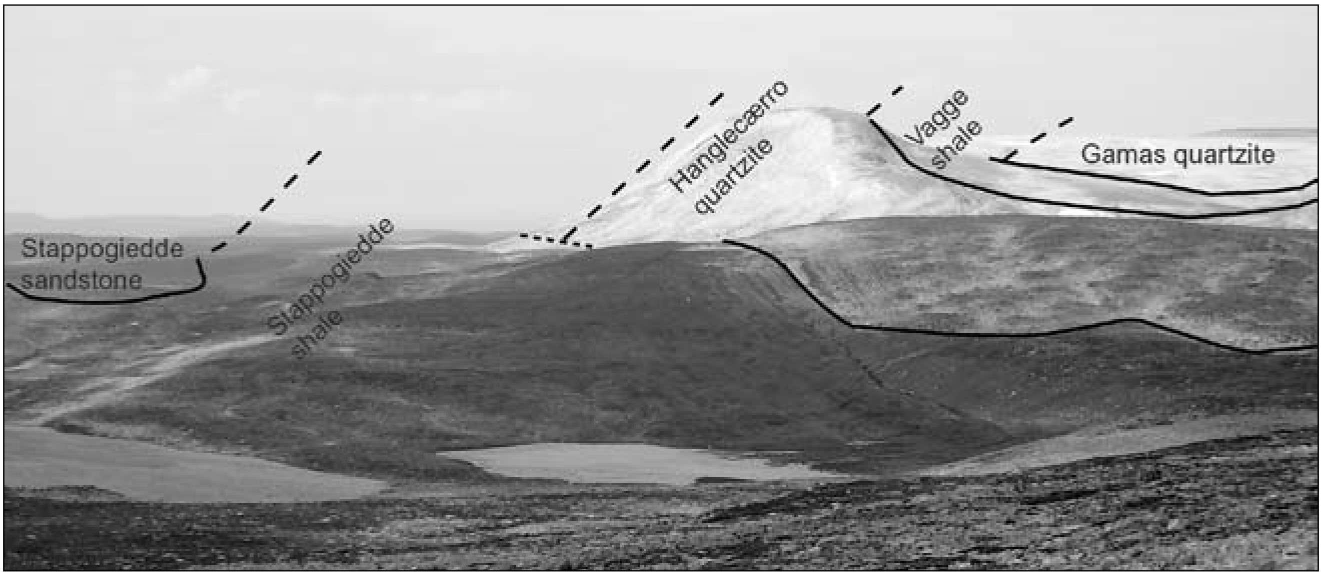

Fig. 3: The photo shows the quartzitic Hakŋalančearru Mt. with the ridge (~600 m a.s.l.) and its south-facing rock wall. Lower plain to the left (~350 m a.s.l.) is in sandstone and mudstone mainly belonging to the Stappogiedde Formation. View towards west.

most of the peninsula at 400-450 m a.s.l. (Riis 1996; Fjellanger & Sørbel 2007). Some quartzitic inselbergs rise up to 300 meters above this surface level. Inselbergs and other heights consisting of outcropping quartzites and sandstones are mostly covered by autochthonous blockfields (Malmström & Palmér 1984; Olsen et al. 1996; Fjellanger et al. 2006), and occasional tors can be found (Malmström & Palmér 1984).

The largest inselberg is located in the western part of the peninsula bordering Tanafjorden, and has undulating summit areas at 500-600 m a.s.l. It consists of quartzites belonging to the Hanglecærro and Gamasfjell Formations which are separated by the Vagge Formation shale. These formations are folded and faulted with strike directions mainly NE-SW. The Hakŋalančearru Mountain constitutes the southeastern part of the inselberg. The folds are truncated by the present summit land surface, and the resulting landscape is a repetitive sequence of anticlinal heights separated by synclinal valleys along a profile from SE to NW (Fig. 2). The Hakŋalančearru Mountain ends in the 250 meters high SSE-facing wall of the Hakŋalančearru ridge consisting of the Hanglecærro Formation quartzite (Fig. 3).

At the foot of the rock wall the Hanglecærro Formation continues underneath mudstones and sandstones of the Stappogiedde Formation (Siedlecka & Siedlecki 1971) which underlie vast areas in the gently undulating palaeo-plain to the south and southeast (Figs. 1, 2 and 3). A rather thin talus covers the lower part of the rock wall, and the nickpoint at the bottom of the rock wall closely follows the geological boundary (Fig. 3).

Erratics deriving from late Archaean to early Proterozoic crystalline bedrock south of Varangerfjorden show that the Fennoscandian ice-sheets flowed over the peninsula, lastly during the Late Weichselian as indicated by most glacial reconstructions (Sollid et al. 1973, Marthinussen 1974, Andersen 1979, Svendsen et al. 1999, Siegert & Dowdeswell 2004). However, large parts of the peninsula lack signs of glacial sculpturing, which only occurs in areas where topography facilitated channelled ice-flow (Fjellanger et al. 2006). The autochthonous blockfields have clearly survived at least one ice-sheet (Ebert & Kleman 2004; Fjellanger et al. 2006). Large systems of V-shaped valleys several hundred meters deep incise the gentle palaeic surface, and systems of lateral melt water channels, sometimes even cross each other, (Sørbel & Tolgensbakk 2004; Fjellanger & Sørbel 2007). This suggests that the Pleistocene ice-sheets preserved rather than eroded the ground surface, indicating cold-based conditions for the sheets.

Methods

Field methods

Field surveying was conducted in the late summers of 2002, 2003 and 2004 and different areas of the peninsula were visited. Other areas were also investigated, including some outcrops of the Hanglecærro Formation along the coast of Tanafjorden. All areas were surveyed for weathering features, traces of glacial activity, and the relationship between geological structures and topography. Samples were collected from weathered and unweathered bedrock and from clasts in blockfields.

Laboratory methods

Thin sections prepared from weathered and fresh quartzite were studied in ordinary polarizing microscope, a scanning electron microscope (SEM) and with a microprobe. These yield information regarding mineral composition and textural relationships. Samples were also studied by SEM. Rock mineralogy was checked by X-ray diffraction (XRD) on smear slides. The slides were prepared from rock samples that had been mortared in a mill. From this the clay fraction was extracted by settling in a water column for 23 hours and 45 minutes and dewatered in a centrifuge. In addition, total carbonate contents in rock samples from the Hakŋalančearru ridge were analysed.

History of the Hanglecærro Formation quartzite

The original quartz sand of this formation was derived from a strongly weathered land surface (Siedlecka & Lyubtsov 1997), transported northwards and deposited in a wave-dominated, shallow marine environment (Johnson et al. 1978) in terminal Riphean time (Sturt et al. 1975; Siedlecka & Roberts 1992). After deposition it was buried and lithified (Gorokhov et al. 2001).

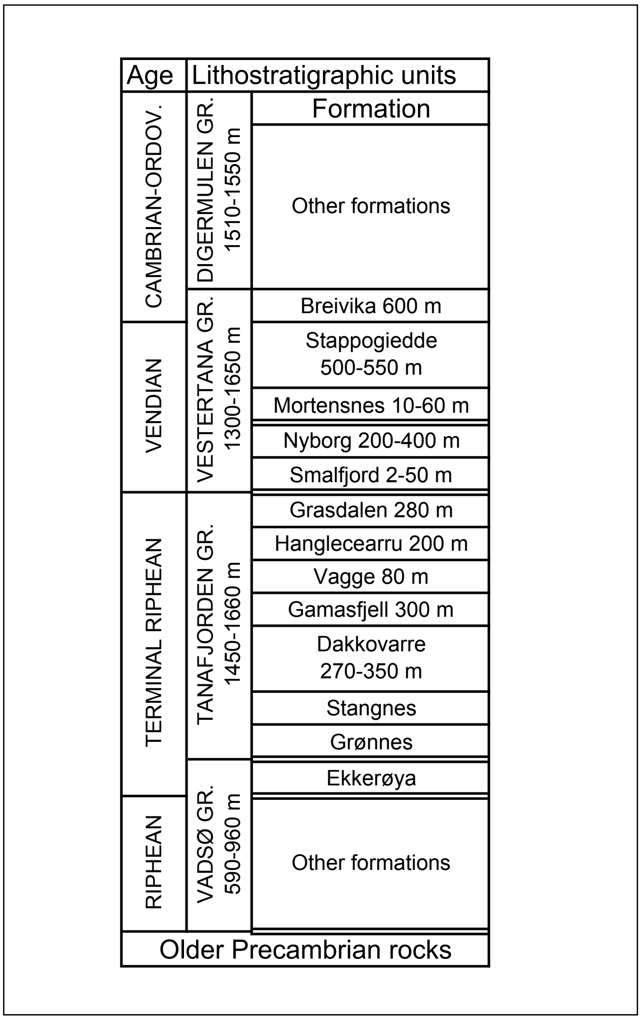

Fig. 4. The main stratigraphic units of the Tanafjord-Varangerfjord region in the southern part of the Varanger Peninsula. Erosional unconformities are shown by double lines.

During a major denudation event, evident over large areas of eastern Finnmark (Holtedahl 1918; Føyn & Siedlecki 1980; Siedlecka & Roberts 1992), the Riphean succession was eroded and a regional unconformity formed upon which younger Vendian sedimentary strata were deposited (Fig. 4). This erosional event is thought to postdate 630 Ma based on Rb-Sr analysis of illite diagenesis in the Stangnes Formation (Gorokhov et al. 2001). During this event the Hanglecærro Formation seems to have been partly exposed as it is directly overlain by the lowest part of the Vestertana Group in the western part of the Hakŋalančearru Mountain area (Siedlecka 1988).

Further east along the Hakŋalančearru ridge the Hanglecærro Formation is directly overlain by the Stappogiedde Formation (middle part of the Vestertana Group), thus indicating a second period of erosional exposure. Rb-Sr dating of the Nyborg Formation (Fig. 4) has linked this denudation event to Timanian orogenic movements at about 560 Ma (Gorokhov et al. 2001, Siedlecka et al. 2004). The stratigraphy of the region thus demonstrates that parts of the Hanglecærro Formation have been exposed twice in the eastern part of the Hakŋalančearru Mountain area. Weathering during these two events may have left textural and mineralogical traces in outcrops of the formation.

Subsequently, the rest of the Vestertana Group and the Digermul Group were deposited on top of the Hanglecærro Formation, burying it to a considerable depth (Siedlecka & Roberts 1992). Rb-Sr dating of the Stappogiedde Formation indicates burial around 440-390 Ma linking it to the Scandian (Caledonian) orogeny (Gorokhov et al. 2001). A final, but considerably more limited burial may have taken place in the Mesozoic (Riis 1996). Extensional tectonics with the formation of fractures, fracture zones and cracks took place in the Devonian times and clearly post-dates the Caledonian diagenesis.

Field survey

The rim-like Hakŋalančearru ridge (Figs. 1 and 3) consists of a 40-60° dipping outcrop of resistant quartzite of the Hanglecærro Formation (Siedlecki 1980). It is slightly curved in plan view as it is part of a truncated dome structure (Fig. 1). Flat summits alternate with gaps along the ridge. The gaps allow water to drain from small ponds or melting snow in depressions created in the outcropping Vagge Formation shale (Fig. 5 A). The sedimentary bedding planes are clearly visible in the rock-wall and strongly control its form. Signs of glacial sculpturing such as striations, crescentic marks or roche moutonnées have not been observed on the ridge during the present study, but Markgren (1962, 1964) reported a few occurrences of striae on the brink of the rock wall. Furthermore, there are signs of glaciofluvial activity, melt water spilling over the ridge crest and leaving a thin layer of silty material probably derived from the neighbouring Vagge shale.

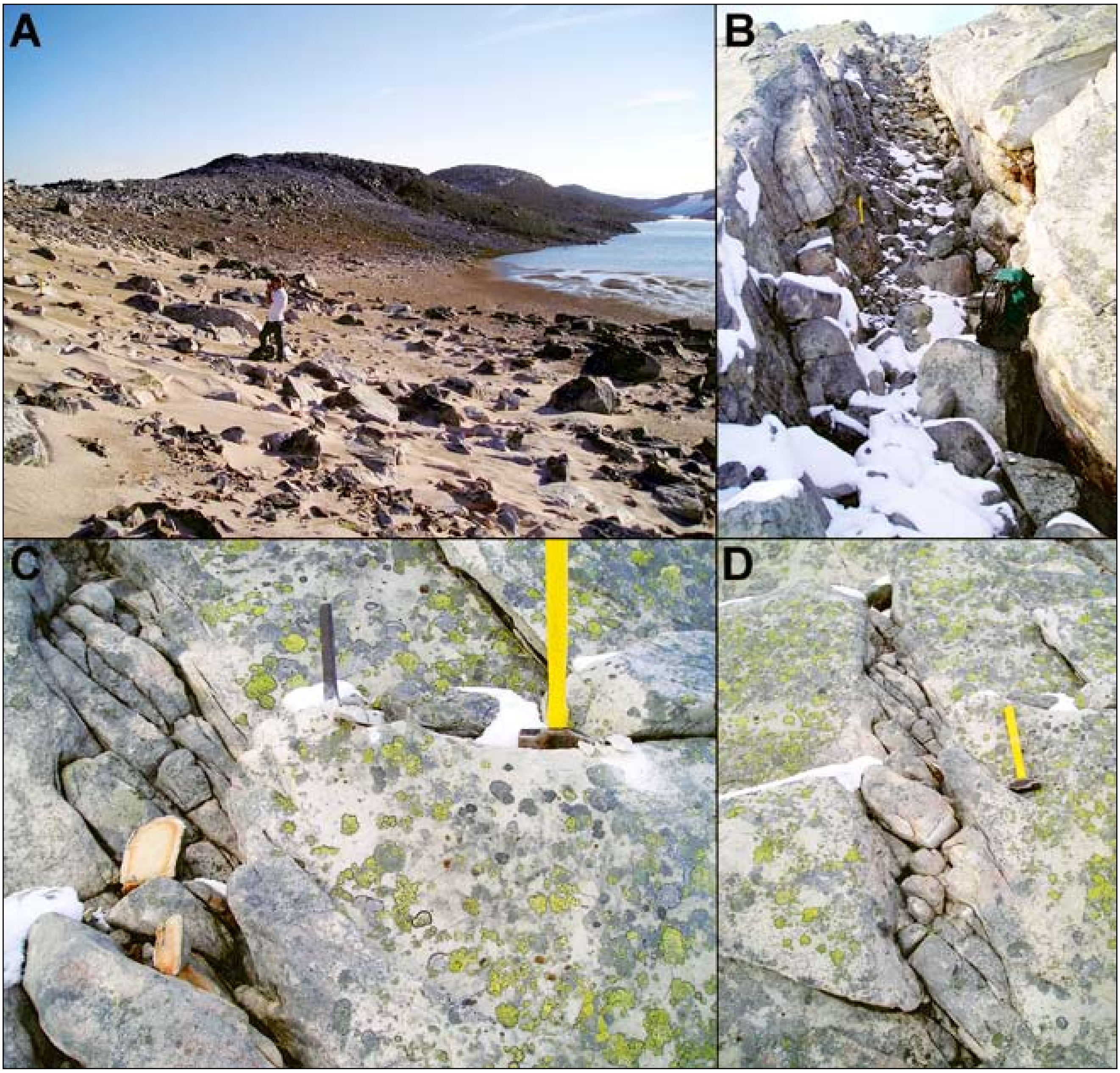

Fig. 5. A) Photo shows the Hakŋalančearru ridge consisting of the Hanglecærro Formation quartzite and parallel depression in Vagge Formation shale. Note the large amounts of quartz sand foreground produced by mechanical weathering in the chemically weakened zones of the quartzite. B) Photo shows a 3 meters wide collapse structure in the weathered zone about 10 meters to the left of C and D. The open space between the boulders, going several meters further down, is observed at the wall to the right. Note backpack and hammer for scale. C) Photo shows a 40 cm wide zone of weathered quartzite near the summit of the Hakŋalančearru ridge (Fig. 3). Samples were taken in the weathered zone, and in fresh quartzite beside it (by chisel and hammer). Zone of precipitated iron oxides is shown inside weathering rind on broken clast. D) Note the en echelon structure in the zone due to vertical tectonic stress. Hammer is 37 cm long.

An abundance of zones with strongly altered quartzite up to 10's of meters wide frequently occur on the Hakŋalančearru ridge (Fig. 5 C). In these zones the mechanical strength of the rock is severely reduced and the rock is friable enough to allow individual quartz grains to be scraped off with a fingernail. Many zones are oriented more or less normal to the bedding planes and parallel or sub-parallel to the TKFZ. One examined zone crosses the ridge from the contact to the Vagge shale in the north to about 150 m down the south-facing rock-wall, where it disappears after thinning and branching.

Weathering zones seem to occur in all parts of the rock wall, all they way down to its foot. Several zones have *en echelon* joint structures indicating brittle deformation due to tectonic shearing (Fig. 5 D). In some of the large weathered se zones enough material has been removed to create depressions or gully-like features (Fig. 5 B). The zones of weathered bedrock do not seem to be correlated with the cols. Weathered quartzite also frequently occurs along fissures which follow sedimentary bedding planes.

Weathered zones are common in quartzite in the Gamasfjellet Formation as well, and have been found in all investigated parts of the Hakŋalančearru and Vaggečearru mountains. In addition, weathered zones have been found in both quartzite formations down to sea level a little north of Lavvunjar'ga, but not in exposures at Leirpollen (Fig. 1).

Petrography of the Hanglecærro Formation

Composition and texture

The Hanglecærro Formation is, in terms of mineral composition a quartz arenite (Siedlecka & Siedlecki 1971). The total content of quartz recorded by modal analysis of the present study material is in the range of approximately 95 to 98 %. Other clastic minerals are minute grains of zircon, apatite, titanite and iron oxides. Pore-filling minerals include quartz, illite, kaolinite, dickite, and pyrophyllite; whereas hematite and quartz occur in thin veins cutting both sedimentary and diagenetic textures.

The primary clastic texture is very prominent, being formed by dominantly rounded to well-rounded quartz grains with grain sizes in the range of 0.1 to 1 mm. A faint sedimentary lamination is developed due to variation in clastic grain size. The clastic quartz grains are all generally tightly packed with scattered pore voids filled with phyllosilicates. Some of the phyllosilicate-filled voids are subrounded to angular with diameters in the same range as the adjacent framework grains of quartz. Grain-to-grain contacts vary from being tangential to contacts where a slight, but distinct disintegration is evident with interpenetrative contacts of adjacent clastic quartz grains as a result. Microstylolites are locally present.

The quartzite has a texture of closely packed clastic quartz grains. Quartz cement occurs as overgrowths in some interstitial spaces. A thin coating of phyllosilicate minerals may be present along clastic grains and along interfaces of quartz overgrowths (Fig. 6). Most of the phyllosilicates occur in well-defined pore voids. In the unweathered quartzite the quartz grains form a very dense texture of interlocking quartz grains. In the weathered fractured zone in Hanglecærro Mountain, as well as in the weathered zones at Tanafjorden, the quartzite has more open spaces between clastic quartz grains, as well as between clastic grains and diagenetic overgrowths and along the interface with quartz overgrowths. Along several quartz grains the intergranular space is open (filled with epoxy from thin section preparation). Bounding surfaces of quartz towards the open spaces are sutured with the appearance of having been slightly etched. The difference in the overall texture of weathered and unweathered quartzite is considered to be of critical importance for the weathering process affecting the Hanglecærro Formation. Before discussing the implication of this, the character and origin of the main mineral constituents will be described below.

Quartz

Quartz occurs as clastic grains and as secondary overgrowths (Fig. 6 A, B, C and D). Cathode luminescence (CL) reveals that the terrigenous quartz is derived from various source rocks, represented both by mono- and polycrystalline grains (Fig. 6 C). Clastic quartz grains have secondary quartz overgrowths towards pore voids that have been primarily filled with clay minerals. Dust rims or thin clay coatings define the boundary of the clastic grains. The secondary quartz has euhedral or irregular boundaries (Fig. 6 C and D). Surfaces of clastic grains as well as surfaces of secondary overgrowth quartz are serrated with a relief of some tens of microns (Fig. 6 A, B and D). Highly irregular small quartz lumps occur in some of the pyrophyllite-filled pore voids; the quartz lumps have obviously been isolated from adjacent clastic quartz grains or from secondary quartz overgrowths during formation of the pyrophyllite (Fig. 6 D).

Illite

Illite occurs in both weathered and unweathered quartzite. It has been identified on the SEM by its long and slender sheet morphology, very light grey colour in backscatter and by its chemical composition (Table 1). The illite preferentially occurs as a clay coating on clastic quartz grains and as a lining of large pore voids now filled mainly with kaolinite and pyrophyllite (Fig. 6 E). Illite is also the dominant phyllosilicate in a few large pores; slender laths of illite occur between kaolinite and pyrophyllite in the large pores where these two clay minerals dominate. The relative age between illite and kaolinite is not distinct in the thin phyllosilicate coatings, as seen in the SEM study.

Kaolinite and dickite

Kaolinite is a prominent phyllosilicate mineral in both the weathered and the unweathered quartz arenite. Kaolinite was identified early in our study by XRD on rock powder enriched in the clay mineral fraction. Later kaolinite was identified on SEM by its typical booklet or vermicular morphology or as masses of crystal platelets (Figs. 6 F and 7 A), by a grey colour darker than for illite and pyrophyllite in backscattered electron imaging (Fig. 6 E og 7), and by its chemical composition (Table 1). Dickite has only been observed on SEM within unweathered quartz arenite from the lower slopes of the Hanglecærro Mountain. Here dickite occurs in a pore void as massive blocky crystals formed at the expense of kaolinite. Kaolinite is in turn replaced by pyrophyllite in the same rock sample (Fig. 7 B).

Pyrophyllite

Pyrophyllite is the most common phyllosilicate mineral in the Hanglecærro Formation. It occurs mainly in the large phyllosilicate-filled voids between the clastic quartz grains. The textural relationship between pyrophyllite and kaolinite is in most thin sections not distinct. However, as mentioned above, in a sample from the unweath-

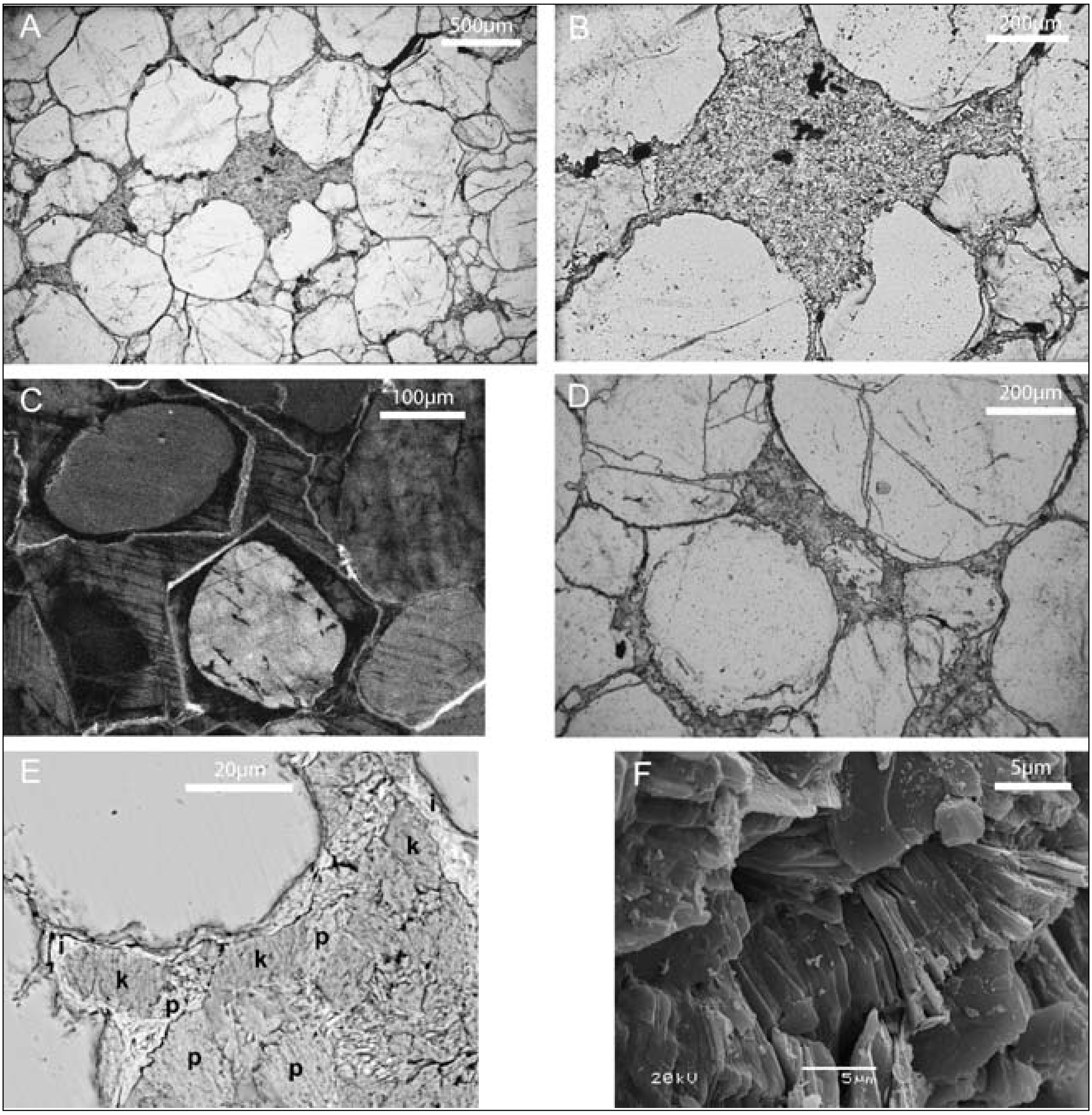

Fig. 6. Microscope images of Thin sections of the Hanglecærro formation quartzite (F is from a stubb) showing minerals and textures. A) Light microscope photo of weathered quartzite sampled near summit of the Hakŋalančearru ridge (see Fig. 5 C). Rounded to subrounded clastic quartz grains, some with secondary quartz overgrowth and original clastic surface defined by dust rim and thin phyllosilicate coatings. Some clastic quartz grains are fractured as a result of mechanical compaction. Phyllosilicate minerals are also present along boundaries of quartz overgrowths and in intergranular pores. B) Detail from A) showing grain-sized pore void with kaolinite and pyrophyllite. Note solutional embayments, both on primary clastic quartz grains and on secondary diagenetic quartz cement outside dust rims bordering the clastic grains. C) Cathode luminiscence image (SEM) of weathered quartzite sampled close to Tanafjorden shore-line showing clastic quartz grains with varying CL properties reflecting different provenances, euhedral quartz overgrowths and thin coatings of phyllosilicates (light streaks) along quartz boundaries. D) Photo of weathered quartzite sampled at the foot of the Hakŋalančearru ridge showing clastic quartz grains and diagenetic quartz cement and phyllosilicates coating quartz and pore fill. All quartz boundaries are etched. The pyrophyllite in the pores has irregular inclusions of quartz which are the remains of a previous quartz cement. E) Backscatter image (SEM) of unweathered quartzite 50 cm from weathered zone shown in Fig. 5 C. Note the distribution of illite (i) aligned along the walls of the pore voide and kaolinite (k) and pyrophyllite (p) which dominate the central parts of the pore. F) SEM picture of stub from the same sample as a) and b) from the top of the Hakŋalančearru ridge, showing vermicular kaolinite (booklet morphology).

ered part of the quartzite the pyrophyllite seems to have grown at the expense of both kaolinite and dickite (Fig. 7 B). Pyrophyllite is recognized in SEM by its sheet-like habit, commonly with a fan-shaped pattern radiating in various directions, thus forming a dense mass in the pore voids (Fig. 6 A, B and E). In electron backscattered images,

Table 1: Chemical com-position (in percent) of phyllosilicate minerals from pore voids in the Hanglecærro formation quartzite based on SEM analysis

	O	Si	Al	K	Mg	Fe	Ti
ILLITE							
Average	53,6	23,9	16,6	5,2	0,3	0,7	0,2
St. dev.	2,2	1,7	1,3	0,8	0,3	0,6	0,1
Max	58,6	28,7	19,1	6,5	1,2	1,8	0,4
Min	47,8	22,0	14,6	3,7	0,0	0,1	0,1
KAOLINITE							
Average	58,5	22,5	19,0			0,1	
St. dev.	1,5	0,9	0,6			0,1	
Max	61,9	24,2	20,2			0,1	
Min	55,8	20,3	17,7			0,0	
PYROPHYLLITE							
Average	54,9	31,3	13,8			0,1	
St. dev.	1,3	1,2	0,6			0,0	
Max	57,1	33,2	15,8			0,1	
Min	52,4	28,5	12,8			0,0	

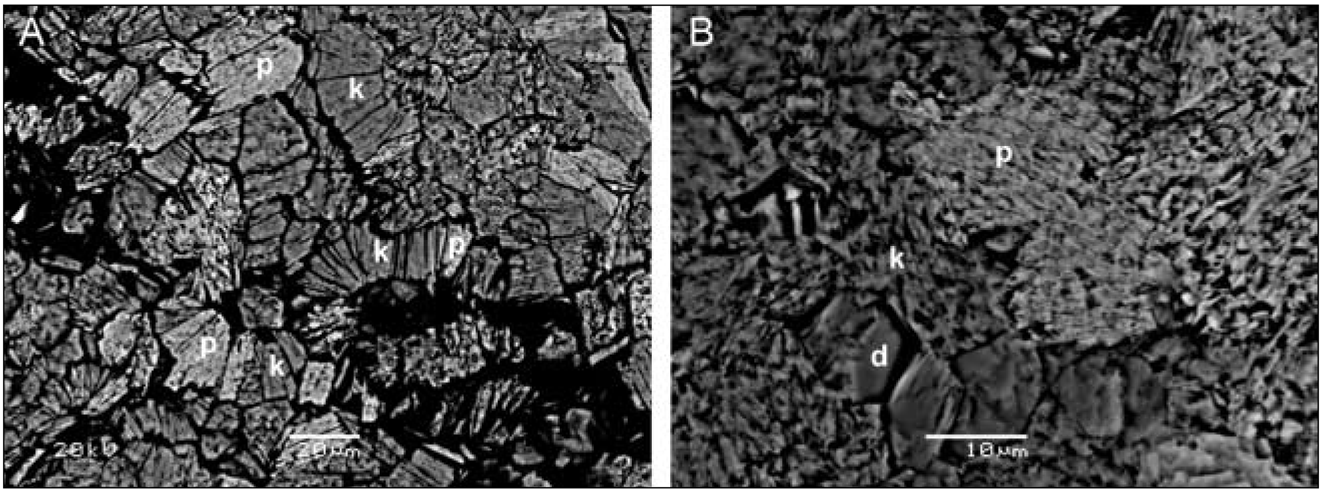

Fig. 7. Backscatter images (SEM) of pore voids in quartzite samples. A) Detail from pore void shown in Figs. 6 A and B showing kaolinite (k) with vermicular morphology with the darkest grey shade and pyrophyllite (p) in a lighter grey shade, partly replacing kaolinite with preservation of the kaolinite morphology. B) Detail from pore void in unweathered quartzite sampled at the foot of the Hakŋalančearru ridge showing kaolinite (k) replaced by blocky dickite (d) and with pyrophyllite (p) as the latest phyllosilicate mineral. Note the fan-shaped morphology of the pyrophyllite indicating growth at the expense of kaolinite.

pyrophyllite has a light grey tone, darker than kaolinite, but not as light as illite (Fig. 6 E). The chemical composition of pyrophyllite is also distinctive with its higher silicon content compared with that of kaolinite (Table 1).

Discussion

Phyllosilicate formation in the Hanglecærro Formation

When kaolinite was identified early in our study by XRD in samples from weathered zones in the Hanglecærro Mountain, we first interpreted it as the result of severe weathering of the quartzite during the formation of the palaeic surface, thought to have taken place in early Cenozoic or Mesozoic times. However, studies by SEM and the microprobe revealed that illite and pyrophyllite also occurred in addition to kaolinite. Thus the mineralogical history of the quartzite turned out to be more complicated. From the textural relationships recorded in ordinary polarizing microscope, on SEM and by microprobe, the order of mineral formation appears to be as briefly outlined below. A more comprehensive discussion of the overall petrogenesis of the Hanglecærro quartz

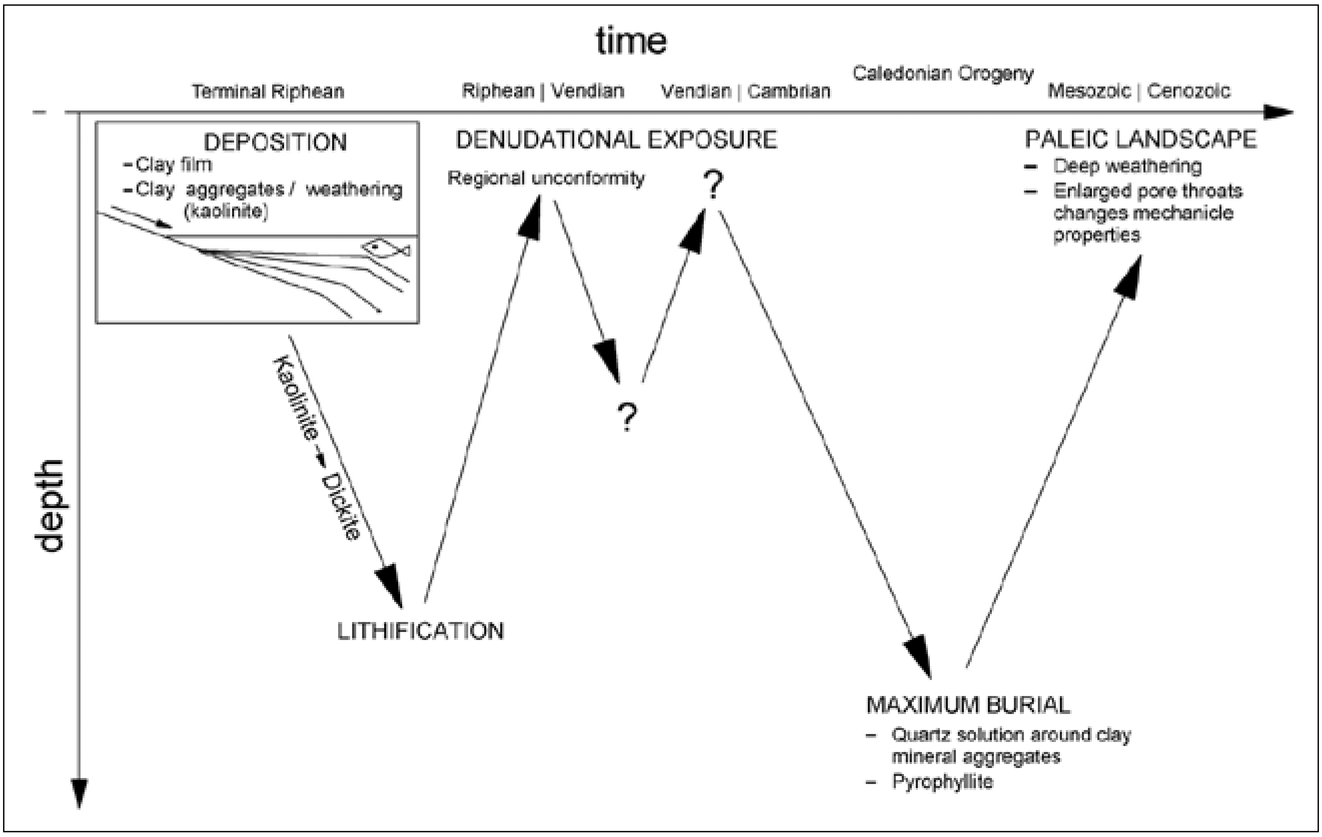

Fig. 8. The drawing shows the possible diagenesis and weathering history of the Hanglecærro Formation quartzite. Maximum burial may, alternatively, have taken place during burial in Riphean time.

arenite is beyond the scope of the present paper.

The Hanglecærro Formation formed as mature quartz sand as a result of chemical weathering of Proterozoic and Archaean bedrock in Neoproterozoic times (Siedlecka & Lyubtsov 1997). The clastic quartz grains were, during sedimentation, to a large extent enveloped by very thin coatings of clay minerals. Pores were also filled with clay minerals. The original clay minerals that formed the coating and primary pore fill may have been clastic kaolinite or some kind of mixed-layer clay minerals. Phyllosilicates present in large pores having the outline similar to that of adjacent clastic quartz grains may have formed by subsurface weathering of detrital feldspar grains shortly after deposition, or during some later event of exhumation. Nevertheless, the present kaolinite represents a stage of diagenesis at relative shallow burial depths.

During burial, the quartz sand was initially densely packed by mechanical compaction with slight fracturing of clastic grains. During further burial and temperature increase dickite formed from the kaolinite. At depths corresponding to a temperature of about 100-140 °C (3-4 km) illite formed at the expense of precursor minerals like kaolinite and remnants of potassium-bearing minerals such as feldspar, mica and any mixed-layer clay minerals available (Bjørlykke, Knut & Egeberg 1993). During this diagenetic stage quartz dissolution and cementation also took place. However, and of great importance, the amount of potassium was obviously too low for transformation of all kaolinite into illite. In such a situation, where the supply of potassium for the formation of illite is critical during thermal diagenesis, kaolinite may remain stable in the rock to a much higher temperature than 140 °C (Bjørlykke, K. et al. 1995).

The pyrophyllite of the Hanglecærro quartzite is the latest phyllosilicate mineral phase that formed in the rock. Pyrophyllite may form by hydrothermal processes from other aluminum-rich silicate minerals or during low-grade metamorphism in phyllites and slates (Deer et al. 1992). Hydrothermal activity is commonly associated with magmatism. Though dolerite dykes have intruded the Neoproterozoic succession along the northern and eastern coast of the Varanger Peninsula (Beckinsale et al. 1975; Roberts 1975), no indications of hydrothermal activity have been reported from the outcrop area of the Hanglecærro Formation. We think the pyrophyllite formed in an approximately similar isochemical system at the expense of kaolinite and quartz with the expulsion of water:

$$\underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{Quartz}}{2SiO_2} = \underset{\text{Pyrophyllite}}{Al_2Si_4O_{10}(OH)_2} + \underset{\text{Water}}{H_2O}$$

The strong corrosion of quartz in contact with pyrophyllite testifies to the disintegration of quartz during formation of pyrophyllite. The formation of pyrophyllite is enhanced by increasing a temperature during burial and normally takes place around 300 °C. Pyrophyllite breaks down to quartz, andalusite or kyanite and water at about 350-420 °C by increasing pressure (Deer et al. 1992, Bucher & Frey 1994). The pyrophyllite thus defines the depth of maximum burial of the Hanglecærro Formation and to be about 10 km depth with a normal temperature gradient corresponding to a temperature of about 300 °C.

The history of uplift, weathering and erosion of the Hanglecærro Formation is considered to include one episode of exposure at the transition from Riphean to Vendian time, and thus just prior to the Varangerian Ice Age, and a new episode later in Vendian time (Siedlecka et al. 1995; Gorokhov et al. 2001). However, as the weathered zones occur along syn- or post-Caledonian tectonic fractures, the recorded weathering must be connected to subsequent exposure and denudation of the quartzite, most probably during the formation of the palaeic surface below which the weathered zones are located.

Weathering of the Hanglecærro Formation

A fundamental question concerns the effects the weathering observed from the field study has had on the rock, as the mineral paragenesis constrains the kaolinite to be Neoproterozoic (Fig. 8). We suppose that the very thin clay phyllosilicate coating of quartz grains is the key to answering this question.

The deep weathering of the Hakŋalančearru Mountain rocks is clearly connected to fracture zones in quartzites of both the Hanglecærro and the Gamasfjell formations. Thin veins filled with quartz are related to some of these tectonic features. Shearing of the quartz arenite created fractures, cracks and thin fissures, and may also have slightly distorted the packing geometry by differential movements along grain contacts, a process that was facilitated by the phyllosilicate coatings of the clastic grains. Thus, the fracture zones and the minute network of space along quartz grains became routes for meteoric water to flow through a large part of the rock volume with the result that grain-to-grain boundaries were weakened.

One evident chemical effect of the weakening process due to this water is the integration of iron by meteoric water depleted in oxygen, followed by concomitant precipitation of Fe^{3+} oxides in zones which lie parallel to the actual rock surfaces where water-filled pores meet air-filled pores (cf. Fig. 5 C). The source of iron was from the illite and the pyrophyllite, together with a few clastic grains of iron oxides. It cannot be excluded that some of the thin kaolinite sheets lining quartz grains may have formed during weathering at the expense of illite depleted in potassium. Though most etched quartz surfaces appear to be related to the formation of pyrophyllite, etching of quartz associated with thin phyllosilicate coatings may also be a result of chemical dissolution connected with the flow of meteoric water through the rock, similar to the removal of iron from the phyllosilicates. Though the rate of dissolution of quartz is very low, particularly at low pH values, quartz is affected by meteoric water flushing over long periods of geological time, and possibly influenced by the activity of bacteria adhered to grain surfaces (White & Brantley 1995).

Clay coatings of clastic quartz effectively reduce the rate of quartz cementation during burial diagenesis and thus preserve reservoir properties for oil and gas accumulation at great depths in sedimentary basins (Storvoll et al. 2002 with further references). The present study also reveals that clay coating of quartz grains in quartzites is critical for determining the weathering properties of a bedrock type that is usually very resistant to chemical weathering and disintegration. Generally, the rate of chemical weathering of silicates increases with water flux and mean annual temperature (Berner 1995). Chalcraft and Pye (1984) ascribed quite similar weathering of quartzite, as found in the Hanglecærro Formation, to weathering under tropical conditions "over a considerable period of time". The formation of the present phyllosilicate minerals can be ascribed to diagenetic mineral transformations in a more or less chemically closed system during the burial stage of the quartz arenite. However, the opening of joints and bedding plane cracks associated with pressure release during erosion of the overlying rock, resulted in a more open system in which meteoric water could invade the bedrock. This has facilitated chemical weathering processes by enlarging pore throats along mineral grain interfaces, and thereby severely weakening the original rock texture.

Age of weathering and the palaeic surface

The age of the palaeic surface of the Varanger Peninsula is uncertain. However, an early Tertiary age has been suggested for the extensive, gently undulating plain around the Hakŋalančearru Mountain (Riis 1996). This was partly based on correlation with subsurface unconformities in the Barents Sea and partly on correlations with the vast plains in northern Sweden and Finland dated by Eocene fossils from clays in bedrock depressions (Fenner 1988). Inselbergs or residual hills occur on these plains (Rudberg 1960, Kaitanen 1985, Lidmar-Bergström 1999), supporting correlation with the palaeic surface at 400-450 m a.s.l. on the Varanger Peninsula.

Residuals of deep chemical weathering have been found in different parts of the northern Fennoscandian plains. In northern Finland a kaolin deposit, interpreted to be the product of *in situ* chemical weathering, was found at 28-43 meters depth during drilling through superficial material in a bedrock depression (Tynni 1982). The deposit was situated below clays with pre-Quaternary fossils and within an area where the Eocene fossils mentioned earlier occur (Fenner 1988). Traces of pre-Quaternary deep weathering have also been described from low-land plains in northern Sweden (Magnusson

1953), at several locations on Finnmarksvidda (Gjelsvik 1956; Olsen 1993; Olsen et al. 1996; Olsen, 1998), and in the eastern part of the Varanger Peninsula (Olsen et al. 1996). Thus, it is not unlikely that the weathered zones in quartzites in the western part of the Varanger Peninsula have been created by deep chemical weathering in early Tertiary times.

The warmer climate at high altitudes in the northern hemisphere, as compared with the present climate in the Varanger region, probably created the conditions necessary for advanced chemical weathering, particularly in areas where meteoric water could seep through fracture zones in the bedrock.

The pre-Quaternary age suggested above may be problematic since weathered zones also occur in the fiord slopes all the way down to sea level at Tanafjorden, which has probably been glacially deepened and widened along most of its course. However, deep weathering is known to occur several hundreds of meters underneath the ground surface (Thomas 1989; Lidmar-Bergström 1995; Olesen 2004). The fact that the comparably weak bedding planes of the rocks in this outcrop stand more or less vertical would ease the passage of the etching ground water. Further, the chemical weathering may well have continued during later parts of the Tertiary, that is to say at a time when a palaeo-Tanafjorden valley had been developed. This would increase the pressure exerted by the head of ground water and facilitate circulation and weathering deep down in the fissured bedrock. In addition, the study indicates less severe weathering along the fiord than on the Hakŋalančearru Mountain, supporting the view that it developed deeper in the ground.

Conclusion

The quartzite bedrock in the Hakŋalančearru Mountain is deeply weathered along fracture zones, resulting in significantly weakened mechanical strength. Clastic quartz grains as well as diagenetic quartz overgrowths covered by very thin phyllosilicate coatings are easily loosened along weathered boundary surfaces, thus producing a sheet of friable sand along the mountain sides.

The phyllosilicate minerals in the quartzite, illite, kaolinite and pyrophyllite, were formed by diagenesis up to a peak temperature of about 300 °C and appear unrelated to the weathering history.

Weathering beneath the palaeic surface in the Hakŋalančearru Mountain is the result of meteoric water flow through the fracture zones and along grain contacts with phyllosilicate coatings. The original phyllosilicate coatings from the depositional stage have prohibited the dominance of quartz-to-quartz interlocking textures that otherwise are common in many pure quartz arenites that have suffered deep burial diagenetic cementation and metamorphism.

Chemical processes associated with the weathering are removal of iron from illite and pyrophyllite and precipitation of the iron as Fe^{3+} oxides. Removal of potassium from illite may have given rise to some kaolinite development related to the weathering stage, but this is an uncertain conclusion.

The study has shown that the presence of distinct amounts of kaolinite in sandstone bedrock beneath palaeic surfaces does not need to be the product of the weathering event itself, but due to a phase of mineralization inherited from an earlier stage in the history of the rock. The presence and textural distribution of original and diagenetically formed clay minerals may have a distinct impact on the permeability of sandstones, and hence on their weathering potential.

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