# Geology of the soapstone deposits of the Linnajavri area, Hamarøy, Nordland, north Norwegian Caledonides — Norway's largest reserves of soapstone

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The Linnajavri area, subdivided in Linnajavri northern and southern area, is located in Hamarøy municipality, Nordland county, northern Norway. During five short field seasons (1–3 weeks) from 2001 to 2006, the ultramafic bodies of the Linnajavri area have been outlined and the soapstone alteration studied in detail for evaluation of its possible potential for exploitation. The Linnajavri area is built up of Caledonian nappes thrust over Precambrian granitic basement exposed to the west of the nappe pile. Our work has focused on rocks of the Seve and Köli nappes of the Upper Allochthon. Within the Köli rocks, a number of tectonic mélange zones have taken up the stress built up between blocks of rock, especially in the area with ultramafic bodies, thereby preserving primary depositional structures and evidence of alteration processes in the rocks between the mélange zones. The ultramafic bodies, gabbros and pillow lavas are interpreted to represent ophiolite fragments. In their present setting, they are associated with conglomeratic weathering products of the ophiolites. The ultramafic rocks are dunite, peridotite and, to a subordinate degree, pyroxenite. All the ultramafic rocks are strongly serpentinised and to an extensive degree also further altered to soapstone. Listwaenite, the end product in this alteration chain, is also encountered in the Linnajavri southern area. Only one of the ultramafic bodies shows cumulate banding, probably originating from the lower, layered part of oceanic crust. Alteration of the ophiolite fragments took place at an early, probably oceanic stage, with development of serpentinite, soapstone and listwaenite. Flushing of $CO_2$ followed joints and brecciated zones in the ultramafic bodies. Introduction of $CO_2$ was focused in certain areas, most extensively in the Kleberflåget ultramafic body, producing the largest volumes of soapstone. At Kleberflåget, the $CO_2$ flushing continued with falling temperatures ultimately leading to breakdown of soapstone to listwaenite. The ophiolite and its alteration products were obducted and exposed for weathering processes with formation of conglomerates; e.g., serpentine conglomerates locally with soapstone pebbles, green mafic conglomerates and conglomerates with mica-schist matrix. The soapstones of the Linnajavri area represent large resources for use as dimension stone. The soapstones also represent potential resources for talc flotation. The size of the mapped reserves as well as possible additional geologically indicated resources, and the potential for exploitation over decades, implies that a thorough study of talc flotation should be undertaken.

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## Introduction

Our first visit to the Linnajavri[1] area (Figure 1) was a once-in-a-life-time experience for two economic geologists. During the reconnaissance trip in September 2000, very large ultramafic-hosted soapstone deposits were partly discovered for the first time, and partly rediscovered, by the authors. The trip, aimed at getting a quick overview of the soapstone potential of the area, was initiated by the authors based on the fact that there were relatively large ultramafic and mafic bodies in the area, but rather limited geological information about these bodies (Foslie 1936, 1942, Brattli and Prestvik 1985, 1987a, b). During our three-day visit to the area we discovered extensive soapstone formation both within and along the border of the Gaskavárri serpentinite ridge as well as its neighbouring body to the northwest, the Njaskasvárri 833 lens (see Figure 2). We also recognised the strong talcification of the northwest end of the Kvitfjell ultramafic lens, earlier shortly described by Foslie (1942, p. 75). On our visit to the Ridoalggičohkka ridge we discovered an overwhelmingly extensive talcification that has affected both limbs of the roughly sheet-formed 2 x 4 km ultramafic body that makes up a part of the open, shallow Ridoalggičohkka synform. The amount of soapstone we discovered, or rediscovered, during this first three-day field trip was so enormously large, at least in our eyes, and the talc content of the soapstone so high, that our findings naturally prompted us to suggest a joint collaboration project set up between landowner Statskog (State Land and Forest Managing Organization) and NGU on investigation of the soapstone deposits.

The *Linnajavri area* in this context is the area just to the north, east and southeast of lake Linnajavri and up to the Swedish border in Hamarøy municipality in Nordland county (Figure 1). Geographically, the Linnajavri area is subdivided in the Linnajavri northern and southern area. A number of new location names are introduced in our reports, due to the scarcity of names on the 1:50,000-scale topographic map. The distance from the central part of the area to the deep-water harbour at Leirfjord is ca. 35 km, with 26 km of existing road, and 6–12 km with no road. The area is mountainous and not forested. The elevation varies between 600 and 1200 m. No signs of previous use or exploitation of the soapstone have been recognised. Parts of the deposit area may in the future be subjected to special environmental regulations.

The results from five short field seasons (1–3 weeks each) from 2001–2006 are presented here. The focus of the work in the area has mainly been to map and systematically sample the resources of soapstone and just one season for mapping the geology of the area (Lindahl and Nilsson 2001, 2002, 2005a, b, c, 2006a, b, Nilsson and Lindahl 2003a, b, Nilsson et al. 2003, Skilbrei et al. 2003, Nilsson 2004, Lindahl et al. 2005, 2006). A topographic map of the Linnajavri area in 1:5,000 scale, based on aerial photographs, has been constructed, and a geological map in ca. 1:50,000 scale is presented in Figure 2 (modified after the 1:15,000-scale map by Lindahl and Nilsson 2006b). Chain saw for sampling of the soapstone has been used extensively. The present paper is meant to give a brief overview of the soapstone deposits, their geology and mineralogy, and a contribution to the geological history of the Linnajavri area.

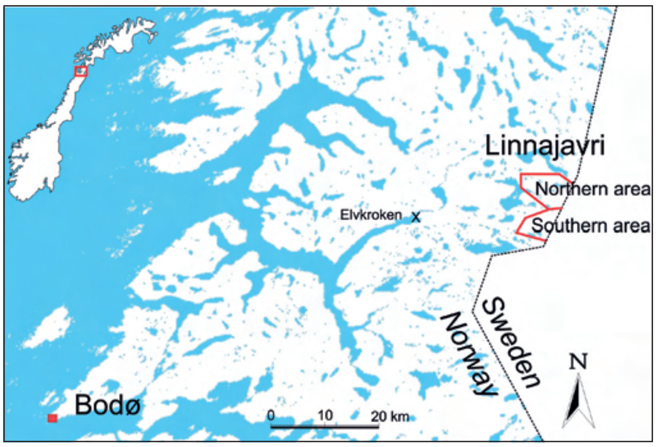


*Figure 1. Location map of the Linnajavri area.*

## Previous work

On the Norwegian side of the border, only granite was recorded in the Linnajavri area on the maps up to 1916. Gunnar Holmsen visited the area in 1916 and was the first Norwegian geologist who registered Caledonian rocks in the area (Holmsen 1917). He also registered the ultramafic rocks at Kvitfjell and Gaskavárri in the Linnajavri northern area. However, no observations of soapstone were recorded.

NGU geologist Steinar Foslie mapped the Linnajavri area during the summer of 1929 in 1:100,000 scale (Foslie 1929, 1936, 1942). Foslie's mapping gave a relatively correct picture of the geology (lithology) of the area. He recognised the major ultramafic bodies and even described serpentinite and briefly mentioned soapstone alteration at various ultramafic bodies. Foslie did not regard the soapstone as a potential economic resource, neither for talc, nor as dimension stone. Therefore, very little information about soapstone is found in his map-sheet description. He concluded that *"No ore and mineral deposits of any importance are known within the map area"* (Foslie 1942, p. 119). However, Foslie's field diary has additional, scattered information of significant value for our investigations.

[1] Our spelling of *Linnajavri* does not follow the spelling on the latest edition of the topographic map from the Norwegian Mapping Authority (Statens Kartverk), in scale 1:50,000, where the name is spelled *Linájávri*. The spelling *Linnajavri* is, however, already introduced in NGU databases, web presentations and NGU reports. For consistency, we have, therefore, kept this spelling. All other geographical names are spelled according to the recommendations from the Norwegian Mapping Authority.

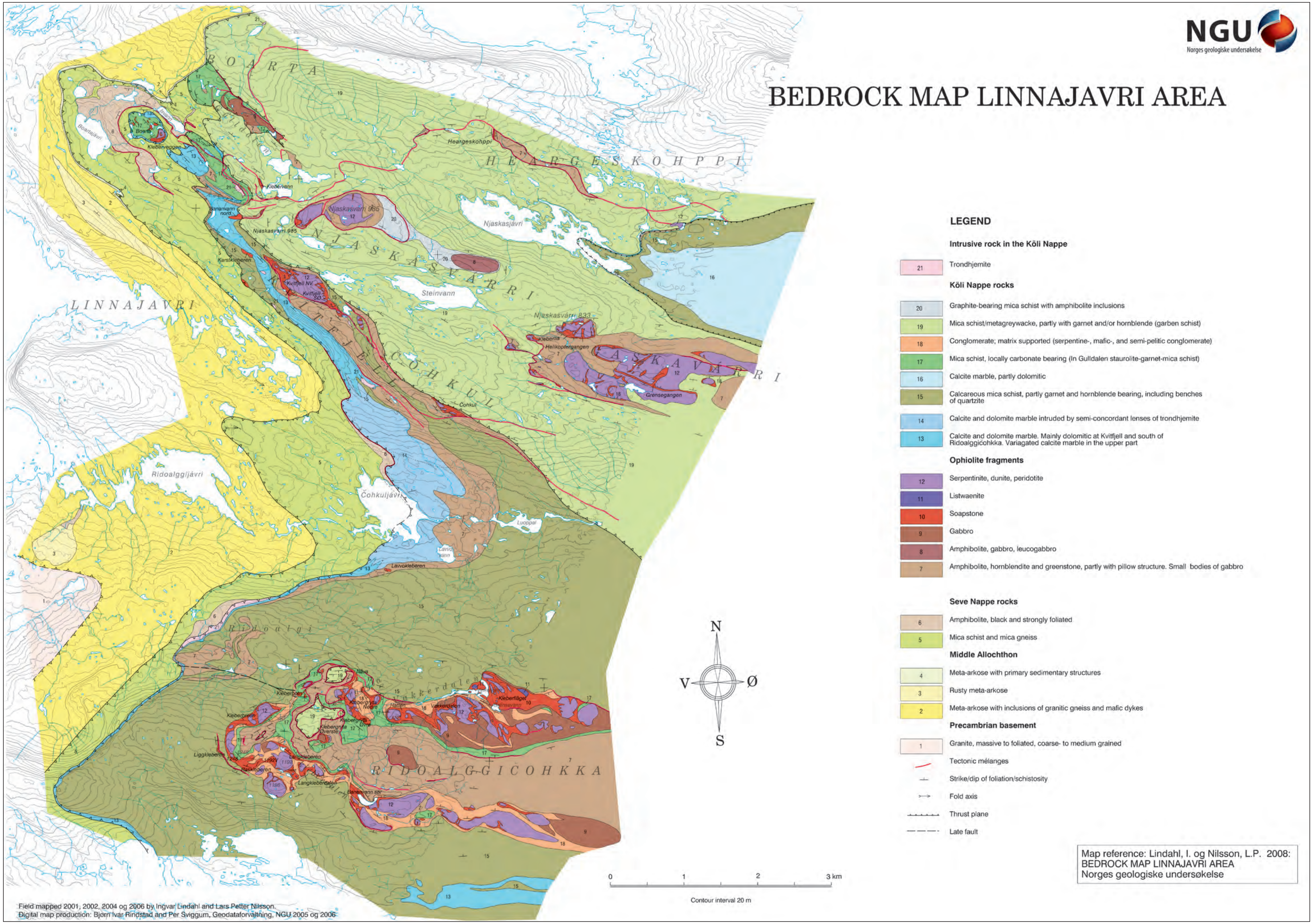


*Figure 2. Geological map of the Linnajavri area.*

Modern mapping in the area with a heavy focus on tectonics and tectonostratigraphic correlation (Foslie's weakest points) was conducted by Bjørge Brattli and Tore Prestvik in the mid 1980s as part of the general upgrading before the compilation of bedrock map-sheet Sulitjelma in 1:250,000 scale (Gustavson 1996) as well as the Nordkalott-project maps (Silvennoinen et al. 1987, Krill et al. 1987). In their publication and preliminary map, Brattli and Prestvik (1987a, b) very briefly mention talc in association with the ultramafic rocks, but without considering it a possible economic resource.

On the Swedish side of the border, Fredrik Svenonius mapped the area between 1880 and 1900 on a large scale (Svenonius 1900). Already at that time, Svenonius recognised bands of ultramafic rocks, which are marked on his maps. In a mineral resource report (Svenonius 1895) he states (p. 15) that the soapstone deposits that he had just discovered on the southern side of lake Virihaure, to the south of the Linnajavri area, were associated with ultramafic rocks, had a very good quality and were plentiful at the place. The serpentinite and peridotite lenses were more densely intersected by soapstone dykes here than at any other of the numerous places where he had previously observed ultramafic rocks in Sweden.

Regional mapping on the Swedish side of the border was later undertaken by Gunnar Kautsky (1953) and Oscar Kulling (1964, 1982). Kautsky (1953) made many detailed descriptions of the rocks and was the first to describe serpentinite conglomerates in connection with the ultramafic rocks. Similar conglomerates were not described from the Norwegian side of the border until after 2000, in reports by the authors. Compilation of the geology of northern Fennoscandia was done in the Nordkalott project (Silvennoinen et al. 1987). Detailed mapping of the Vietjervaratj ultramafic body and its soapstone alteration was done by Jimmy Stigh in 1978 and 1980 (Zachrisson and Stigh 1981, Stigh 1982). The soapstone deposits at Vietjervaratj were regarded to be among the largest soapstone deposits in Sweden, and one out of only two plotted on the industrial mineral map from the Nordkalott project (Shaikh et al. 1987).

The area between Linnajavri and the Swedish border was, therefore, in geological respect not a virgin area when we started our work in 2001, but no one had paid attention to the previous work in the area concerning economic geology.

Based on the descriptions of Foslie (1942), state geologist A. O. Poulsen in his compilation of the first detailed map of industrial mineral deposits of Norway (Poulsen 1958, 1959) included two deposits of serpentinite in the Linnajavri area (Gaskavarre and Hurrejiekna (note old spelling)), but none of the soapstone deposits were registered.

## Geology

The rocks of the Linnajavri area are built up of Caledonian nappes thrust onto Precambrian granitic basement (Figure 2). The geology of the area is dominated by tectonic nappes and thrust sheets, separated by thrust planes of regional significance. The Tysfjord culmination comprises Proterozoic granitic gneisses dated at 1742 ± 46 Ma (Andresen and Tull 1986, Gustavson 1996). Recent dating by Rehnström and Corfu (2004) of granite in a window in the Akkajaure Complex gives an age of 1871 ± 11 Ma. The basement also contains remnants of older, supracrustal sedimentary and volcanic rocks. The granitic basement consists of various types of granitic rock, and the Tysfjord Granite Complex is clearly indicative of multiple intrusive events (Mogaard 1992). The granites were later intruded by mafic dykes of varying density, locally associated with formation of aplitic granite. Most dykes tend to follow an approximate N–S trend with a moderate easterly dip, at least in the mountains around the upper part of Gjerdalen valley.

The basement granite due west of the Linnajavri area is massive to foliated and coarse- to medium-grained. The benching of the granite dips towards the east, parallel to the foliation of the overlying Caledonian nappes close to the contact and steeper farther (10 km) west. On the geological map (Figure 2) these rocks are shown as unit no. 1.

The lowermost Caledonian nappes in the Linnajavri area cut down into the granitic basement, with thin nappe sheets involving both basement rocks and younger sedimentary rocks. It is typically difficult to recognise the true nature and origin of these strongly sheared rocks in the field.

The major part of the nappes in the Linnajavri area are Köli rocks, with the Seve rocks wedging out towards the north in the Linnajavri northern area. The metasedimentary and metavolcanic rocks are relatively flat lying and gently folded in two open synforms with weakly dipping fold axes towards the ESE. Further, the Linnajavri area is characterised by an uncommonly dense set of tectonic mélange zones that are strongly altered with abundant large blocks of exotic rocks. These zones are found nearly exclusively in the Köli rocks, they are only sporadically observed in the Seve unit. In certain sub-areas, the mélange zones occur rather densely spaced and make up a net of zones, e.g., in the Boarta area. The tectonic mélanges consist of long, narrow zones of crushed and metasomatically altered rocks, and are preferably developed where bodies of serpentinite and soapstone are involved, e.g., in connection with ophiolite fragments. However, the tectonic mélanges also occur in the sedimentary rocks, or at the contact between sedimentary rocks (mica schist) and marble units or amphibolite units.

Ultramafic lenses constitute important parts of the rock sequences in the Caledonian mountain belt in Scandinavia, so also in the Linnajavri area. Several of these bodies, together with their associated rock suite of gabbro and greenstone, have been recognised as ophiolite complexes or more strongly dismembered and commonly spatially isolated fragments of ophiolites. In the Linnajavri area, the assembly of mafic and ultramafic bodies most probably represent dismembered ophiolite fragments, some of which are very illustrative and diagnostic for specific levels of an ophiolite pseudostratigraphy. Reviews on Caledonian ophiolites in Norway are given by Sturt et al. (1984), Sturt and Roberts (1991) and Pedersen and Furnes (1991).

## The lowermost nappes — Middle Allochthon

The lowermost thrust and sheared rocks of the Caledonian nappes are in general a thicker zone than described by Foslie (1936, 1942). Most likely, this rock unit represents the Middle Allochthon of Caledonian tectonostratigraphy, as first suggested by Gee et al. (1985) and more recently by Solli and Nordgulen (2006). In the lowest part of this zone, a strongly foliated granitic gneiss dominates (i.e., strongly deformed and recrystallised Tysfjord granite) and in the upper part quartzite and meta-arkose. Some of these metasedimentary rocks are fine-grained and rusty due to thin layers of weathered biotite acting as cleavage planes. A thin layer of arkosic sedimentary rocks with preserved soft sedimentary structures is found in one of the uppermost thrust sheets towards the base of the overlying Seve Nappe. On the geological map (Figure 2), the rocks belonging to the Middle Allochthon are shown as units no. 2, 3 and 4.

## Seve Nappe

The Seve Nappe in the Linnajavri area forms the lowermost part of the Upper Allochthon. On the geological map (Figure 2), two rock units are distinguished, mica gneiss/schist (no. 5) and amphibolite (no. 6).

The mica schist to mica gneiss is a monotonous greyish rock, typically with a pronounced crenulation folding and a poorly developed schistosity, locally strongly folded (Figure 3). This is in contrast to the mica schists in the Köli Nappe where the schistosity usually is well developed. In the field, the rock has a massive appearance, often forming ridges, hills and locally also steep slopes. The relief is at its most spectacular just east of lake Boartajávri where the terrain locally is very rough. The rock is coarse- to medium-grained and contains garnet (2–5 mm), on average larger than in the overlying Köli rocks, and abundant


*Figure 3. Locally strongly folded mica schist to mica gneiss of the Seve Nappe. The Seve mica schist typically shows crenulation cleavage. Location: ca. 300 m north-northwest of Boartajávri.*

*Figure 4. Randomly oriented kyanite crystals grown upon primary layering of Seve rocks. Location: between Boartajávri and Bananvann N.*

kyanite, locally up to 3 cm. Garnet and kyanite enrichments are found along the primary layering of the schist. The porphyroblasts of kyanite are randomly oriented (Figure 4). The mica schist to mica gneiss has small irregular lenses and veins of quartz. Based on the mineralogy, the metamorphism is medium grade, cf., Brattli and Prestvik (1987b, p. 68).

Three bodies of amphibolite have been mapped in the Seve Nappe, all of them in the upper part of the unit, e.g., south of Ridoalggijávri (Figure 2). The amphibolite in the Seve Nappe is dark grey to black and relatively coarse-grained. The amphibolite is strongly sheared and may represent volcanic rocks, dykes or intrusive rocks. Amphibolite interfingered in mica schist just north-northwest of lake Boartajávri may represent dykes, probably feeders to the largest body of amphibolite in the Seve unit in the Linnajavri area.

## Köli Nappes

The Köli Nappes are often subdivided in a lower, middle and upper part, each with characteristic rock units. According to Brattli and Prestvik (1987b), the rocks above the garnet-mica schists (i.e., the Seve rocks) in the Linnajavri area are all metamorphosed under low-grade conditions and typical for Lower and Middle Köli lithologies. In their Table 1, Brattli and Prestvik (1987b) assign the majority of the Köli rocks in the Linnajavri area to the Middle Köli Nappes. We support their main conclusions, but we have a somewhat different division of the local nappes and their extent compared to that shown in their Figure 3 and on their preliminary 1:50,000-scale bedrock map (Brattli and Prestvik 1987a).

Our map (Figure 2) is subdivided in three local nappes. A lower nappe, here named *Ridoalggičohkka nappe*, occurring in the Linnajavri southern area and in the western part of the northern area. Above that is a middle nappe, named *Čohkul nappe,* that makes up most of the Linnajavri northern area.

The uppermost nappe, named *Stipok nappe*, occupies a minor area in the northeast, but continues and widens significantly towards the Stipok mountain in the northeast on the Swedish side of the border.

Our local subdivision of the Köli Nappes resembles that of (Sundblad 1986, his Figure 1). All our local nappes constitute parts of Sundblad's Stipok terrane. The ophiolite fragments are nearly exclusively found in the Köli Nappes.

## Ridoalggičohkka nappe

The base of this nappe is a unit with alternating calcite and dolomite marble (no. 13). Variegated (red and white) calcite marble is found along strike in the uppermost part of the unit. The thickness varies along strike from south of Ridoalggičohkka to Boarta, with largest thickness between Čohkuljávri and Kvitfjell, where it is mostly dolomitic (Figure 5). South of Ridoalggičohkka, the same marble unit, here developed completely as a homogenous greyish white dolomite marble, is outcropping on the Swedish side close to the national border. This carbonate comes through the carbonate mica schist in an antiform as a result of nearly horizontal and undulating fold axes in this area (Figure 2).

*Figure 5. Outcropping of the thickest part of the marble unit (ca. 100 m) in the southwest slope of Kvitfjell. View towards northwest.*

Trondhjemitic intrusions (unit no. 21) and small pegmatites are commonly found in connection with the marble unit. The three largest bodies occur on the northwestern part of Ridoalggičohkka, east of Kvitfjell and west of Klebervann. Around Čohkuljávri, a swarm of semi-concordant layers of trondhjemite is found within the calcite and dolomite marble unit in the open antiform that separates the Linnajavri northern and southern area (unit no. 14). The weakly dipping rocks and fold axes cause a mixed unit of semi-concordant trondhjemite sills and lenses in marble outcropping over a large area (unit no. 14 in Figure 2).

Calcareous mica schist (unit no. 15) underlies the Ridoalggičohkka ophiolite fragments, has a thickness of more than 1 km at the greatest and wedges out towards Boarta in the northwest. In the Kvitfjell area it interfingers with the ophiolite fragments. The nappe is dominated by calcareous mica schist, but also includes thin layers of quartzite, garnet-bearing, carbonate-free mica schist and smaller (a few cm to dm) and larger

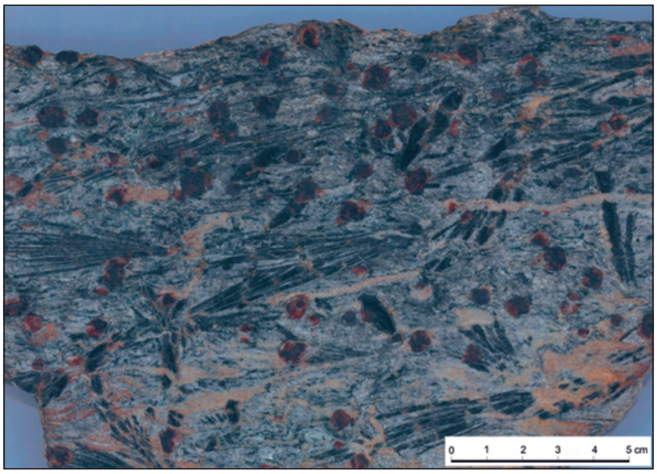


*Figure 6. Polished slab of garnet-amphibole schist (garben schist) from Hurre, south of Ridoalggičohkka.*

(up to 5 x 50 m) lenses of hydrothermal quartz. Strongly foliated lenses of amphibolite are found and locally thin (1 m) layers of marble occur. The metamorphic grade increases gradually southwards to garben schist south of Ridoalggičohkka, with very coarse-grained, dark green to black hornblende and reddish garnet. This rock was observed and described already by Svenonius (1896) and Foslie (1936, 1942), who both emphasised its spectacular textures and recognised it as a decorative rock. The rock has been sampled and test polished during the present work in the area (Nilsson and Lindahl 2003a) (Figure 6).

The rocks of the ophiolite fragments in the Ridoalggičohkka nappe are described below.

## Čohkul nappe

The main rock type in the Čohkul nappe (unit no. 19) is garnet-mica schist to meta-psammite, representing greywacke sediments with transitions from greywacke to meta-arkose. This rock is monotonously developed over large areas. The nappe is located in the Linnajavri northern area, but with three additional small flakes, representing erosional remnants, of the nappe occurring in the western part of Ridoalggičohkka between the Klebergryta and Kleberbotn deposits (Figure 2). The rock unit lies as an open synform with the Gaskavárri ridge at the Swedish border in the central part.

The garnet in the garnet-mica schist is bright red. In a few localities, small amounts of blue kyanite has been seen. Thick (1–10 m) arkosic benches are typical for the garnet-mica schist. Typical for the unit is semi-concordant quartz lenses and near vertical N–S-trending quartz veins. Exposure of this rock unit is close to 100%. The garnet-mica schist locally contains thin, rusty layers, most likely a result of small amounts of iron sulfides. Thin layers of amphibolite occur locally within the unit.

The Čohkul nappe discordantly overlies the Ridoalggičohkka nappe and hosts the ophiolite fragments of the Klebervann–Gulldalen field, and is overlain by the Gaskavárri, Njaskasvárri 985 and 833 ophiolite fragments in the core of the northern syncline (Figure 2). An extensive tectonic mélange zone through

Heargeskohppi, hosting several small ultramafic and one large amphibolitic ophiolite fragment, has been mapped.

At all the above-mentioned locations, we find possibly inverted ophiolite sections where amphibolites are overlain by ultramafic rocks or gabbro. The observed sequence could, however, also likely be the result of stacking of individual dismembered pieces of the ophiolite during thrusting. This would not require folding with inversion involved in the process.

Underneath the ophiolite fragments, tectonic mélanges/ local thrust zones occur. East of the Njaskasvárri 985 ultramafic body, a graphite-bearing mica schist is found. The schist is intruded by a swarm of mafic rocks, hornblendite, amphibolite and gabbroic rocks. The rock unit is strongly brecciated and represents a tectonic mélange beneath the ultramafite lens. The tectonics of the Gulldalen field is very complex, with blocks of rock separated by tectonic mélanges.

### Stipok nappe

Sundblad (1986) introduced the Stipok allochthon or Stipok terrane as an exotic terrane including large areas on both sides of the national border. He included all the Köli rocks in the Linnajavri area, as well as a very large part of adjoining Swedish areas extending to the south of lake Virihaure, in this terrane. In the present account, we restrict the term Stipok nappe to the tectonostratigraphically uppermost part of Sundblad's Stipok terrane, starting with his marble unit no. 3 which crops out on the Norwegian side of the border east of lake Njaskasjávri with a well-defined underlying thrust-plane. The rocks in the nappe are mostly flat lying, medium- to coarse-grained, off-white to more greyish marble. The marble is dominantly calcitic, but also with dolomitic layers (unit no. 16). The dolomite marble is mostly finer grained and white.

Underneath the marble lies a thin layer of calcareous mica schist, similar to that of the Ridoalggičohkka nappe. Based on the interpretation of Sundblad (1986), this marble and its thin, underlying, calcareous mica schist represent a repetition of the lowermost parts of the Ridoalggičohkka nappe (Sundblad's Arajaure complex).

## Tectonics

Our work has not focused on the tectonics or tectonostratigraphy of the Linnajavri area. However, the main features of thrusting, folding and faulting can relatively clearly be studied in such a well-exposed area. Structurally dominating the area are two open synclines with shallowly dipping, ESE fold axes. South of Ridoalggičohkka, the fold axes are nearly flat lying and undulating with the marble unit exposed at the surface in a valley floor (see Figure 2). The strike and dip of the sedimentary and volcanic rocks are in general less than 30° dipping easterly. Commonly, the lineation in the different rock units is better developed than the foliation. One E–W-trending fault with a few metres displacement, post-dating the tectonic mélanges, is mapped on the western slope of Ridoalggičohkka (Figure 2).

### Thrusts

In the Linnajavri area, the Seve Nappe totally wedges out towards the northwest at Boarta in the Linnajavri northern area. In the overlying Köli Nappes, the stratigraphy of the lowermost part is repeated in the uppermost thrust sheet of the Köli Nappe succession.

The thrust planes are very commonly located in depressions in the terrain and covered by till. Discordances may be seen at several localities, but typically both lineation and foliation have the same orientation both below and above thrust planes. Outcrops of both the base and the top of the Seve Nappe can be seen. The thrust plane at the base of the Seve Nappe crops out south of Ridoalggijávri as a mylonitic zone. Here, the foliation in the Seve Nappe is clearly discordant to the underlying meta-arkoses of the Middle Allochthon. The lithologies in the lower nappe are cut by the overlying Seve Nappe (Brattli and Prestvik

*Figure 7. Mylonite at the base of the Seve Nappe. Folded foliation in tectonic fragments shown in the enlarged part of the picture. Location: southwest of Čohkuljárvi.*

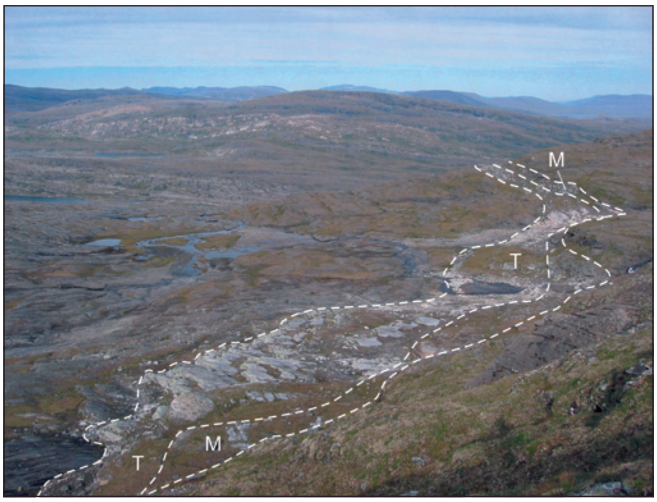


*Figure 8. Elongated body of white, sheared trondhjemite (T) overlain by marble (M) at Ridoalgi, constituting the lowest unit of the Ridoalggičohkka nappe. In the background, Čohkul and Kvitfjell with the same white marble horizon. View towards north.*

*Figure 9. Example of ptygmatic folding of mylonitic trondhjemite at the base of the Ridoalggičohkka nappe.*

1987b). The border between the two nappes therefore represents a major unconformity (Figure 7). The thrust on top of the Seve rocks can be seen north of Ridoalgi on the northwestern slope of Ridoalggičohkka. The thrust plane is located along the base of a Köli marble unit that is hosting or bordering elongated, concordant trondhjemite intrusions (Figure 8). Along the thrust, the coarse-grained trondhjemite has developed a mylonitic texture. The trondhjemite is completely ground and recrystallised and looks like an arkose, and the other rocks are mixed and phylonitic (Figure 9).

Along the thrust plane at the base of the Čohkul nappe, both discordances and rock units are being cut off. Typically, the thrust plane is covered by till or scree, but crushed and ground rocks can be seen in the southern slope of Čohkul and at Kvitfjell. The thrusting at the base of the Stipok nappe may best be seen south of the wedge east of Njaskasjávri where the foliation in the Stipok nappe is clearly discordant to that in the underlying Čohkul nappe. Further, the thrust plane of the Stipok nappe is developed as a mylonite zone where up to 3 cm, partly rotated garnet may be seen.

## Tectonic mélanges

Mixed rocks of various origin has been described in a wide spectre in geology as *mélanges* (Raymond 1984a). The genesis of the rock named mélange is different, but mostly of tectonic origin. Raymond (1984b) has made a classification of mélanges. A number of tectonic mélanges have been described from the Appalachians as well as from the Scandinavian Caledonides.

In the well-exposed Linnajavri area, a large number of tectonic mélange zones can be observed. A number of these have been mapped out in different types of Köli rocks, however, preferably connected to the ophiolite fragments. The mélange zones have concentrated strain and thereby contributed to conserve primary structures in blocks of rock between the zones. The mélange zones may be characterised as both crushing zones, alteration zones and zones accommodating a large number of blocks or fragments of rocks commonly exotic to them. We have chosen to call these zones 'mélange zones' as this term denotes one of their most important, and perhaps in a more general sense, most rarely observed characteristics, namely the abundance of exotic fragments. In fact, we are not aware of similar zones reported from other parts of the Scandinavian Caledonides.

In the mélange zones, some rock fragments can clearly be recognised as similar to that of their immediate neighbouring rocks, e.g., the zones are crushing zones. In addition, the mélange zones are characterised by extensive alteration as the zones have been more permeable to volatiles than the rocks immediately surrounding them and thereby triggering mineral reactions. Especially reactions between carbonates and amphibolites have formed spectacular, coarse-grained and colourful mineral associations.

In addition to the above characteristics, the mélange zones host a large number of rock fragments exotic to them, foremost a large number of serpentinised rocks, or more abundantly, totally soapstone-altered ultramafic rocks. Trondhjemite bodies are also located within the zones. Most fragments or blocks of ultramafic rock are small or very small, but occasionally they may be large. The 40 x 200 m Klebervann soapstone lens is the largest individual ultramafic body associated with a mélange zone, and the neighbouring and equally large trondhjemite body, located just northeast of Karstdalen in the Linnajavri northern area, is the largest trondhjemite body (cf., Figure 2 and Lindahl and Nilsson 2002).

The density of the zones varies. It is at its highest in the Boarta area where they nearly make up a network. The thickness of the zones also varies a lot, from a few metres to tens of metres (Figure 10). The orientation and extent of the zones also vary a lot. They may follow the contact between different rocks or in part follow thrusts. They may also intersect rock units and thrusts. The most extensive individual mélange zone mapped by us has its western extremity in the Klebervann area and extends some 8–9 km to the east through Heargeskohppi and then into Sweden (see Figure 2).

*Figure 10. Tectonic mélange zone outcropping in Klebergryta Øvre, Ridoalggičohkka area. View across the ca. 8 m-thick zone.*

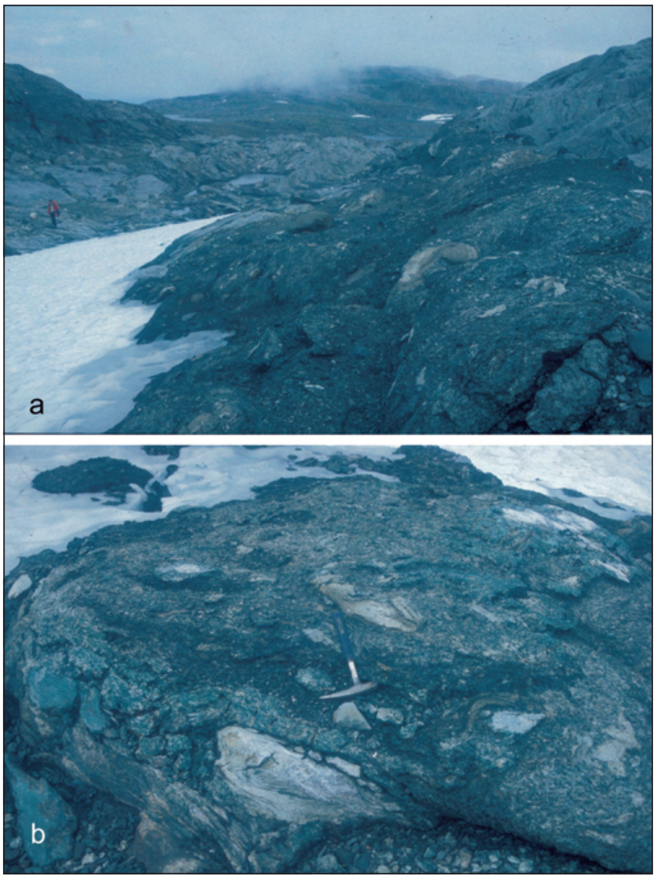


*Figure 11. The mélange zone northwest of the Klebervann deposit. (a) The ca. 15 m-thick tectonic mélange at the base of the Klebervann deposit. View towards southeast along the zone from a location ca. 200 m northwest of the deposit. (b) Detail of the tectonic mélange showing fragments of trondhjemite, marble, soapstone, amphibolite and mica schist in a hydrothermally altered matrix of various minerals including talc.*

The deformation in the mélange zones has mostly been plastic (Lindahl and Nilsson 2002), but some localities show a brittle deformation. The different rock fragments are both foliated and folded (Figure 11). As mentioned above, reactive solutions have percolated through the zones, especially in connection with ultramafic rocks, volcanic rocks and marbles. The result of the alteration is spectacular, coarse-crystalline, black hornblendites, intensely green serpentinite and actinolite-fels and rusty brown ferro-dolomite. The solutions have also formed unusually talc-rich soapstone bodies in gabbroic rocks in Gulldalen and at Ridoalggičohkka (Klebergryta Øverste, Liggkleberen and at Grensevann). Commonly, ultramafic rocks and amphibolites are found in contact with the mélange zones, resulting in fragments of soapstone with talc and chlorite in the matrix of the mélange, a good lubrication for the development of the mélange. Within the large amphibolite body making up the central part of the Ridoalggičohkka synform, a large, concordant mélange zone is developed not far above the base of the amphibolite. Here, the mélange zone runs parallel to the contact to the amphibolite as a 10 to 15 m-wide zone of black, strongly schistose and easily weathered chlorite schist (chlorite phyllonite) with massive amphibolite at both the hanging-wall and foot-wall sides. Other minor mélange zones within this amphibolite body are characterised as talc-chlorite zones.

The development of the tectonic mélange zones seems to be more or less contemporaneous with the thrusting. The percolation of fluids, however, seems to be greater in the mélange zones than along most of the thrusts planes.

## The ophiolite fragments

### Lithologies

The ophiolite fragments occur in the Köli rocks in two different local nappes, the Ridoalggičohkka and Čohkul nappes. The most complete section is found at Ridoalggičohkka in the Linnajavri southern area and includes ultramafic rocks, pillow lava, gabbro, amphibolite and conglomeratic weathering products with well-rounded pebbles from these rocks. Well-preserved pillows are found in little deformed rock segments between mélange zones (Figure 12). Only a single mafic dyke has so far been registered intersecting pillow lava. However, no detailed investigations looking for mafic dykes of a possible sheeted-dyke complex within the mafic rocks have been undertaken. In the Linnajavri northern area, ophiolite fragments are located both in the Ridoalggičohkka nappe and the Čohkul nappe, however, in a different lithological setting than in the southern area (see Figure 2).

The major ophiolite fragments in the Čohkul nappe in the Linnajavri northern area are more tectonically disrupted than

*Figure 12. Weakly deformed basaltic pillow lava at Ridoalggičohkka.*

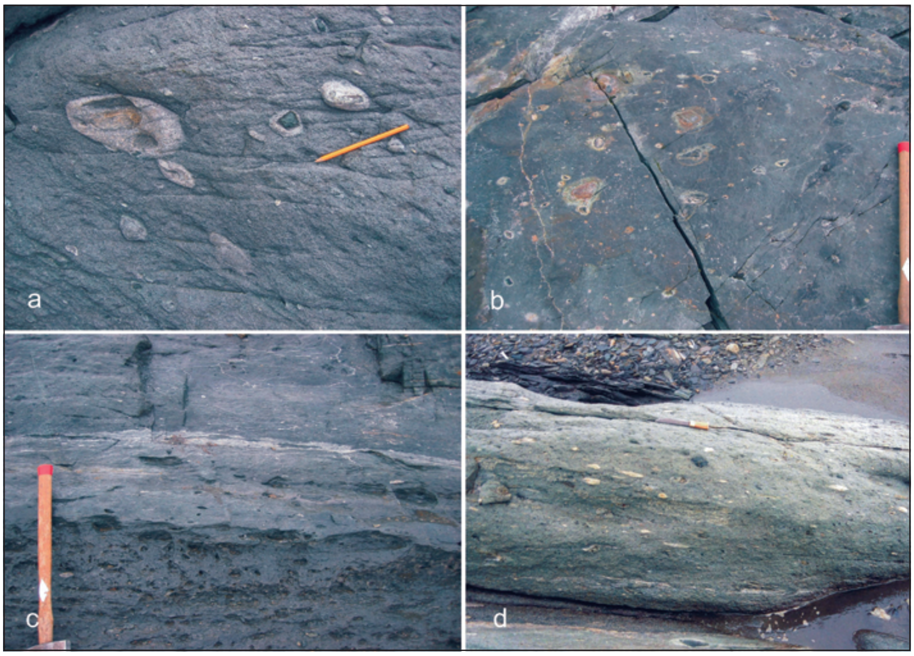


*Figure 13. Types of matrix-supported conglomerates at Ridoalggičohkka. The pebbles most commonly show onion-skin weathering texture. (a) Conglomerate with micaceous matrix. (b) Serpentinite conglomerate with clearly developed onion-skin texture. (c) Micaceous conglomerate beds of varying facies development. (d) Conglomerate with mafic matrix and mafic and siliceous clasts.*

those at Ridoalggičohkka (see Figure 2). The rock suite includes ultramafic rocks and dark, medium-grained amphibolites, the latter probably mainly with a gabbroic precursor. A body of amphibolite, gabbro and leucogabbro is located at the central portion of the Njaskasvárri ridge. Ultramafic scree material and immature ultramafic breccia-conglomerate are also found as minor occurrences along the southern side of the Gaskavárri ridge. These include weakly rounded pebbles of soapstone among non-talcified boulders and gravel, one of several important key locations constraining talc formation to a pre-obduction, or at least pre-conglomerate formation stage. These tiny occurrences of ultramafic conglomerate seem to have been fixed to the ultramafic body, making this assemblage a single tectonic entity during thrusting onto its amphibolitic substrate. There is no evidence of deposition of ultramafic breccia-conglomerate onto the mafic (amphibolitic) substrate. On the contrary, the foliation in the amphibolite bends neatly around the conglomerate pockets. We do not know if and/or to what extent, these tiny conglomerate occurrences represent relics of a larger lithological unit that was excised during thrusting of the nappe pile. It should, however, be noted here that identical tiny occurrences of serpentine breccia-conglomerate are found at the same tectonostratigraphic position all the way along the southern border of the ca. 5 km-long Vietjervaratj ultramafic body, just to the east of Gaskavárri (Kautsky 1953, p. 92 and map, Kulling 1972, 1982, Stigh 1982). These occurrences are 'glued' to their ultramafic substrate in a way that makes it difficult to see where the breccia-conglomerate started to develop from its pseudo-conglomerate-like base. It is definitely a matter of a transition zone.

The rocks constituting the ultramafic bodies in the Linnajavri northern and southern areas are petrographically similar, comprising dunite and peridotite, both probably basically of mantle origin, extensively serpentinised and to a large degree also talcified. Only in one ultramafic body, the Njaskasvárri 985 body, a section of a well-preserved ultramafic cumulate sequence representing the lower oceanic crust in an ophiolite stratigraphy is found. This section was discovered and described for the first time by Brattli and Prestvik (1987b). The cumulate rocks of the Njaskasvárri 985 body are generally less serpentinised than the rest of the ultramafic rocks in the Linnajavri area. The dunitic bodies are normally the most fine-grained and the peridotite coarser grained. The ultramafic rocks locally contain small pods of chromite, which have survived morphologically during the alteration of their host rocks to serpentinite and further to soapstone. Mineralogically, however, the chromite has changed almost completely to magnetite and the pods are, therefore, now of limited or no value as depth indicators in a general ophiolite pseudostratigraphy. The gabbro bodies normally consist of medium-grained, massive metagabbro. No layered gabbros were recorded, but an example of a fresh-looking varitextured gabbro is located in the Ridoalggičohkka area, 1 km east of the national border.

The suite of rocks of the ophiolite fragments have been exposed to weathering and then become the source rock for conglomerates and grit deposits. The conglomeratic rocks (Figure 13) vary a lot in composition. At the southern side of Gaskavárri, the above-mentioned conglomeratic breccia consists of fragments and pebbles of peridotite and serpentinite with barely rounded soapstone. The conglomerates at Ridoalggičohkka, on the other hand, have well-rounded pebbles, in most cases with onion-skin structure (Figures 13a, b). They vary from serpentinite conglomerate, green conglomerate with large amounts of mafic material and epidote, to grey conglomerates with a micaceous matrix. The type of conglomerate varies from monomict (serpentinite conglomerate) to polymict. Mostly, the conglomerates are strongly matrix supported with transitions to grit and coarse-grained sediment. The conglomerate beds vary in composition and thickness, down to half a metre (Figure 14), in an

*Figure 14. Thin bed of a mafic conglomerate between two micaceous-rich beds. Location: Ridoalggičohkka area between the 1192 and the 1248 peaks.*

*Figure 15. Veinlets with tourmaline, chlorite, albite and quartz with bleaching of adjacent host mica schist. Location: Klebergryta Nedre area.*

alternating sequence.

Alteration of the rocks in the ophiolite fragments is extensive. In the pillow lava at Ridoalggičohkka, sulphur- and magnesium-bearing solutions have flowed through tiny vents ('hot spots') and fissures. These solutions have caused sulphide impregnation, and in the aureole (1 m thick) around the vent, growth of flaky talc with random orientation has occurred. The sulphides are strongly weathered at the surface, and today do not make up much more than a rusty crust, where elevated values of Cu and Zn have been recorded. Along shear zones in the amphibolites within the Ridoalggičohkka synform, magnesium has been introduced and talc growth can be seen as half centimetre unoriented flaky crystals within the more fine-grained amphibolite. Late hydrothermal activity, both in the ophiolitic rocks and the various mica schists, has bleached the rocks around veins, wherein quartz, carbonates, chlorite and tourmaline are deposited (Figure 15). Silicification along mm-thin veinlets in the conglomeratic rocks is also common, possibly a later phase than the quartz-carbonate-chlorite-tourmaline veins. This locally extensive hydrothermal activity is otherwise common in the greater region, and Kautsky (1953, p. 129 and 192) reported similar development of veins from the Virihaure area and from the area east of border post 242.

## Formation of soapstone

The soapstone formation in the ultramafic rocks in the Linnajavri area varies from nearly zero to extensive. The soapstones in the Linnajavri area formed where hot solutions, enriched in dissolved $CO_2$, penetrated the host serpentinised ultramafic rocks. Some of the ultramafic bodies are only moderately altered to soapstone whereas others are totally (e.g., Klebervann lens) or almost totally (e.g., Kleberflåget body) altered. Alteration has taken place out from cracks, joints and breccia zones in the ultramafic rocks, typically leaving a very irregular front where the pervasive alteration has ended (Figure 16). It is the reaction between serpentinite and $CO_2$ in hot solutions that has instantly triggered formation of talc and magnesite from the serpentinite. At the reigning high temperatures, the talc-magnesite formation seems to have happened instantaneously (at or just behind the reaction front) and been total inside the volume of serpentinite affected by the $CO_2$-enriched solutions. We never find soapstone with relics of serpentine (ca. 300 specimens investigated), nor

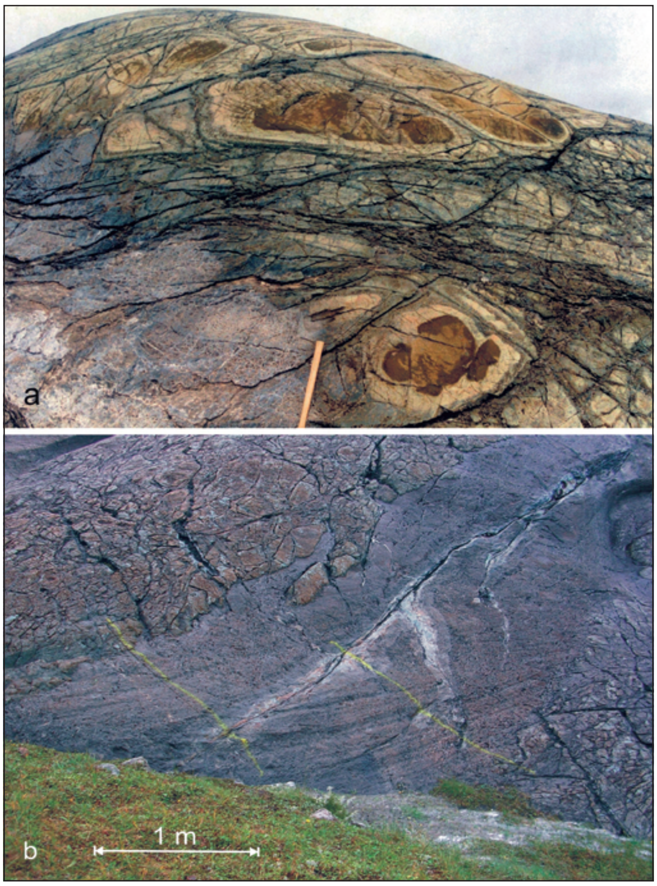


*Figure 16. Soapstone alteration. (a) Alteration of dunite (dark brown weathering crust) to serpentinite (yellow to green) with a soapstone front 'moving' up from the lower left corner of the figure. Location: Klebergryta Øvre. (b) Soapstone alteration starting from a crack in serpentinite. Yellow marking prepared for slice sampling. Location: Kvitfjell NV deposit.*

do we observe serpentinites with incipient talc-magnesite formation in the field. Serpentinites showing a gradual alteration to soapstone are otherwise rather abundant in many ultramafic rocks from other places within the Scandinavian Caledonides. However, we occasionally find smaller and larger xenoliths of non-talcified serpentinite within the soapstone and always with sharp borders between the two rock types.

In several places, primary magmatic textures are inherited from the dunite or peridotite. This is for example the case at the western end of the Njaskasvárri 985 body where the layered structure is visible, though faintly, in the ultramafic rocks after its alteration to soapstone. At one locality (the Kleberflåget deposit, by far the largest individual deposit in the Linnajavri area), there has been a quite massive alteration of serpentinite to soapstone. This very voluminous alteration of what was probably once part of the mantle below oceanic crust in the Iapetus Ocean, has no direct counterparts in the rest of the Scandinavian Caledonides as far as we know (see Figure 2 for dimensions of the Kleberflåget deposit). This voluminous alteration was not accompanied by visible deformation of the ultramafic body. All the structures, such as joints and fissures as well as minor textural details in the precursor serpentinite, are perfectly well preserved in the soapstone. The $CO_2$-enriched fluids have virtually 'flushed' through a large volume of serpentinite, probably at an early, oceanic stage, and totally changed its mineralogy. At the same time, however, the transformation process has left all the rock structures completely untouched. Elsewhere in the Scandinavian Caledonides the soapstones are typically strongly sheared.

The Kleberflåget deposit is not only by far the largest individual soapstone deposit in the Linnajavri area. At Kleberflåget, the alteration process has also taken a step further than soapstone formation. Due to excess $CO_2$ and falling temperature (excess in the sense that there is no more serpentinite available for soapstone formation from the local and persistently active $CO_2$ source), the soapstone has just started to break down to listwaenite (Figure 17 and Figure 2), a rock consisting of magnesite/(dolomite) and quartz. Two small areas of listwaenite have been found and mapped (Figure 2), one on each side of the Kleberflåget deposit. The formation of listwaenite is among our strongest indications/proofs that the soapstone did not form from $CO_2$ derived from a sedimentary source (e.g., calcite or dolomite marble, black shale) at a late, compressional stage during the Caledonian Orogeny, i.e., after such rocks had been juxtaposed or come close to the ultramafic rocks. In contrast, we believe that the $CO_2$ was derived from a strong and lasting mantle source at an early, probably oceanic, stage; a $CO_2$ source that was active even down to very low temperatures (ca. 200–300°C). This is below or near the lower stability temperature of talc in ultramafic rocks, hence the start of decomposition of talc to quartz and additional magnesite in the soapstone. The amount of listwaenite cropping out is very small compared to the volume of soapstone at Kleberflåget, i.e., we have probably just reached the critical temperature where talc started to decompose when the $CO_2$ source was turned off and the process was frozen yielding the proportions of variably altered rocks we se today. In other, more mature systems where a $CO_2$ source has been available at even lower temperatures, as in the Raudfjellet ophiolite fragment in Nord-Trøndelag county, central Norway (Nilsson et al. 2005), about three quarters of a 4.5 km long and up to ca. 50 m thick, sheet-formed soapstone deposit was transformed to listwaenite before the system came to rest.

*Figure 17. Border between listwaenite and soapstone (lower part of picture). The listwaenite contains ribs of quartz in a magnesite/dolomite matrix. Location: Kleberflåget deposit.*

The mode of formation of the Kleberflåget deposit also applies to the majority of the other soapstone deposits in the Linnajavri area, and perhaps in the whole greater region to the Sulitjelma area to the south (i.e., Sundblad's (1986) Stipok allochthon). The exception is the minor, mélange-associated, gabbro-derived soapstone occurrences.

The major parts of the ultramafic rocks are altered. Only to a limited extent are relics of the primary magmatic mineral assemblages of the ultramafic rocks found, and then typically in the cores of bodies (the Njaskasvárri 985 body makes an exception). In the centre of the Kvitfjell body, near its 914 m summit, a metaperidotite with 3–4 cm, dark, rounded spots of metamorphic olivine (forsterite) ('leopard texture'), makes up the very erosion-resistant, steep top area. This is the only case where we have encountered metamorphic olivine in the ultramafic rocks in the Linnajavri area. Most of the ultramafic rocks are serpentinites, some of them with an unusually sharp and bright green (emerald green) colour.

Hydrothermal activity has been pervasive through the whole nappe sequence of the area. Numerous small, near vertical, quartz-rich pegmatitic veins intersect the sediments, dominantly oriented N–S or parallel to the schistosity.

## Mineralogy and chemistry

Soapstone is basically a talc-carbonate rock. The soapstone in the Linnajavri area is of the same type as known from other areas with abundant ultramafic rocks, basically of ophiolitic origin, in the Scandinavian Caledonides. Talc derived from alteration of

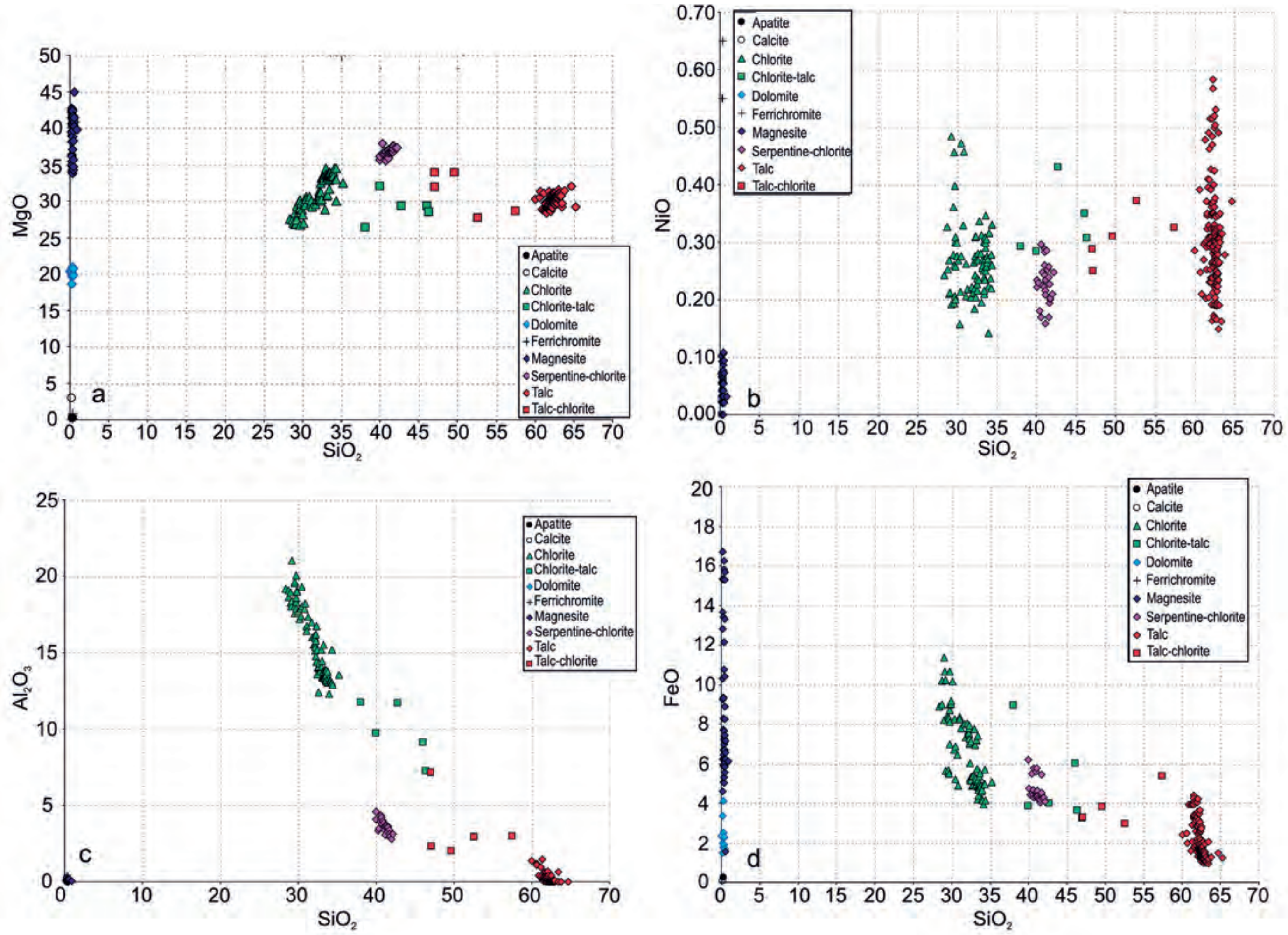


*Figure 18. Scanning electron microscope (SEM) mineral analyses in various plots (a–d). Contents in weight percent. See text for discussion of results.*

ultramafic rocks to a certain extent inherits both the major and trace element chemistry of the precursor ultramafic minerals (foremost olivine and serpentine).

The mineralogy of the Linnajavri soapstone is fairly simple. The number of mineral phases is strongly restricted and basically comprises talc, magnesite, chlorite and dolomite in decreasing order. Minor amounts of disseminated chromite and secondary magnetite further occur in the soapstone. Though the mineralogy is simple, the minerals' internal proportional distribution, textural variation, grain-size distribution, intergrowths, crystal zoning and degree of recrystallisation varies. There are, for example, significant compositional differences between the soapstones of the Linnajavri northern and southern area. Further, there are differences within individual soapstone deposits within the areas. There are also significant differences at a more local scale, even down to what may be observed in thin sections from originally adjoining parts of sample slices.

*Table 1. Average values (arithmetic mean) for NiO and $Cr_2O_3$ in talc, chlorite, magnesite and dolomite in soapstone from the Linnajavri area. Scanning electron microscope analyses with long counting time (60 s). Analytical numbers in wt.%.*

| Mineral | NiO | $Cr_2O_3$ | n |
|---|---|---|---|
| talc | 0.29 | 0.02 | 173 |
| chlorite | 0.25 | 1.27 | 88 |
| magnesite | 0.05 | 0.00 | 55 |
| dolomite | 0.00 | 0.00 | 13 |

n = number of analyses; 329 analyses in total.

The content of talc in the soapstone is about 50% on average, locally reaching as much as 70–80%. Examples of very talc-rich soapstone are found both within the ultramafic rocks and as a peculiarity where soapstone is formed directly from gabbro in association with mélange zones, see details in Nilsson et al. (2003). The talc content is on average slightly higher in the northern area compared to the southern area. The iron content in the talc varies between 1 and 4.5 wt.% and replaces magnesium in the talc lattice (cf., Figures 18a, d). The soapstone abundantly shows a bimodal grain-size distribution with coarse and well-developed magnesite crystals set in a more fine-grained matrix of platy talc with some intergrown chlorite. The coarse-grained magnesite commonly exhibits a marked zoning with a Mg-rich core becoming gradually more Fe-rich towards the rim (Figures 18a, d). The chlorite tends to cluster in two groups: one group enriched in Si and Mg relative to the other, which in turn is strongly enriched in Al relative to the former (Figures 18a, c). The chlorite content is otherwise significantly higher in the southern area compared to the northern area. Varying amounts of fine-grained, anhedral to subhedral dolomite occurs evenly disseminated between the silicates. Cl-apatite is recorded as an accessory mineral. In addition to the above minerals, relatively fine-grained chromite and fine-grained to very fine-grained magnetite is disseminated in the soapstone. Sulphides and other trace constituents such as sulpharsenides, arsenides and alloys, are extremely rare in the Linnajavri soapstone deposits.

The soapstone texture is mostly massive, but locally it may show a pronounced foliation or banding, schlieren structures and carbonate veining with colours varying from a soft grey tone to more greenish grey. In general, the foliation is most pronounced towards the rims of the ultramafic bodies, and close to zones of tectonic mélanges.

Where soapstone borders calcite and dolomite marble units, pale brown tremolite is locally developed close to the contact, e.g., in the Karstkleberen and Kleberveggen lenses. However, tremolite is only locally developed in the soapstones in the Linnajavri area, and not observed at all to the southeast and south of the Kvitfjell body.

A large number of bulk chemical analyses as well as mineral analyses of soapstones have been performed. In Figures 18a–d, 374 selected mineral analyses are plotted in scatter diagrams to illustrate variations in compositions.

The analyses of the trace elements Ni and Cr are summarised in Table 1. The data show that both talc and chlorite host Ni in roughly equal amounts (cf., also Figure 18b), whereas chlorite is the principal host for Cr. The carbonates, magnesite and dolomite to a very limited extent, or not at all, accommodate lattice-bound Ni and Cr.

## Mineral potential for the Linnajavri area

The soapstones of the Linnajavri area may be exploited either as an ore for talc flotation or as dimension stone. Other potential mineral resources (marble, schist and gold) may be evaluated when infrastructure is established. The average content of talc in the soapstones is about 50% (Figure 19). The other minerals are carbonates (magnesite and some dolomite), chlorite and oxides, mostly magnetite. The sulphide content is very low to zero in the Linnajavri soapstones, which may be an advantage for use both as dimension stone and for talc flotation.

The soapstone reserves are calculated based on geology (geological structures and the 3D-pattern of outcrops) and detailed mapping of the size of the outcrops. For the Linnajavri northern area, the distances are surveyed using GPS, compass and laser instrument, and in the southern area from the mapping on 1:5,000-scale aerial photographs. The very good and extensive outcrops of the area, including the soapstone deposits, make it possible to carry out reliable estimates of the soapstone volumes. Close to 20 individual soapstone bodies carry in excess

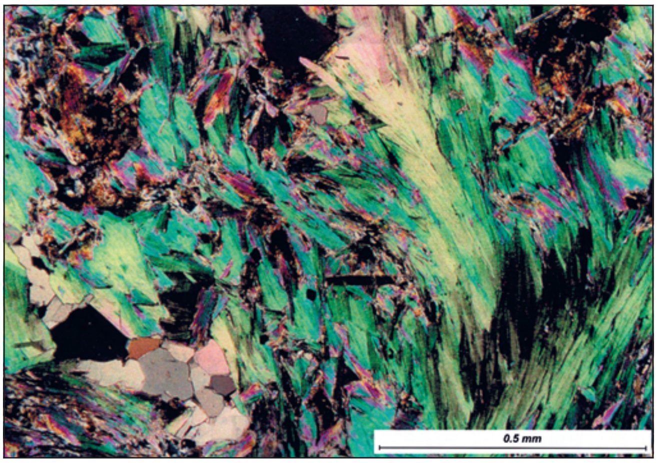


*Figure 19. Thin section of talc-rich soapstone from the Linnajavri area (crossed nicols). Location: Kleberlia, Njaskasvárri 833 lens.*

of 1 million tonnes each, with a total estimated reserve of some 100 million tonnes of soapstone, equivalent to some 50 million tonnes of talc. The largest single body is Kleberflåget, containing 70 million tonnes of soapstone; 50 tonnes on the Norwegian side of the border and 20 million tonnes on Swedish ground. The geological potential for possible additional soapstone resources in the Linnajavri area is estimated to be at least 2–3 times the calculated reserves. The hidden resources are basically hosted in the shallow ca. 2 x 4 km Ridoalggičohkka synform in the Linnajavri southern area. In addition, there is an unknown but relatively surface-near soapstone potential connected to the Čohkul magnetic anomaly caused by the Čohkul ultramafic body (Mogaard 1992, Skilbrei et al. 2003). This body has a thin schist cover (only about 40 m) and crops out as an 80 x 400 m soapstone deposit with large serpentinite xenoliths in the steep southern wall of the Čohkul mountain, in the Linnajavri northern area (Lindahl and Nilsson 2002).

### Talc

The global market for talc as a filler mineral is relatively large at 7–8 million tonnes annually. Most of the supply comes from sedimentary deposits. However, soapstone altered from ultramafic rocks like the Linnajavri area is exploited in Finland on a large scale (Niemela 2002), where flotation of soapstone gives a talc concentrate for the paper industry. Most likely, talc from the soapstones of the Linnajavri area can also be extracted.

The very large reserves of soapstone in the Linnajavri area, sufficient for mining into the unforeseen future, justify a thorough testing of the raw material for flotation of talc. Our work on the mineralogy and mineral chemistry (Nilsson et al. 2003, Nilsson 2004) contains some of the background information needed for these tests.

### Dimension stone

Scandinavia, especially Finland and Norway, is the leading region in Europe for exploitation of soapstone deposits for producing

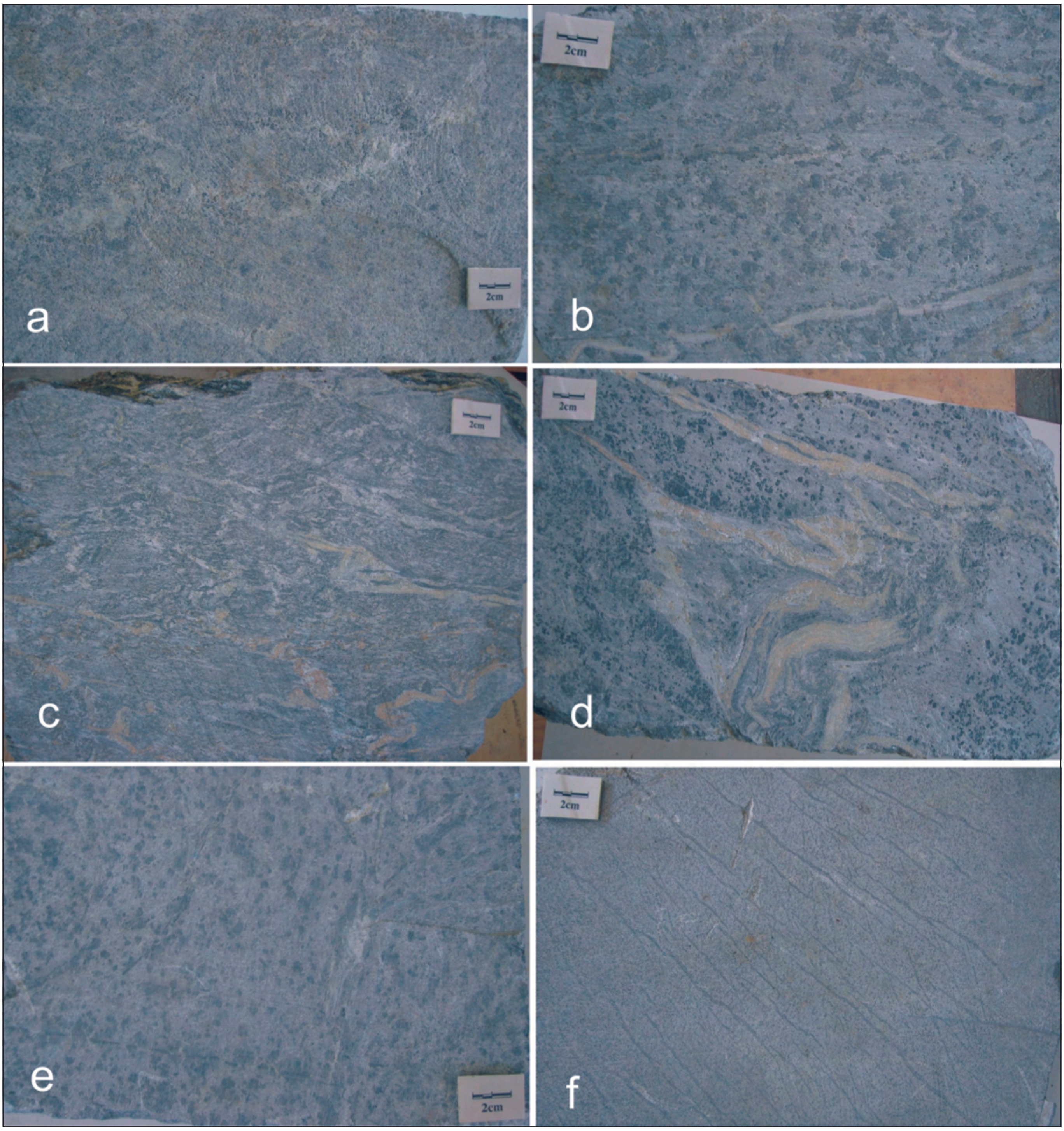


*Figure 20. Selection of soapstone slabs from the Linnajavri area. See map in Figure 2 for locations. (a) Kvitfjell NV, (b) Kleberflåget, (c) Hatten, (d) Langkleberdalen (e) Kleberbreen, (f) Ridoalggičohkka 1192 V.*

ovens and open fire places. The market is strongly growing, both in Scandinavia and other places where winters are cold. The end product for this industry is usually made close to the quarries, and there is no international block market for soapstone. This means that exploitation of soapstone creates more local jobs than block production from other types of massive dimension stone.

The soapstones of the Linnajavri area are generally massive, only locally weakly foliated. The colour of the soapstone varies from dark greyish to off-white. The darkest types may locally have a dull greenish tint from a certain amount of chlorite. The whitish type may be foliated and has a high content of talc, up to 70–80%, and as such has a poorer quality as dimension stone. Soapstone quarried for dimension stone normally contains minor amounts of sulphides and oxides. The sulphides may in some cases cause rusty surfaces. In the soapstones of the Linnajavri area, sulphides are absent and therefore do not have this potential problem. In Figure 20, a selection of the various soapstone types is presented. The textures vary to a certain extent both between and within the soapstone bodies and the soapstone industry can quarry the type of stone the market wants. Because the typical soapstones from Linnajavri are massive and little sheared, the mechanical strength is probably better than for several other soapstones from the Caledonides.

The soapstone reserves in the Linnajavri area are calculated for bodies larger than 1 million tonnes. Lenses or bodies smaller than this may be exploited for soapstone quarrying for dimension stone. The very large reserves and high quality of the soapstone in the area definitely make this rock type a potential resource for the industry for a very long period of time.

## Conclusions

During our work in the Linnajavri area we have documented and evaluated the economic potential of the unusually large and talc-rich soapstone deposits of the area. Geological mapping has been conducted focusing mainly on the many ophiolite fragments dispersed throughout the ca. 70 $km^2$ area (cf., Figure 2). The rather detailed geological map might also, however, be of some general interest to the study and correlation of Seve and Köli tectonostratigraphy on a more regional scale.

The Linnajavri area is built up of granitic basement and a sequence of Caledonian nappes, the Middle Allochthon to the west and above it the Upper Allochthon with the Seve and Köli Nappes. The Seve Nappe comprises one single nappe in the mapped area whereas the Köli Nappes may be subdivided into three individual sub-nappes, here informally named the *Ridoalggičohkka*, *Čohkul* and *Stipok* nappes. The nappes vary considerably in thickness in the area. Both the Seve Nappe and the Ridoalggičohkka nappe wedge completely out in the Linnajavri northern area. Repetitions of internal Köli Nappes also occur in the area, and we interpret the lower parts of our Ridoalggičohkka nappe to be repeated in the Stipok nappe. At three places in the core of the northern synform in the Čohkul nappe, we find possible inverted ophiolitic sections where amphibolites are overlain by ultramafic rocks or gabbros. In the Ridoalggičohkka synform in the south, we find Köli rocks including a well-preserved assemblage of semi-continuous ophiolite fragments where ultramafic rocks are overridden by a large sheet of dominantly unspecified amphibolite, but with abundant, easily identifiable massive gabbros and basaltic pillow lavas, the opposite situation compared to the north.

The Linnajavri area is characterised by what we have chosen to call *tectonic mélange* zones. Where these are at their densest, as in the Boarta area in the northwest, they occur as a net of zones that are up to 20–30 m thick and up to several kilometres long. These zones are characterised by fragmentation and crushing of rocks as they have acted as stress releasers between large rock masses. The crushed rocks in the mélange zones have in turn been more permeable to fluids than the enclosing compact rock masses and are typically strongly metasomatised. The third feature that characterises the mélange zones is fragments of variable size of exotic rocks, i.e., not from the immediate host rock to the zones.

The ubiquitous testimony of the soapstone alteration processes that were once at work within the ophiolitic ultramafic rocks in the Linnajavri area are impressive, and measured by volume probably unique in the Scandinavian Caledonides. The various mineralogical details concerning this alteration may be studied in great detail in the Linnajavri area due to the relatively weak deformation of the rocks between the above-described tectonic mélange zones. The $CO_2$ infiltration into dunite (Figure 16a), peridotite and serpentinite along breccia zones, joints, the mélange zones and a few regular, focused '$CO_2$ spots' may be studied in detail. Both larger structures as well as minor textures in the ultramafic rocks are often inherited in the soapstone without any signs of accompanying deformation in the latter. The Kleberflåget deposit is the best example. After the metasomatic transformation process had ceased, fragments of the once probably large ophiolite complex were obducted and exposed to weathering. This may clearly be seen south of the Gaskavárri ridge, where slope breccia-conglomerate includes angular pebbles of intermixed, massive soapstone and serpentinite. Conglomerates are also found within the Ridoalggičohkka synform, where we may see various more mature conglomeratic facies developed; there are more matrix-supported conglomerates, from serpentinite conglomerates through mafic and more pelitic conglomerates and grits.

The soapstone resources in the Linnajavri area must be classified as being of *national importance for Norway and significant for Europe* both for talc flotation and as dimension stone. It is also of great importance for future mineral industry in the region and can thereby create jobs on a long-term basis. Such activity will also be important for the population pattern in the region.

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## References

Andresen, A. and Tull, J.F. (1986) Age and tectonic setting of the Tysfjord gneiss granite, Efjord, North Norway. *Norsk Geologisk Tidsskrift*, **66**, 69–80.

Brattli, B. and Prestvik, T. (1985) Feltundersøkelse på kartblad Linnajavrre sommeren 1985. *NGU Map Archive 112/85.032D, Field report*, 31 pp.

Brattli, B. and Prestvik, T. (1987a) Linnajavrre, bedrock geology map 2230 III, scale 1:50,000, preliminary edition, *Norges geologiske undersøkelse*.

Brattli, B. and Prestvik, T. (1987b) Tysfjord granite and overlying rocks in the area of Linnajavrre, central-north Norway. *Norges geologiske undersøkelse Bulletin*, **410**, 65–72.

Foslie, S. (1929) Feltdagbok for gradteigskartene Hellemobotn og Linnajavri. Bind I og II. *NGU Map Archive*.

Foslie, S. (1936) Linnajavrre, bedrock geology map, scale 1:100,000, *Norges geologiske undersøkelse*.

Foslie, S. (1942) Hellemobotn og Linnajavrre. Geologisk beskrivelse til kartbladene. *Norges geologiske undersøkelse*, **150**, 119 pp.

Gee, D.G., Kumpulainen, R., Roberts, D., Stephens, M.B., Thon, A. and Zachrisson, E. (1985) Scandinavian Caledonides Tectonostratigraphic Map, scale 1:2,000,000. *In* Gee, D.G. and Sturt, B.A. (eds.) *The Caledonide Orogen—Scandinavia and Related Areas*, Wiley and Sons Ltd., Chichester.

Gustavson, M. (1996) Sulitjelma, bedrock geology map, scale 1:250,000, *Norges geologiske undersøkelse*.

Holmsen, G. (1917) Sørfolden–Riksgrensen. *Norges geologiske undersøkelse*, **79**, 46 pp.

Kautsky, G. (1953) Der geologische Bau des Sulitelma–Salojauregebietes in den nordskandinavischen Kaledoniden. *Sveriges geologiska undersökning*, **C 528**, 232 pp.

Krill, A.G., Kesola, R., Sjöstrand, T. and Stephens, M.B. (1987) Metamorphic, Structural and Isotopic data map of Northern Fennoscandia, scale 1:1,000,000, *Geological Surveys of Finland, Norway and Sweden*.

Kulling, O. (1964) Översikt över Norra Norrbottensfjällens kaledonberggrund. *Sveriges geologiska undersökning*, **Ba 19**, 166 pp.

Kulling, O. (1972) The Swedish Caledonides. *In* Strand, T. and Kulling, O. (eds.) *Scandinavian Caledonides*, John Wiley and Sons Ltd., pp. 149–285.

Kulling, O. (1982) Översikt över Södra Norrbottensfjällens kaledonberggrund. *Sveriges geologiska undersökning*, **Ba 26**, 295 pp.

Lindahl, I. and Nilsson, L.P. (2001) Kartlegging av talk/klebersteinsforekomstene i Linnajavri-området i Hamarøy kommune, Nordland. *NGU Report 2001.112*, 91 pp.

Lindahl, I. and Nilsson, L.P. (2002) Oppfølgende undersøkelser av talk- og klebersteinsforekomstene i området Boarta-Gaskavárri (Linnajavri Nordområde), Hamarøy kommune, Nordland. *NGU Report 2002.090*, 63 pp.

Lindahl, I. and Nilsson, L.P. (2005a) Klebersteinsforekomstene i Linnajavri-området, Hamarøy kommune, Nordland. Statusrapport. *NGU Report 2005.034*, 57 pp.

Lindahl, I. and Nilsson, L.P. (2005b) Prøvetakingen i Linnajavri-området feltsesongen 2005: Kvitfjell NV. *NGU Notat*, 9 pp.

Lindahl, I. and Nilsson, L.P. (2005c) Prøvetakingen i Linnajavri-området 2005: Sørområdet. *NGU Notat*, 10 pp.

Lindahl, I. and Nilsson, L.P. (2006a) Kjemiske og mineralogiske undersøkelser av kleberstein fra forekomsten Kvitfjell NV, Linnajavri. *NGU Notat*, 38 pp.

Lindahl, I. and Nilsson, L.P. (2006b) Geologisk oversikt over Linnajavri-området fra kartlegningen 2000–2006. *NGU Report 2006.093*, 27 pp.

Lindahl, I., Furuhaug, L. and Nilsson, L.P. (2005) Undersøkelsene i Linnajavri-området feltsesongen 2005: Gulldalen. *NGU Notat*, 10 pp.

Lindahl, I., Nilsson, L.P. and Furuhaug, L. (2006) The soapstone deposits in the Linnajavri area, Hamarøy community, Nordland county–the largest deposits in Norway–a resource of national importance. *PNASTINA project report*, 11 pp.

Mogaard, J.O. (1992) Geofysiske målinger fra helikopter over et område i indre Tysfjord, Nordland. *NGU Report 1992.229*, 9 pp.

Niemela, M. (ed.) (2002) Talc-magnesite deposits in Finland. *In Magnesite and Talc—Geological and Environmental Correlations. IGCP 443, Third Field Correlation*, 49 pp.

Nilsson, L.P. (2004) Prosjekt Linnajavri talk/kleberstein. Bulkanalyser av oppredning-skonsentrater samt SEM-analyser av rågods til oppredning, m.m. *NGU Notat*, 180 pp.

Nilsson, L.P. and Lindahl, I. (2003a) Skifer i Linnajavri-området, Hamarøy og Sørfold kommuner, Nordland. *NGU Report 2003.018*, 18 pp.

Nilsson, L.P. and Lindahl, I. (2003b) Status for Linnajavri talkprosjekt ved årsskiftet 2002–2003. *NGU Notat*, 15 pp.

Nilsson, L.P., Lindahl, I. and Gautneb, H. (2003) Mineralkarakterisering av talk/kleberstein fra Linnajavri-området, Hamarøy kommune, Nordland. *NGU Report 2003.027*, 209 pp.

Nilsson, L.P., Roberts, D. and Ramsay, D.M. (2005) The Raudfjellet ophiolite fragment, Central Norwegian Caledonides: principal lithological and structural features. *Norges geologiske undersøkelse Bulletin*, **445**, 99–115.

Pedersen, R.B. and Furnes, H. (1991) Geology, magmatic affinity and geotectonic environment of some Caledonian ophiolites in Norway. *Journal of Geodynamics*, **13**, 183–203.

Poulsen, A.O. (1958) Industrielle mineraler og bergarter, scale 1:1,000,000, *Norges geologiske undersøkelse, Bergarkivet no. K 2675*.

Poulsen, A.O. (1959) Navneliste til kart over Industrielle mineraler og bergarter. *Norges geologiske undersøkelse, Bergarkivet*, 90 pp.

Raymond, L.A. (ed.) (1984a) *Melanges: their nature, origin, and significance*. Geological Society of America Special Paper, **198**, 170 pp.

Raymond, L.A. (1984b) Classification of melanges. *In* Raymond, L.A. (ed.) *Melanges: their nature, origin and significance*, Geological Society of America Special Paper, **198**, 7–20.

Rehnström, E.F. and Corfu, F. (2004) Palaeoproterozoic U-Pb ages of autochthonous and allochthonous granites from the northern Swedish Caledonides; regional and palaeogeographic implications. *Precambrian Research*, **132**, 363–378.

Shaikh, N.A., Tontti, M.B. and Øvereng, O. (1987) Industrial Minerals and Rocks of the Nordkalott area, scale 1:1,000,000, *Geological Surveys of Finland, Norway and Sweden*.

Silvennoinen, A., Gustavson, M., Perttunen, V., Siedlecka, A., Sjöstrand, T., Stephens, M.B. and Zachrisson, E. (1987) Geological map of the Nordkalott area, scale 1:1,000,000, *Geological Surveys of Finland, Norway and Sweden*.

Skilbrei, J.R., Nilsson, L.P. and Lindahl, I. (2003) Magnetisk modellberegning av talk/klebersteinforekomst ved Cohkul (Linnajavri Nord-område), Hamarøy kommune, Nordland. *NGU Report 2003.044*, 17 pp.

Solli, A. and Nordgulen, Ø. (2006) Berggrunnskart over Norge og kaledonidene i Sverige og Finland, scale 1:2,000,000, *Norges geologiske undersøkelse*.

Stigh, J. (1982) Talk–magnesitförekomsten i Vietjervaratj, Vestre Padjelanta, Norrbottens Kaledonidberggrund. *SGU Report 191/1982*, 19 pp.

Sturt, B.A. and Roberts, D. (1991) Tectonostratigraphic relationships and obduction histories of Scandinavian ophiolitic terranes. *In* Peters, T., Nicolas, A and Coleman, R.G. (eds.) *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*, Ministry of Petroleum and Minerals, Sultanate of Oman, pp. 745–769.

Sturt, B.A., Roberts, D. and Furnes, H. (1984) A conspectus of Scandinavian Caledonian ophiolites. *In* Gass, I.G., Lippard, S.J. and Shelton, A.W. (eds.) *Ophiolites and Oceanic Lithosphere*, Geological Society of London Special Publication, **13**, 381–391.

Sundblad, K. (1986) The Stipok allochthon—an exotic terrane in the northern Swedish Caledonides. *Geologiska Föreningen i Stockholm Förhandlingar*, **108**, 309–311.

Svenonius, F. (1895) Forskningsresor i Kvikkjokks fjälltrakter åren 1892 och 1893 med särskild hänsyn till apatitförekomster. *Sveriges geologiska undersökning*, **C 146**, 36 pp.

Svenonius, F. (1896) Några bidrag till belysning af eruptivens betydelse för fjällbildningarna. *Sveriges geologiska undersökning*, **C 164**, 31 pp.

Svenonius, F. (1900) Öfversikt af Stora Sjöfallets och angränsande fjälltrakters geologi. 2. Berggrunden. *Geologiska Föreningen i Stockholm Förhandlingar*, **22**, 273–322.

Zachrisson, E. and Stigh, J. (1981) Ultramafiter i fjällen. *SGU Report to NSG. BRAP 81522*, 55 pp.