Origin of the palaeic landforms and glacial impact on the Varanger Peninsula, northern Norway

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The palaeic surface of the Varanger Peninsula has been studied to evaluate formational processes and glacial remoulding. The peninsula largely consists of a plateau (the palaeic surface) where quartzite heights resembling lithostructurally controlled inselbergs, protrude above a broadly undulating surface largely developed on sandstones. The lowest parts of the palaeic landscape are mainly developed on less resistant rocks like shales, and are often in the form of broad valleys. Along lithostructurally controlled escarpments depressions often occur and pediment-like forms are seldom found. An abundance of weathered zones, probably of pre-Quaternary age, occur in the quartzites, and autochthonous blockfields up to more than 3 meters thick are extensive on quartzites and sandstones. Weathering mantles are extensive also outside the blockfields. It is suggested that differential etching and etchplanation has played an important role for the formation of the palaeic surface, but surface levels also indicate cyclic processes related to former sea levels. Large parts of the plateau show no or only limited signs of glacial erosion. The incision of V-shaped valleys reflects the changing climatic-geomorphic conditions in the late Cenozoic, the increased relief created by selective glacial erosion, and uplift. The late Cenozoic uplift is estimated to be at the most 200 meters for the Varanger Peninsula, but may be significantly less.

Introduction

Palaeosurfaces play an important role in historic genetic geomorphology as they may yield information on denudational processes, palaeoclimate and uplift events far back in time. However, detailed studies of palaeosurfaces in Norway have been rather few. Traditional geomorphic methods coupled with the increasing use of modern computers and software (GIS), and supplemented by new methods for surface dating, offer new possibilities for geomorphic analysis.

At the beginning of the 20th century Reusch (1901) introduced the term Palæic surface (here called “palaeic surface”) for the gentle landscape on the high plateaux in southern Norway, in contrast to the sharply incised fluvial and glacial valleys and fjords. Being inspired by Davis (1899) and his concept of the peneplain as the end product of the cycle of erosion, Reusch concluded that the palaeic surface was formed in preglacial times and graded to sea level before a late Tertiary uplift.

Many geoscientists have observed the stepped appearance of the plateau surfaces, in southern Norway (Reusch 1901; Strom 1948; Schipull 1974; Peulvast 1985; Lidmar-Bergström et al. 2000), and in northern Norway (Wråk 1908; Peulvast 1986). Bonow et al. (2003) carried out a detailed mapping of flats and slopes in the Kjølen mountain area based on digital elevation data. They found a pattern of regularly spaced flats at three major levels, assumed to have developed by fluvial incision and back-wearing of valley sides in response to major changes in the general base level. Peulvast (1986) noted a pattern of stepped surfaces in the Lofoten-Vesterålen area, at least partially of cyclic origin, but he also noted structural control of escarpments between the main levels reducing the importance of backwearing for the development of slopes that has been generally suggested. Thomas (1995) assumed that (re)activation of deep weathering systems during Cenozoic uplift events, driven by increased hydraulic gradients supplying water to the saprolite-rock interface, had been important for the development of pre-glacial relief in Fennoscandia. Gjessing (1967) argued that depressions in the palaeic surface had been created by deep weathering, with subsequent widening by back-wearing thus creating pediments. Although he did not deny the existence of palaeosurface levels separated by steps, he rejected the idea that the summits of the Palaeic rounded hills represented a different and older palaeo-surface level than the depressions.

Elevated surfaces and incised valleys have lately been used for evaluating uplift in different settings (Schoenbohm et al. 2004; Clark et al. 2005; Kuhlemann et al. 2005; Bonow et al. 2006a; Bonow et al. 2006b). However, skeptics still question interpretations often incorporated in surface chronology studies (Thomas 1994; Summerfield 2000), for example that slope retreat is the main process responsible for surface formation.

In the present work the meso-scaled bedrock geomorphology, and its relation to the lithostructures, is ana-
Fig. 1. Simplified map of the study area with location of weathering sites visited by the present or other authors. D = Dakkučearru Mountain, G = Geatnjajávri (lake), H = Hakpalančearru Mountain, L = Leirpollen, St = Staŋgašćaka Mountain, T = Trollfjorden, TKFZ = Trollfjord Komagelv Fault Zone, V = Vagge Mountain.

Fig. 2. Simplified geological map based on digital geological map of Finnmark (Norwegian Geological Survey) draped over a hill shade map. Abbreviations see Fig. 1. Black lines indicate position of topographic-geologic profiles (see Figs 6 and 10).
lyzed to find out if slope retreat and pediment formation (backwearing) were the main components in the formation of the palaeic landscape or if it was due to deep weathering processes like differential etching and etchplanation (downwearing). A landscape chronology and uplift are briefly discussed and the geomorphic effect of Pleistocene ice-sheets evaluated.

### Study area

The Varanger Peninsula is situated at 28-31° E and 70-71° N, and has an area of about 6,200 km². It is delimited by the Barents Sea in the N and E, Tanafjorden in the W and Varangerfjorden in the S (Fig. 1). Apart from a small area belonging to the Caledonian Kalak nappe in the far NW, the bedrock consists of Riphan to Vendian shales, mudstones, sandstones and conglomerates (Fig. 2). The Trollfjord-Komagelv Fault Zone (TKFZ), divides the peninsula into two parts and has been activated several times from the Proterozoic up to the Mesozoic or Tertiary (Siedlecka 1975, 1985; Karpuz et al. 1993; Karpuz et al. 1995). The geological succession in the Barents Sea region north of the TKFZ has not been correlated with the succession in Tanafjorden-Varangerfjorden region (Fig. 3), and it is possible that the Barents Sea region has been moved from an earlier position much further west (Siedlecki 1975).

The rock formations have often broadly undulating structures (Fig. 2) (Siedlecki 1980), and show a limited degree of metamorphism (Siedleck & Roberts 1992). A strongly folded and faulted area between Trollfjorden, Leirpollen and Geatnjajávri (here called “the Hakpakalančcarru-Dakkucčcarru Heights”, see Fig. 1) has NE-SW trending structures due to compression from the northwest during the Caledonian orogeny. South of Varangerfjorden the bedrock is of late Archaean to early Proterozoic age and mainly consists of gneisses and plutonic rocks (Siedlecki 1980, Geological surveys of Finland 1987).

The peninsula can be characterized as an undulating plateau with altitudes generally between 200 and 600 m a.s.l. (Fig. 4). It is largely bordered by steep coastal or near coastal escarpments. The highest altitudes are in the Hakpakalančcarru-Dakkucčcarru Heights where Stanganasčok'ka reaches 725 m a.s.l. and the Skipskjølen area 633 m a.s.l (Figs. 1 and 4).

Syltefjorden is 125-130 meters deep while Kongsfjorden and Båtsfjorden are seldom more than 80-90 meters. Thus, from their water depths these fjords seem to be only slightly over-deepened. Tanafjorden is mostly 200-300 meters deep and only slightly shallower in its outer part. Seismic profiles show that the sediment cover in the fjord is thin. In contrast, thicknesses of about 200 meters occur in the deltaic deposit at the mouth of the river Tana, and possibly up to 375 meter at Masjok 20 km up river (pers. com. Geoffrey Corner, University of Tromss, Oct. 2004). Varangerfjorden is less than 200 meters deep in its inner parts but reaches 400 meters east of the peninsula. Off the eastern and northern coast of the Varanger Peninsula, the sea-depth is less than 100 meters 10 – 15 km from land, but increases to 350-400 meters 15 – 25 km from land in a coast-parallel trench (Kristoffersen et al. 1988).

Topographic heights on the Varanger plateau are often covered by block fields (Malmstrøm & Palmér 1984; Olsen et al. 1996b; Fjellanger et al. 2006) and have occasional turs (Malmstrøm & Palmér 1984). Systems of narrow fluvial valleys penetrate up to 45 km inland from the northeastern and western coast. Only a few lakes exist on the Varanger Peninsula, and most of them occur in Kongsfjordalen and southwards (Fig. 4). Erratics from the crystalline bedrock south of Varangerfjorden occur on the highest summits (Markgren 1964), indicating that the Varanger Peninsula has been overrun from south to north by thick Fennoscandian ice-sheets, the last during the Late Weichselian (Sollid et al. 1973; Marthinussen 1974; Andersen 1979; Svendsen et al. 1999; Siegert & Dowdeswell 2004). However, large parts of the Varanger Peninsula plateau lack signs of glacial sculpturing, which is mainly restricted to areas where topography facilitated
Fig. 4. A height layer map where transparent height layers are draped over a hill shade map, both created from a digital elevation model with 25 m pixel size. See Fig. 1 for abbreviations.

Fig. 5. Map showing relative relief calculated within a 2 km diameter circular window around each pixel. It is draped over a hill shade map. Large relative relief often coincide with lithostructural boundaries (see Fig. 2). See Fig. 1 for abbreviations.
enhanced ice-flow. It is also clear that the autochthonous blockfields must have survived the coverage by at least one, probably several ice-sheets (Ebert & Kleman 2004; Fjellanger et al. 2006).

**Methods**

Analyses of topography, analyses of the relation between landforms and geology, and inventories of weathering residues, were the main methods used. An overview of geomorphology, superficial materials and glacial erosion was obtained from aerial photos. Relative chronology and published exposure dating (Fjellanger et al. 2006) were used to get some idea of the time scale.

Profile curves have been derived from a digital elevation model (DEM) with 25 x 25 m resolution (resampled to 50 x 50 m resolution) within a Geographical Information System (GIS) framework. Profile curves were constructed along lines trending north-south and west-east with 5 km spacing, and along some other selected lines. Maximum, minimum and mean elevations within a circular calculation window of 2 km diameter were used to calculate the relief parameters along the profile lines (Brown et al. 1999; Fjellanger & Etzelmuller 2003; Bonow et al. 2006b). Maps showing altitude layers (Fig. 4) and relative relief (Fig. 5) calculated from the DEM aided the interpretation.

The topography along the profiles has been analyzed in relation to geological maps at a scale of 1:250 000 and some at a scale of 1:50 000. Some profiles have been coupled with digital geological maps.

During field surveying in the summers 2002, 2003 and 2004, some shallow pits were dug for brief evaluation of the types of superficial material present. Rock samples from blockfields and glacial features were collected for exposure dating purposes (Fjellanger et al. 2006) and rock samples from weathered zones in quartzites were collected for analysis of the weathering process (Fjellanger & Nystuen In press). Additionally, all available information regarding weathering mantles on the Varanger Peninsula was obtained from the literature.

**Results**

*Topography*

Gently undulating surfaces dominate the landscape over large parts of the Varanger Peninsula down to about 200 m a.s.l., and even lower in the southeastern areas (Fig. 4). It is evident that areas with low relative relief are most extensive in the central and southeastern parts of the peninsula (Fig. 5).

In the summit areas between the northern fjords a gently undulating surface can be followed southwards (Fig. 6 profile 2 and northern parts of profiles 1 and 3). The altitude is 350-450 m a.s.l., here and there as low as 300 or up to 500 m a.s.l. (Fig. 4). This surface will be called the main level as it is the most extensive and forms the summit surface over large parts of the peninsula. South of the TKFZ the main level is extensive on both sides of the broad informally called South Central Valley (Fig. 1). The relative relief is for the most part less than 100 meters within a 2 km calculation window (Figs 5 and 6, also see Fig. 7). Between the northern fjords the main level starts to descend 5-10 km from the main coast line (Fig. 6 profiles 1, 2 and 3). It largely ends in coastal escarpments up to 300 m high. The transition from the main level to lower and higher parts of the Palaeic surface partly consists of escarpments up to 250 meters high (Fig. 5 and 6). The lowermost parts of the Palaeic surface at 150-300 m a.s.l. are found in the South Central Valley (Figs. 1 and 4), in a network of wide, high level valleys south of Syltefjorden (Fig. 4 dark grey colour, and Fig. 8), in the northwest, and in the very easternmost part of the peninsula, where the surface descends down to about 150 m a.s.l (Fig. 6 profile 5). The South Central Valley is slightly less than 200 m a.s.l. in the south, gradually increasing to 250 m a.s.l. in the north, and has low relative relief (Fig. 6 profile 4). The network of broad, high level valleys south of Syltefjorden has an altitude mainly of 250-300 m a.s.l., and is developed between heights reaching 400-450 m a.s.l. (Figs. 4 and 6: profile 5). The bottoms of the valleys are partly rugged, specifically those close to Syltefjorden, but are smooth at the water divide towards Dávatjohka to the south (Fig. 8 southern part).

The lower Palaeic landscape usually ends in escarpments up to 200 m high at or close to the coast. Thus, along parts of the eastern and southern coasts the descent down to sea level is characterized by surfaces with step-wise arrangements (Fig. 6 profiles 2, 3 and 5). Along the southeastern coast the 150-300 meters level is more fragmentary, and is replaced by plains below 100 m a.s.l. gently sloping down towards the coast. This is the case inside Ekkerøy, between Skallnes and Holmfjellet, and along the lower part of Komagely (Fig. 1). Between Skallnes and Holmfjellet the slope gradually steepens up to the rounded summit of Falksfjellet (Fig. 6 profile 4).

Three areas have summits or summit areas that rise significantly above the main level. The Håkpalâncearru-Dakkûcèarru Heights have gentle summit areas mainly at 500-600 m a.s.l. (Figs 4 and 9 and 10 profile 6). The Håkülâncearru-Dakkûcèarru Heights are delimited by more or less distinct escarpments towards the main level. The highest escarpment is the south-facing wall of the Håkülâncearru ridge reaching 250 meters above the main level. Skipskjølen further east has the form of a ridge with summits up to 633 m a.s.l. Abrupt escarpments face north, whereas towards the south and southwest, the mountain side slopes more gently. Falksfjellet to the south reaches up to 545 m a.s.l. but is not delimited by steep escarpments.
Fig. 6. Topographic profiles extracted from a digital elevation model with 25 m resolution. The maximum, minimum and average altitudes are calculated within a circular calculation window, 2 km in diameter, for each point along the profile. Vertical exaggeration is 13. See figures 2, 4 and 5 for position of the profiles. Profiles 2 and 5 show examples of surface reconstructions representing previously much more extensive paleosurfaces as assumed in models with stepped cyclic surfaces (see discussion).
Narrow V-shaped valleys have been incised into the floor of the more gentle high level valleys south of Syltefjorden (Figs 4 and 8). Several of them drain into Syltefjorden, while the longer Đåvatjohka ends in Sandfjorden. Đåvatjohka extends for about 45 km inland and ascends rather steadily reaching 150 m a.s.l. about 30 km from the coast. The V-shaped cross profile is evident in large parts of this valley system and the valley width is rather constant (Fig. 4). The broad valleys leading down to Båtsfjorden and Kongsfjorden reach 150 m a.s.l. 10-15 km from the sea, and have a rugged topography (Fig. 4).

Lithostructures and landforms
Lithology and structure of the bedrock play an important role for the main geomorphic features of the plateau of the Varanger Peninsula. First, the highest areas consist of the most resistant rocks, while the lowest areas are underlain by less resistant rocks. Second, where resistant structures are near horizontal, the land surfaces are gentle, but where resistant structures dip more steeply, ridges or scarps have often developed.

The Hakšalančearru-Dakkučearru Heights and the Skip-
skjølen and the Falkfjellet mountains consist of quartzites of the Gamasfjellet and/or Hanglecærro Formations (Fig. 2). Whether these heights are delimited by abrupt escarpments or not is determined by the structural dip-angle of the quartzite. Profile 6 (Fig. 10), crossing the Hakọlančearru-Dakkucėarrru Heights, shows that the summit surface at about 500-600 m a.s.l. truncates folds in the quartzites of the Hanglecærro and Gamasfjellet Formations and the intervening Vagge Formation shale. This has resulted in a repetitive sequence of plateaux separated by valleys along synclines. Strike parallel shallow depressions have been formed in the outcropping Vagge Formation shale (Fig. 11).

The Hakọlančearru ridge (up to 604 m a.s.l.) consists of a 40°-50° dipping outcrop of the Hanglecærro Formation quartzite. The ridge has several gaps where water from small ponds or melting snow has drained. The sedimentary bedding plane is clearly visible in the rock wall and exerts a strong control on its form (Fig. 12). Although zones of strongly weathered quartzite occur (Fjellanger & Nystuen, In press), in some cases crossing the whole ridge, the gaps do not seem to be associated with such zones.

The 200 m thick massive quartzite of the Hangelcærro formation was studied by Siedlecka & Siedlecki (1971) and Fjellanger & Nystuen (2007). The rock formation consists of tightly packed quartz grains cemented together by quartz overgrowths. Microscope studies indicate similar properties for the 300 m thick Gamasfjellet Formation quartzite. It is assumed that these two formations, which cover large areas south of the TKFZ (Fig. 2), are relatively resistant to weathering processes, although long-term chemical weathering by meteoric water along cracks and faults has significantly altered the mechanical properties of the rock (Fjellanger & Nystuen 2007).

At the bottom of the south-facing rock wall, the Hanglecærro Formation continues underneath the stratigraphically overlying mudstones and sandstones of the Stappiegiedde Formation (Siedlecka & Siedlecki 1971), which underlie the gently undulating surface (main level) to the south (Fig. 9). The knick at the scarp foot follows the lithological boundary (Figs 9 and 10 profile 1). No gently sloping foot slope or pediment is identified. Small lakes occur rather frequently in a 2-3 km wide zone below the rock wall (Fig. 4), and several elongated lakes are situated along the nick, below the steepest parts of the wall.

In the southwestern part of the peninsula the red, quartzitic Stappiegiedde Formation sandstone forms a series of saucer-shaped synclines (Siedlecki 1980). The formation crops out in circular patterns (Fig. 2) embracing broadly undulating summit areas developed in mudstone interspersed with quartzite (Breivik Formation). Where escarpments occur around this area they are always connected to outcrops of the red quartzitic sandstone (Fig. 2, 4 and 10 profile 2).

The Stappiegiedde Formation rocks are, together with older tillites, part of a Vendian succession of rocks. They have been deposited on an unconformity truncating different terminal Riphean (or early Vendian) rocks, including the Gamasfjellet Formation quartzite (Fig. 2 and Siedlecki 1980). Rocks deposited on the unconformity are also preserved as two isolated relicts further east in gentle synclines. The quartzitic mountains Urdfjellet and Falkfjellet (Gamasfjellet Formation) occur between what remains of Vendian rocks (Fig. 2).

North of the TKFZ massive sandstone formations belonging to the Sandfjord and the Båsnæringen Formations, dominate in the higher lying areas, while phyl-
Fig. 10. Selected topographic profiles coupled with geology showing the relationship between lithostructures and geomorphology. See figures 2, 4 and 5 for position of the profiles. Max., min. and average topographic curves are added in profiles 5 and 6. Vertical exaggeration is 13x in profiles 2 and 4, and 5 in profiles 5 and 6.
lites and mudstones, in some instances interspersed with sandstones or calcereous rocks, dominate lower areas. Thus, Kongsfjorden, Båtsfjorden and Syltefjorden, with associated broad valleys, are linked to the less resist-ant rocks of the Båtsfjord and Kongsfjord Formations (Fig. 2). South of Syltefjorden the topographic heights Suologáisasá and Skadjacˇearru (Ekkovidda) consist of domed anticlines of the quartzitic Båsnæringen Formation sandstone (Fig. 10 profile 5). These anticlines have been truncated, exposing stratigraphically underlying mudstone which is often associated with depressions (Fig. 10 profile 5). Juovkkaidcˇearru (Langryggen) further southeast and Noiddiicˇearru (Kjøpmannskjølen) further southwest consist of sandstones of the Tyvjoﬁell Formation. The broad interconnected depressions between the heights are developed in the less resistant Båtsfjord Formation (Siedlecki 1980). The lithological borders mainly coincide with the scarp foot around the heights.

The systems of narrow V-shaped valleys south of Syltefjorden mainly follow the Båtsfjord Formation rocks (Figs 2 and 8), but in the upper reaches of Syltefjorddalen with tributaries, the valleys have been cut in massive sandstones. Valleys and depressions are developed along parts of the TKFZ exploiting this structural weakness. The valleys draining to Leirpollen in the west mostly follow mudstones of the Stappogiedde Formation, but have also been developed along synclines in the Stappogiedde Formation sandstone (Fig. 10 profile 4).

**Regolith and weathering**

Blockfields cover about 25% of the Varanger Peninsula, are mostly confined to higher areas, and are for the most part autochthonous (Malmström & Palmér 1984; Olsen et al. 1996b; Sorbel & Tolgensbak 2004; Fjellanger et al. 2006). They cover the inselberg-like quartzitic massifs and much of the undulating surface below (main level). However, in the southwestern part of the main level blockfields are confined to the very highest areas (Olsen et al. 1996b). The maximum thickness of the autochthonous blockfields is not known, but investigations in the Basecearru area (Fig. 1) indicate thicknesses of significantly more than 3 meters (Malmström & Palmér 1984; Meier 2001). Here the block mantle is more weathered at depth and the interstitial spaces are filled with a fine-grained, rust red well compacted matrix (Malmström & Palmér 1984).

In the Hanglecærro and Gamasfjell formation quartzites in the Hakŋalančearru-Dakkucˇearru Heights weathered zones frequently occur along previous cracks and faults. In the weathered zones the mechanical strength of the quartzites is significantly reduced, probably due to slight chemical dissolution of quartz along grain contacts (Fjellanger & Nystuen 2007). The weathering was facilitated by the opening of intergranular routes for water, first by slight distortions of the packing geometry by differential movements along grain contacts during episodes of shearing, and second by pressure release during erosion of the above-lying rock resulting in a more open system where meteoric water could percolate into the rock (Fjellanger & Nystuen 2007). In the depression created in the Vagge shale between the ridge and the rest of the mountain Hakŋalančearru (Fig. 10), the surface generally consists of a rather fine-grained regolith. Large amounts of quartz sand up to more than one meter in thickness cover parts of the slope from the contact to the Hanglecærro Formation (Fig. 11). Gravity-driven processes most probably have transported the sand, but small dunes indicate that aeolian processes have also contributed. The quartz sand comes from chemically weathered zones in the Hanglecærro Formation quartzite where the resulting increase in permeability and significant reduction in mechanical strength have greatly facilitated disintegra-
tion by frost wedging.

The south-facing rock wall of the Hakŋalančearru ridge is, in the lower half, covered by a talus, which is thin as observed along scars exposing the underlying bedrock. The talus has a slightly undulating appearance down slope, probably caused by undulations in the underlying bedrock surface. In some areas talus blocks have been deposited on the ground surface (main level) up to about 300 m from the scarp-foot, and partly forming a blanket covering the ground.

Inspection of shallow pits, e.g. in the northeastern part of Annacearru and northwest and south of Syltefjorden, indicates that in situ developed weathering mantles may be widespread also outside the blockfields. The red quartzitic sandstone in the Stappogiđđe Formation is covered by a weathering mantle at least 1 meter thick. Northwest and south of Syltefjorden, the geological structures of the Båtsfjord Formation are often expressed as parallel stripes on the ground surface (Fig. 8). This formation mostly outcrops below 300 m a.s.l. Field surveying and pits up to 1.2 meters deep around Suologáisá showed that the shale is weathered to fine-grained material and is usually covered by vegetation, while the interspersed sandstone layers weather to form blocks and stones exposed at the surface. Thus, the bedrock structures are visible through the weathered mantle (saprolite).

Along the eastern border of Suologáisá red quartzitic sandstone boulders (Båsnæringen Formation) derived from Suologáisá itself form a blanket on the ground surface up to about 300 meters from the scarp foot, much like what was observed below the south-facing escarpment of Hakŋalančearru ridge. Sandstone clasts have also been deposited on top of a ridge underlain by the Båtsfjord Formation shale separated from the scarp foot by a 30-40 m deep depression.

River bluffs along the rivers Komagelva and Leirelva have been studied in the eastern part of the Varanger Peninsula (Olsen et al. 1996a). Along Leirelva, about 120 m a.s.l. which is 35 m above the postglacial marine limit, 14 meters of glacigenic sediments are underlain by sandstone bedrock. The uppermost 1 meter of the bedrock is strongly weathered, and consists of a fine-grained material showing gradational colour changes and colours resembling rubification known from soils in warmer climates. The colours are clearly different from the fresher, but densely fractured, bedrock exposed below. Horizons and lenses of kaolinitic material were taken as evidence of formation during pre-Quaternary climates (Olsen et al. 1996a). Along Komagelva, at about 55 m a.s.l., a succession of sediments containing kaolinitic horizons, and thus correlated with the succession along Leirelva, was interpreted as saprolites eroded and deposited by glacial processes. The underlying bedrock, however, was not exposed.

Discussion

Preservation of the pre-Quaternary surface

Signs of glacial sculpturing on the Varanger Peninsula plateau mainly occur in areas where topography has facilitated channelled ice-flow, e.g. along pre-existing valleys parallel to the ice movement (Fjellanger et al. 2006). Significant glacial erosion has occurred in Kongsfjorden, Båtsfjorden and Syltefjorden where the lowest palaeic level, assumed to have existed there (see below), has been obliterated (Fig. 4). In other areas the bedrock geomorphology and superficial material show no or only very limited signs of glacial erosion, despite previous coverage by several ice sheets (see below). Here, several meters thick autochthonous blockfields (Malmström & Palmér 1984; Meier 2001; Fjellanger et al. 2006) have incised meltwater channels and superimposed circular ablation moraines (Sørbel & Tolgensbakk 2003; Ebert & Kleman 2004). Large systems of parallel lateral meltwater channels slope gently along the sides of valleys and mountains, and crossing systems of meltwater channels frequently occur (Sørbel & Tolgensbakk 2004). The ice sheets have mainly been cold-based and thus non-erosive on the plateau (Ebert & Kleman 2004; Fjellanger et al. 2006; Sørbel & Tolgensbakk 2004). During interglacial periods like the Holocene the weathering seems to have been limited as indicated by the exposed bedrock surfaces in the bottom of meltwater channels (Fjellanger et al. 2006).

Weathering profiles indicative of warmer climates (Olsen et al. 1996a), support the view that much of the plateau-surface has been preserved during the Quaternary. Its gentle form and position above the glacially eroded fjords, and the fact that it is under destruction by V-shaped valleys, justifies the label “palaeic surface” (Reusch 1901).

Development of the palaeic surface

Structurally controlled relief

Even though the highest areas of the main level are less than 100 meters below most of the summits of the Hakŋalančearru-Dakkučearru Heights, the height difference is generally significant (Fig. 6 profiles 1 and 5). Therefore the Hakŋalančearru-Dakkučearru Heights, and also the quartzitic Skipskjølen ridge reaching 633 m a.s.l., resemble lithostructurally controlled inselbergs rising above the main level (Figs. 4 and 9).

The lowest palaeic level mainly follows less resistant rocks like the Båtsfjord Formation between more resistant heights. Based on the distribution of these lithologies (Fig. 2) and surfaces remaining inside the fiords (Fig. 4) it is assumed that the lowest palaeic level has also existed in the Syltefjorden, Båtsfjorden and Kongsfjorden areas. The highest level developed on quartzites, the main level developed mainly on sandstones and the lowest level mainly developed on shales and mudstones indicate a
more or less systematic relation of rock types to the different surface levels. In addition, the escarpments, which in many cases separate the surface levels, are located at the borders between different rock formations. Together, these facts show that lithological differences and structures have a clear impact on the Palaeic relief. On the other hand, all three surface levels truncate different rock formations, indicating a more complex role played by the lithostructures in connection with the formational processes (see below).

The Vendian succession of rocks in the southern part of the Varanger Peninsula (Fig. 2 and Siedlecki 1980) is deposited on a regional unconformity representing a major erosional event (Holtedahl 1918; Føyn & Siedlecki 1980; Siedleca & Roberts 1992) dated to sub-Vendian time (Gorokhov et al. 2001). The quartzite mountains Urdjellet and Falkjellet (Riphean Gamasjell Formation) have gentle slopes (Fig. 6 profiles 3 and 4), and are located between the remnants of Vendian cover rocks with modest dip angles (Siedlecki 1980). This indicates that the slopes of these mountains are re-exposed and tilted parts of the sub-Vendian surface.

Deep weathering

Residues of chemical deep-weathering have been found in different parts of the northern Fennoscandian plains. From different sites on Finnmarksvidda sediments from several glacial-interglacial cycles have been reported, and luminescence-dated (TL and OSL) up to more than 300 ka (Olsen et al. 1996a; Olsen 1998). Underneath these deposits deeply weathered bedrock amounting to at least 35 meters in thickness was identified (Olsen et al. 1996a; Olsen 1998). These saprolites were assumed to be of pre-Quaternary age (Olsen et al. 1996a).

In northern Finland kaolin deposits, interpreted to be the product of in situ chemical weathering, have been found below clays in which early Tertiary microfossils occur (Fenner 1988). Traces of pre-Quaternary deep-weathering have also been described from lowland plains in northern Sweden (Magnusson 1953), from the western part of Finnmarksvidda (Gjelsvik 1956), and on islands in the Lofoten-Vesterålen archipelago (Peulvast 1985; Paasche et al. 2006). More comprehensive summaries of weathering residues in Fennoscandia may be found in Lidmar-Bergström et al. (1999) and Migoñ & Lidmar-Bergström (2001).

The numerous weathered zones occurring on the surface of the quartzitic Hakŋalanćearru-Dakkucěarru Heights are interpreted as the product of pre-Quaternary deep weathering (Fjellanger & Nystuen 2007). Fresh bedrock exposed in the bottom of lateral meltwater channels shows that very limited weathering has occurred on bare rock surfaces since the late Weichselian deglaciation. Together with abundant signs of coverage by several non-erosive ice sheets this indicates that the weathering residues, like the extensive and up to more that 3 meters thick autochthonous blockfields (Malmström & Palmér 1984; Olsen et al. 1996b; Meier 2001; Fjellanger et al. 2006), are much older than the Holocene, and a pre-Quaternary age is not unlikely. The saprolites identified by Olsen et al (1996a) along Komagelva support the preservation of saprolites through the Quaternary. However, more information about the blockfield material and other weathering residues is needed in order to reach firmer conclusions regarding the type of weathering processes responsible for these residues.

Formation of scarp

Pediments seldom occur along the lithostructurally controlled escarpments, and instead depressions may be found. Several of the depressions are presently filled with water, and are best developed where the escarpments are high, e.g. at the foot of the Hakŋalanćearru rock wall. These depressions may have resulted from enhanced deep weathering due to increased water supply from the rock wall, during surface formation. However, it cannot be excluded that glacial erosion has played a role in the formation of these depressions, although more signs of such strong erosional events were to be expected in the area.

In most cases where escarpments separate surfaces at different levels on the Varanger Peninsula, the escarpments follow steeply dipping rock formations, e.g. the Hakŋalanćearru rock wall, and along the sides of the palaic valleys south of Syltefjorden (Figs 8, 9 and 10 Profile 5 and 6). This indicates downwearing as it seems less likely that slope retreat, after levelling large areas, would stop more or less abruptly at the border to rocks of higher resistance.

However, Römer (in press) pointed to the coexistence of inselbergs developed by backwearing and others developed by differential weathering, and concluded that lithological and structural properties were the primary reasons for the different modes of formation. Thus, it seems possible that backwearing, in some cases, may stop at the border to more resistant rocks. But it is uncertain what other conditions must be fulfilled for this to be possible, like the angle of the retreating slope, types of weathering, types of lithologies etc.

Strong lithostructural control of escarpments in tropical regions has been ascribed to differential etching (Thomas 1989, 1994). A steeply dipping rock surface without a saprolite cover may be relatively stable in climates suitable for deep-weathering (Bremer 1993).

In the southwestern part of the Varanger Peninsula (Figs. 2 and 10 profile 2), scarp retreat by undermining of the red Stappogiedd Formation quartzite may have played an important denudational role. However, differential etching may still have played a decisive role elsewhere within the study area.
Formation of the palaeic surface

It may be argued that the partly stepped appearance of the Palaeic surface on the Varanger Peninsula where each surface level truncates different rock formations, calls for a model with stepped cyclic surfaces. In such a model each surface has been initiated by an uplift event and developed in relation to relative sea level (Baulig 1935, King 1967). Denudation is usually assumed to have occurred by fluvial incision and subsequent retreat of valley sides (Ahnert 1998; Bonow et al. 2003) by the process of pedimentation (King 1967).

The tentatively reconstructed surfaces shown in Fig. 6 profiles 2 and 5 fit such a model. This implies that the highest surfaces previously had a much larger extent than at present and that each surface has been consumed by the development of the lower surface. In profile 5 (Fig. 6) the lowest reconstructed surface slopes gently towards the east, where it broadens out (Fig. 4), while in its inner parts it continues in valleys cutting into the main level. Profile 2 (Fig. 6) also indicates that the lowest surface previously existed in the Kongsfjorden and Båtsfjorden areas. Remaining parts of the reconstructed main level are preserved in the summits of the resistant heights between these valleys and fiords. The summit surfaces of the Hakṣalancčarru Heights could likewise represent parts of the highest surface preserved on the most resistant lithologies.

However, if the surface on top of the quartzitic Hakṣalancčarru inselbergs has been developed by slope retreat (backwearing), it may be asked why slope retreat stopped at the border to the same quartzites during development of the main level. The same question arises for the lithostructurally controlled borders of the lowest level (Figs. 2, 4, 10). This indicates that backwearing alone cannot explain the development of all surface levels, unless vastly different time periods are invoked.

Furthermore, the undulating surfaces, with up to several meters of thick weathering residues (maximum thickness is unknown) also resemble partly stripped etchplains as described by Thomas (1995). According to Büdel (1982) and Thomas (1994) etchplains may truncate different lithostructures if the resistance towards the etch process is not too different. Therefore, an alternative explanation to the backwearing concept is that differential etching created the lithostructurally controlled escarpments, and that the surfaces have developed by etchplanation, or alternating periods of etching and stripping, but with a greater lowering rate in the less resistant rocks.

Thus, the gently undulating form of the surfaces may reflect the process of formation, (e.g. etchplanation), rather than closeness to sea level. On the other hand, closeness to sea level does not dismiss etch processes from being decisive for surface development. Differential etching may have lowered a surface to a position close to sea level, while more resistant lithologies (Thomas 1989) remain as higher ground.

Many of the inselbergs in northern Finland occur in areas where deep weathering residues are preserved. This caused Kaitanen (1985) to assume that differential weathering in preglacial times had played an important role during their development. On Finnmarksvidda Olsen et al. (1996a) identified thick pre-Quaternary saprolites. Thus, the correlation of plains in northern Finland and on Finnmarksvidda with the main level on the Varanger Peninsula (Riis 1996) supports the view that deep weathering has played an important part there also.

That deep weathering has played an important role for the formation of palaeosurfaces in Fennoscandia, or at least had a very important preparatory role, has also been suggested by several other authors (Gjessing 1967; Schi-kpul 1974; Peulvast 1985; Söderman 1985; Gjessing 1987; Lidmar-Bergström 1988; 1995, Thomas 1995).

From a study of inselbergs in granitic terrains in Zimba- bwe, Römer (In press) concluded that inselbergs developed by backwearing exist side by side with lithostructurally controlled inselbergs showing no sign of back- wearing. This points to the possibility that both slope retreat and differential etching may work simultaneously, and that rather than being totally different concepts, they should be viewed as end members of a continuum of process types (Peulvast & Sales 2004).

It is also possible that the intensity of different processes, like differential etching, etchplanation, pedimentation and fluvial abrasion, has changed between the periods of formation of different surface levels on the Varanger Peninsula. For example the processes being responsible for the upper surface truncating the Hanglecærro and Gamasfjell Formation quartzites may be different from the processes forming the “main” level which do not truncate these formations.

It is possible that former base levels have been of impor- tance for the formation of surfaces at three distinct lev- els and we note that rock resistance has been decisive for their present distribution. We conclude that differential weathering has played an important role for slope develop- ment and etchplanation for surface formation while pedimentation and parallel scarp retreat have played a minor role. Nevertheless both processes seem to have been involved.

Landscape chronology, uplift and climatic change

A Mesozoic age and an early Tertiary age have been sug- gested by Riis (1996) for the summit surface of the resis- tant heights and for the main level, respectively. This was based on extrapolation of the erosional boundaries (hiatuses) between the outcropping depositional forma- tions beneath the Barents Sea. Riis also correlated the main level on the Varanger Peninsula with the surface in northern Finland, where Eocene microfossils (Fenner 1988) were assumed to give a minimum age for the land
Based on estimates of glacial erosion (Vorren et al. 1991; Vågnes et al. 1992) leading to denudational unloading, and the counter effect of the water load after transgression, the crustal uplift of the Barents Sea area has been calculated to lie between 350 and 600 meters since middle-Pliocene (Dimakis et al. 1998). Riis (1996) used the present elevation of the main level and suggested 400 meters of uplift during the Pliocene - Pleistocene period.

However, it is clear that the lowest palaic surface level, which extends at least down to 200 m a.s.l., could not have developed beneath the contemporaneous sea level. Thus, even if the eustatic sea level during formation of this surface level was as much as 50 meters lower than at present, which might have been the case for shorter periods at about 2.5 and 10 Ma. (Haq et al. 1987), a maximum uplift of about 200-250 meters may be inferred for the Varanger Peninsula since the middle Pliocene. But this estimate also seems too high, as the pre-glacial coast line may have been located as much as 400 km further west in the Barents Sea (Vorren et al. 1991). Thus, the altitude reached by the palaeo-rivers running 400 km inland from the coast line (Vorren et al. 1991), should be subtracted from the 200-250 meters. In addition Olsen et al. (1996a) detected saprolites assumed to be of pre-Quaternary origin at 120 m a.s.l., possibly also at 55 m a.s.l., in the eastern part of the Varanger Peninsula, indicating a further reduction of the Quaternary uplift in this area.

Several of the V-shaped valleys, e.g. the Davatjohka river (Fig. 1), maintain about the same width along much of their lengths, indicating that headward erosion has occurred relatively fast. They have regularly sloping longitudinal profiles indicating development by sub-aerial fluvial processes. Thus, their formation is restricted to periods without ice sheet cover. River captures (Svensson 1971; Malmström & Palmér 1984) and frequently occurring steep valley heads indicate that the valleys are presently working their way into the land block. These valley systems often follow less resistant rocks like the Båtsfjord Formation (Fig. 2), but are also incised into more resistant rocks, e.g. the massive sandstones along parts of the Oarddojohka and Basávžžejohka valleys. They have survived at least one ice sheet, as is shown by meltwater channels from the bordering high-level surface which continue down into some of these valleys, sloping obliquely along their sides (Sorbel & Tølgensbakk 2004).

The river incision may have been facilitated by surface uplift as a response to the denudational unloading of the Barents Sea (Vorren et al. 1991; Vågnes et al. 1992; Dimakis et al. 1998). However, their development may also reflect the change to a colder and wetter climate with increased runoff and production of coarser sediments assumed to have taken place in the late Cenozoic. It should also be mentioned that glacial erosion e.g. along fjords obviously accounts for much of the increase in local relief. Thus, surface uplift may have been of limited importance for the development of the V-shaped valleys.

The points mentioned above give the impression that the palaic surface was developed in a climate-geomorphic regime with much less vigorous fluvial abrasion than during the formation of the V-shaped valleys.

Assuming that the lowest palaic level has also existed in Kongsfjorden, Båtsfjorden and Syltefjorden (see above) then the late Cenozoic erosion by rivers creating V-shaped valleys and ice sheets amounts to 200-300 meters of rock in these fjords.

Conclusions

The palaic surface seems to be well preserved on the Varanger Peninsula, despite having been covered by several Quaternary ice sheets. Three undulating levels may be distinguished in the palaic surface, at 150-300, 300-500 and 500-700 m a.s.l. Their distribution is to a large extent related to the lithology of the bedrock, with quartzites in inselberg-like heights, sandstones dominating the middle (main) level, and shales and mudstones dominating the lowest level. All levels truncate different rock formations. Many escarpments separating the surface levels are lithostructurally controlled. In the southeastern part of the peninsula the slopes of the quartzite mountains represent sub-Vendian surfaces. Differential etching and etchplanation is thought to have formed the palaic surface, but cyclic processes related to former baselevels is also thought to have played a role. Late Cenozoic climate deterioration, increased local relief by selective glacial erosion, and surface uplift, facilitated the formation of V-shaped valleys. Surface uplift of the Varanger Peninsula is not thought to exceed 200 meters since the middle Pliocene, and may be significantly less. In Kongsfjorden, Båtsfjorden and Syltefjorden 200-300 meters of rock have been removed by rivers and ice sheets during the Late Cenozoic.

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