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Early Proterozoic nappe formation: an example from Sodankylä, Finland, Northern Baltic Shield

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Abstract – The Central Lapland Greenstone belt comprises rift-related metavolcanic and metasedimentary rocks representing one of the largest supracrustal belts in the Baltic Shield. The Sodankylä area in the central part of the belt represents a complex thrust duplex within a nappe overlying Belomorian Archaean basement and autocthonous Luirojoki calc-silicate rocks. Here, an early D_1 schistosity is axial planar to at least three coaxial generations of southward-verging, subhorizontal, E–W-plunging D_1 folds associated with major southwards thrusting. D_2 is represented by broad, map-scale, upright, NE-trending folds in the south and crenulations in the north. Staurolite-grade metamorphism represented by post-tectonic andalusite + staurolite + kyanite assemblages occurred after D_2 folding. Later D_3 deformation was limited to local NW-trending folds and sinistral faults. The internal nappe-like structure of the Central Lapland Greenstone belt suggests that it represents the foreland of a large collisional complex cored by the Lapland Granulite belt.

1. Introduction

The Central Lapland Greenstone belt represents one of the largest supracrustal belts of the Baltic Shield. It is a 200 km long, 100 km wide belt that consists of *c.* 2500–1800 Ma metasandstones, metapelites and metalavas deposited and extruded on late Archaean basement (Hanski, 1987; Lehtonen *et al.* 1998; Saverikko, 1987, 1988). The palaeovolcanism, sedimentology and stratigraphy of the belt have been studied extensively (Meriläinen, 1976; Saverikko, 1987, 1988). However, the internal structure of the Central Lapland Greenstone belt has usually been overlooked. In the Sodankylä area (in the centre of the belt), Saverikko (M. Saverikko, unpub. M.Sc. thesis, Univ. Helsinki, 1977; 1987, 1988) focused on stratigraphy and sedimentology, concluding that the rocks were deposited or extruded in an aulacogen. Saverikko (1988) also considered most of the major structures to be a result of formation of this intracontinental rift in an extensional setting. Later, Sorjonen-Ward (Sorjonen, 1993; Sorjonen, Nironen & Luukkonen, 1997) hypothesized that the structural pattern of the Central Lapland Greenstone belt was the result of Svecofennian compression and that the belt may represent a foreland fold and thrust belt. Recent studies have uncovered thrust sheets, including the Nuttio ophiolites of the Kittilä Greenstone belt northwest of Sodankylä (Hanski *et al.* 1997), within the Central Lapland Greenstone belt and its continuation as the Karasjok Greenstone belt in northern Norway (Braathen & Davidsen, 2000). Along with the well-documented evidence of compressional nappes from the Lapland Granulite belt (Marker, 1985; Gaal *et al.* 1989; Korja *et al.* 1989, 1996) north of the Central Lapland Greenstone belt, this discovery highlights the need for structural mapping throughout the Central Lapland Greenstone belt and reappraisal of its current position and tectonic setting (Fig. 1a).

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2. Geological setting of the Sodankylä area

The Sodankylä area is bordered on the west by the ophiolite-bearing, allochthonous Kittilä Greenstone belt (Hanski *et al.* 1998), to the north and northwest by Belomorian Archaean basement, and to the south by autochthonous and allochthonous units of the Central Lapland Greenstone belt which are intruded by the *c.* 1.8 Ga (Lauerma, 1982) Central Lapland granitoids (Fig. 1a). Just north of the Central Lapland Greenstone belt, a sliver of Archaean metavolcanics (the Tana Elv belt) underlies the Lapland Granulite belt, which was thrust to the south at *c.* 1.87 Ga (Tuisku & Huhma, 1998). On aeromagnetic maps, two distinct structural and lithological domains are apparent within the Central Lapland Greenstone belt east of the Kittilä Greenstone belt (Fig. 1b). The eastern domain is dominated by strong magnetic anomalies distributed in a chaotic wormlike pattern. This domain is tentatively named the Luirojoki autochthon and, although very poorly exposed, is said to be composed dominantly of calc-silicates in probable unconformable contact with the Archaean basement (Korsman *et al.* 1997). To the north and south of the

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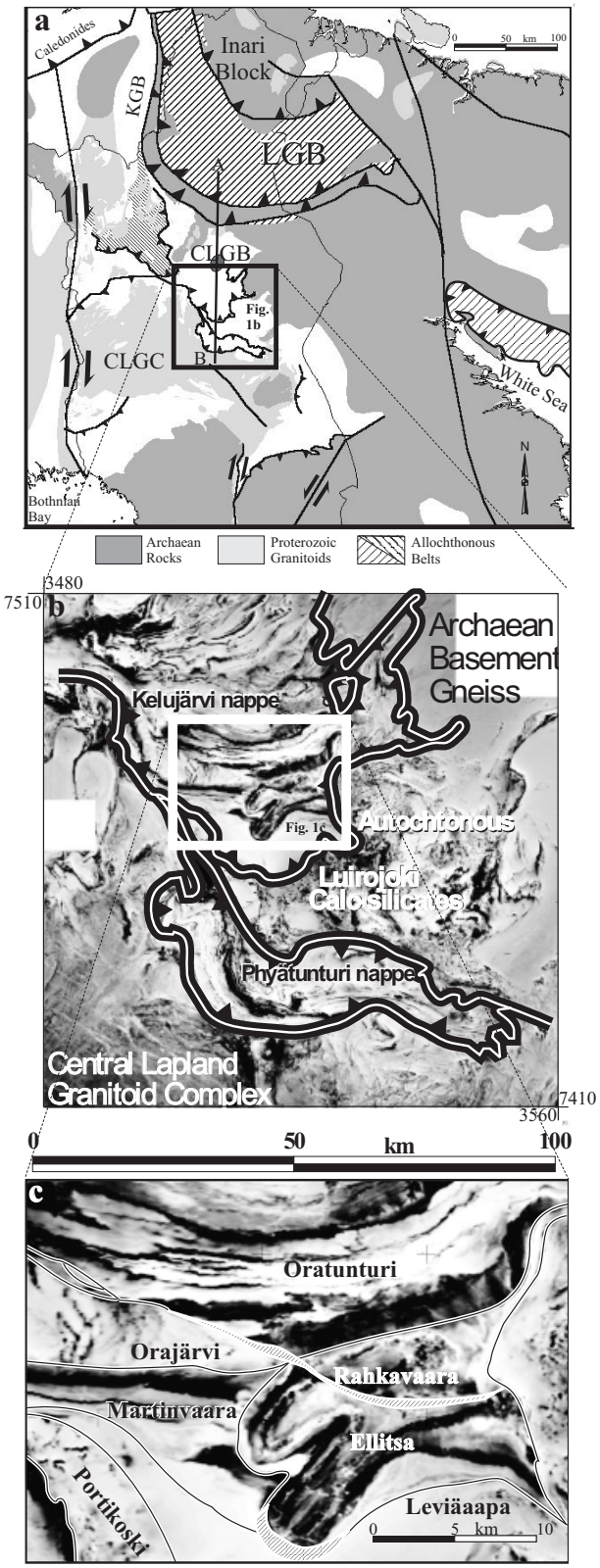


Figure 1. (a) Generalized geological map of the northern Baltic Shield showing major Palaeoproterozoic faults. LGB = Lapland Granulite Belt, KGB = Karasjok Greenstone belt, CLGB = Central Lapland Greenstone belt, CLGC = Central Lapland Granitoid Complex. (b) Aeromagnetic map of the central part of the Central Lapland Greenstone Belt (darker shades represent more magnetic rocks) showing the Kelujärvi and Pyhätunturi nappes. Coordinates from Finnish National Grid. (c) Close-up of (b) showing the Sodankylä study area (seen in Figs 2, 7, 10) and its fault-bounded structural domains. Aeromagnetic maps published with permission of the Geological Survey of Finland.

Luirojoki autochthon are more homogeneous domains of E–W-trending, alternating bands of low and high magnetic signature. These domains consist of Karelian quartzites, schists, and greenstones thrust into their current position and are tentatively named the Kelujärvi nappe to the north and Pyhätunturi nappe to the south. The Sodankylä area represents the south-central part of the Kelujärvi nappe (Fig. 1b).

3. Regional lithostratigraphy

Following Lehtonen *et al.* (1998), the early Proterozoic cover sequence of the late Archaean basement in the study area is subdivided into the Onkamo Group and its overlying Sodankylä Group (Figs 2, 3). The late Archaean basement represented by the Porttikoski window was not studied by the authors and will not be treated in this paper. East of the Sodankylä area, the Onkamo Group lies atop *c.* 2350 Ma gabbro dykes (Vuollo *et al.* 2000) and is intruded by *c.* 2210 Ma gabbroic sills (Hanski, 1987), suggesting the Onkamo and Sodankylä groups were deposited from *c.* 2350 to 2210 Ma.

3.a. Onkamo Group

The non-magnetic greenstone and volcaniclastic rocks in the southern part of the area as well as the smaller greenstone occurrence in the north are included in the Onkamo Group (Fig. 2). The greenstones are highly deformed chlorite and amphibolite schists lacking well-preserved primary structures or textures. They represent shallow, submarine lavas and their volcaniclastic equivalents (Saverikko, 1987, 1988). They display a well-developed S_1 foliation and often one or two generations of later crenulation. Volcaniclastic rocks occupy the northern margin of the southern greenstones against the Sodankylä Group. In the east, they are epiclastic conglomerates with up to boulder-size clasts of various volcanic rocks. The rocks south of the Ellitsa thrust sheet are pebbly, volcaniclastic amphibolite schists. Occasionally they contain conglomerates with 1–2 cm long clasts of both basement granitic orthogneiss and volcanogenic rocks. Both the conglomerate clasts and the pebbles within the amphibolitic schists show a well-developed L_2 stretching lineation.

3.b. Sodankylä Group

The Onkamo/Sodankylä Group contact is not exposed, but according to Lehtonen *et al.* (1998) it is a hiatus; the basal formations (to be described below)

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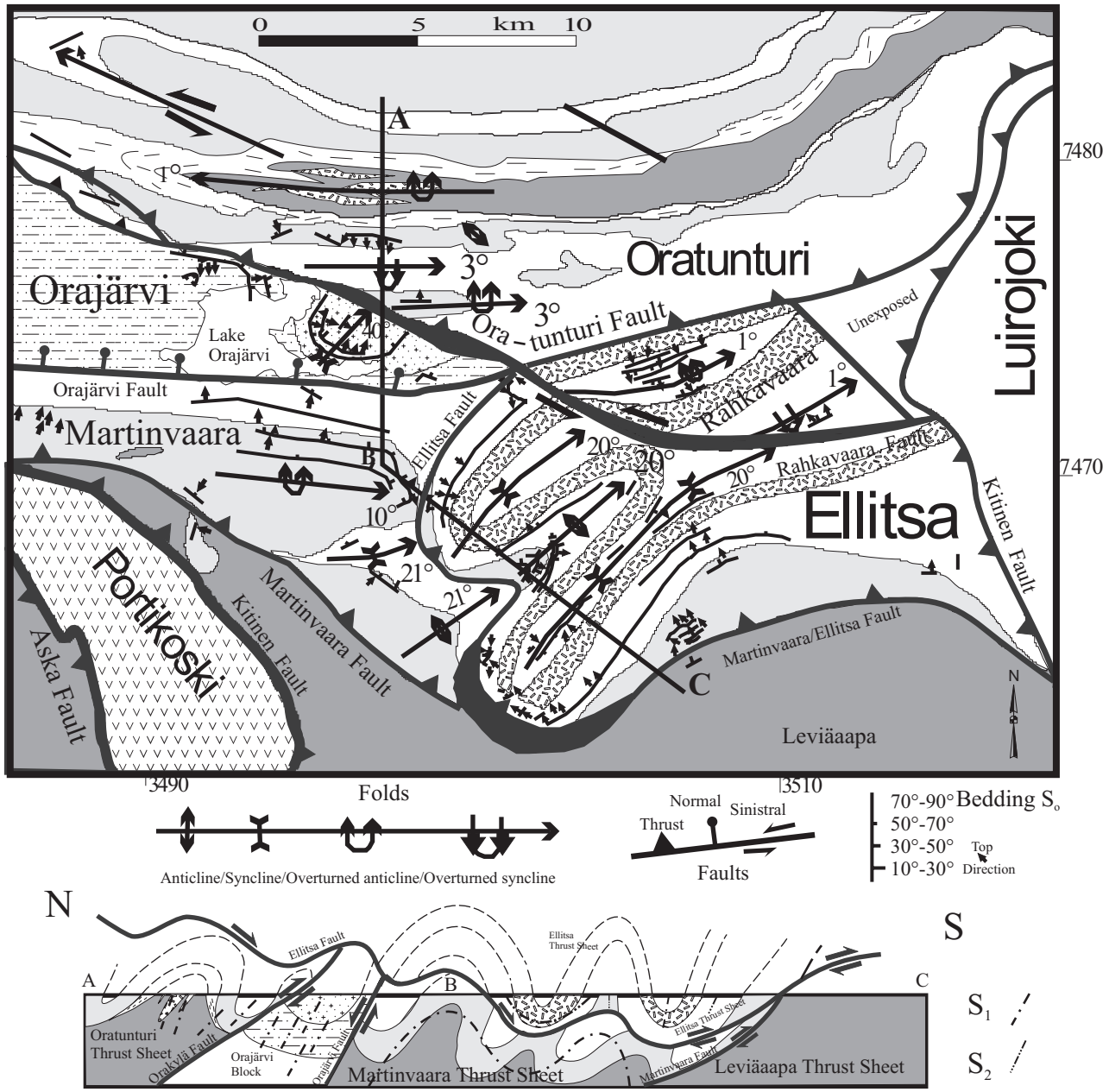


Figure 2. Geological map and cross-section of the Sodankylä area showing bedding orientations, younging directions, and the major fold structures (see Fig. 3 for legend). Coordinates from Finnish National Grid.

indicate that the contact is an unconformity. The Sodankylä Group is subdivided into four formations: the Orakoski, Ellitsanvaara, Orajärvi and Tepsanniemi formations. Radiometric age determinations indicate an Archaean provenance for most of the detrital zircons of the Sodankylä Group sediments (Lehtonen *et al.* 1998).

3.b.1. Orakoski Formation

The lowermost feldspathic arenite formation of the study area has previously been called the Orakoski quartzite (Mikkola, 1941) or the Orakoski arkosite (M. Saverikko, unpub. M.Sc. thesis, Univ. Helsinki, 1977; Saverikko, 1987, 1988). We follow Lehtonen *et al.* (1998) and call it the Orakoski Formation. This 1000 m thick, monotonous formation consists of fluvial deposits of trough-cross-bedded quartzite with variable amounts of feldspars, mostly microcline (Fig. 4). Microcline gives the rock a pinkish or light-brown colour and was likely derived from the surrounding Archaean granitoid gneisses. In the southern part of the area, the bottom of the formation contains conglomerate interbeds with vein-quartz and basement orthogneiss clasts in a greenschist matrix. Further north, the Orakoski Formation begins with a layer

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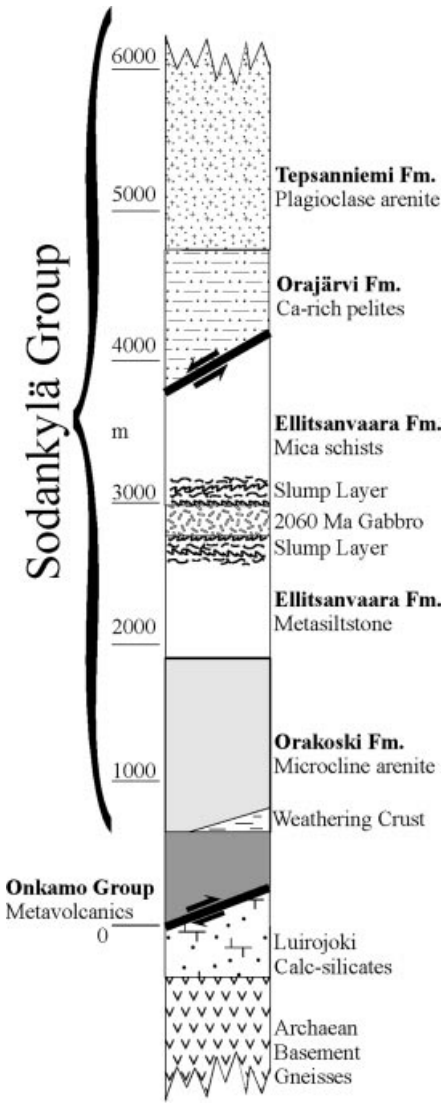


Figure 3. Lithostratigraphy of the Sodankylä area.

composed only of this matrix. These bottom layers most likely represent a weathering crust above the Onkamo Group, implying surface exposure and weathering of the Onkamo Group lavas before deposition of the Orakoski quartzites.

3.b.2. Ellitsanvaara Formation

This new name applies to *c.* 1500 m of mica schists and metasiltstones conformably overlying the Orakoski Formation. It is a counterpart to Saverikko's (M. Saverikko, unpub. M.Sc. thesis, Univ. Helsinki, 1977; 1987, 1988) metapelite unit. The lower contact is transitional over the space of a few metres. The lower part of the formation is often metamorphosed and deformed into strongly magnetic mica schists. Less-deformed sections reveal that the formation begins with a laminated/graded-bedded or ripple-laminated



Figure 4. Trough cross-bedding in quartzite from the Orakoski Formation in the Ellitsa thrust sheet. Younging direction is towards the top of the photo. Scale in centimetres.

siltstone overlain by a more pelitic (finer-grained) metasiltstone–mudstone with well-preserved ripples and even hummocky cross-stratification (Fig. 5). These were deposited in a tidal submarine environment. The higher stratigraphic levels are characterized by strongly magnetic mica schists containing abundant porphyroblasts of kyanite, andalusite, staurolite, chloritoid or plagioclase.

A 50 m thick, highly magnetic gabbro sill intrudes siltstones of the lower parts of the formation providing an excellent marker layer for mapping. It is often bound on both sides by a 100 m thick slump layer of siltstones with soft-sedimentary deformation structures indicative of ongoing tectonic activity during sedimentation (Fig. 6). Contact metamorphism from the sill commonly produces small, millimetre-sized garnets in the Ellitsanvaara Formation. Intrusion of this sill occurred at 2060 ± 2 Ma (Patchett *et al.* 1981).

3.b.3. Orajärvi Formation

This new name applies to the slightly calcareous and scapolite-bearing laminated to ripple-laminated pelitic rocks west of Orajärvi Lake. These rocks correspond to Saverikko's (M. Saverikko, unpub. M.Sc. thesis, Univ. Helsinki, 1977; 1987, 1988) calc-silicate rock and sericite quartzite. He suggested these rocks were deposited in a tidal environment during tectonic instability. The underlying rocks are not exposed, but it is likely that the formation conformably overlies the Ellitsanvaara Formation. However, their contact is tectonic. The Orajärvi and Ellitsanvaara formations are easily distinguishable by the former's calcareous nature and the latter's higher magnetic signature. This poorly exposed formation is probably *c.* 1000 m thick and a counterpart to Saverikko's (1988) calc-silicate rock.

3.b.4. Tepsanniemi Formation

This new name applies to the folded arkosic arenites east of Lake Orajärvi (Fig. 2). Saverikko (M. Saverikko, unpub. M.Sc. thesis, Univ. Helsinki, 1977; 1987, 1988)

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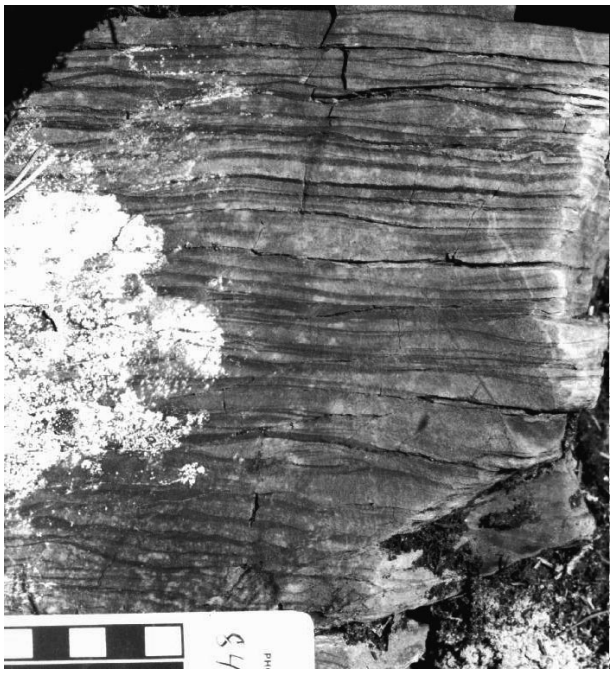


Figure 5. Ripples in siltstone from the Ellitsanvaara Formation in the Ellitsa thrust sheet. Younging direction is towards the top of the photo. Scale in centimetres.

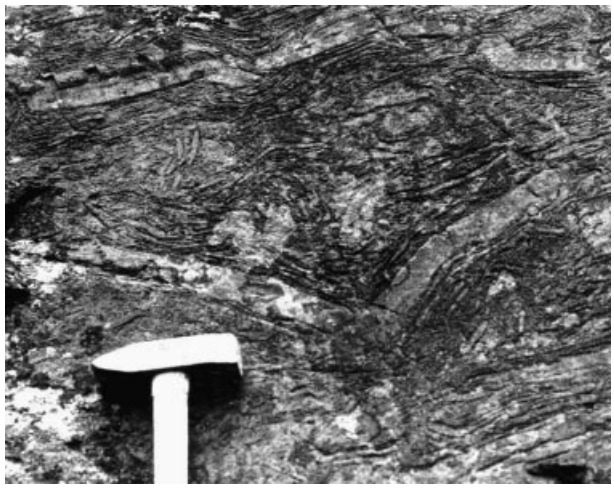


Figure 6. Soft-sediment deformation in siltstone from the Ellitsanvaara Formation near the gabbro sill in the Rahkavaara domain. Hammer head is 15 cm long.

included these rocks in his arkosite quartzite of the Sodankylä quartzite Formation. Its unexposed lower contact with the Orajärvi Formation lies under Lake Orajärvi. However, younging directions (Fig. 2) indicate these arenites lie above the Orajärvi Formation, not below as in Saverikko's (M. Saverikko, unpub. M.Sc. thesis, Univ. Helsinki, 1977; 1987, 1988) stratigraphy. This *c.* 1500 m thick formation is characterized by large-scale, mostly planar, cross-bedding and abundant feldspar, mostly plagioclase. Tepsanniemi quartzites are distinguishable from Orakoski quartzite by their abundance of plagioclase and higher stratigraphic position (above siltstones and schists).

4. Tectonostratigraphy (from north to south and west to east)

The stratigraphy described above is repeated in a N–S direction throughout the area. Folding of this stratigraphy was responsible for some of this repetition, however, breaks in stratigraphy (also corresponding to breaks in aeromagnetic patterns in Fig. 1c) are interpreted as faults (Fig. 2). These breaks are usually unexposed, however, outcrops near them are marked by an increase in foliation intensity. Repetition of stratigraphy across these faults along with southward vergence of macroscopic folds associated with them (described below in the deformation history) and the nappe-like geometry of the Karelian formations in Figure 1b indicate that the faults are thrusts. The interpretation of these faults as thrusts is also consistent with the identification and characterization of thrusts in the Lapland Granulite Belt to the north (Marker, 1985; Gaal *et al.* 1989; Korja *et al.* 1989, 1996) and Karasjok Greenstone belt to the west (Braathen & Davidsen, 2000) that resulted from a period of N–S compression responsible for most of the structures in the region (Berthelsen & Marker, 1986; Sorjonen, Nironen & Luukkonen, 1997; Evins 2001). For structural interpretations, the Sodankylä area is best divided into seven domains (from north to south and west to east): Oratunturi, Orajärvi, Martinvaara, Rahkavaara, Ellitsa, Leviäaapa and Luirojoki (Figs 1c, 2). All are bound by the faults mentioned above and display unique lithologies, metamorphic conditions, structural patterns and/or aeromagnetic anomalies.

4.a. Oratunturi thrust sheet

The Oratunturi thrust sheet consists of relatively strongly deformed, E–W-trending members of the Onkamo Group, Orakoski Formation and Ellitsanvaara Formation. Here, relatively high-grade schists of the Ellitsanvaara Formation provide the most abundant outcrop. The presence of chloritoid, kyanite and staurolite solely in the schists of the Oratunturi thrust sheet attests to its higher metamorphic grade and presence at deeper crustal levels than the other domains. The schists are folded about moderately N-dipping axial planes that verge southward (Fig. 2). Approaching the southern boundary of the Oratunturi thrust sheet, this folding becomes asymmetric on a smaller scale indicating top-to-the-south movement near the unexposed Oratunturi fault. This arcuate, E–W-trending, fault truncates aero-

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magnetic anomalies on either side of it (Fig. 1c) and is interpreted as a thrust due to the asymmetry and vergence of folds near it. Northward the thrust sheet continues out of the study area towards probable fault contacts within the Kelujärvi nappe and eventually with Archaean Belomorian basement.

4.b. Orajärvi Block

The Orajärvi Block represents a small, down-dropped section of the upper part of the Sodankylä Group. Rocks of the Orajärvi block are unexposed in the west. It is the only domain in the study area where the Tepsanniemi and Orajärvi formations are exposed. It is bounded to the north by the above-mentioned Oratunturi thrust and to the south by the steeper, E–W-trending Orajärvi normal fault, which was responsible for dropping the stratigraphically higher Tepsanniemi and Orajärvi formations to their current structural level alongside the stratigraphically lower Ellitsanvaara and Orakoski formations.

4.c. Martinvaara thrust sheet

The Martinvaara thrust sheet consists of moderately deformed rocks of the Orakoski and Ellitsanvaara formations. It is bounded to the north by the aforementioned, E–W-trending, unexposed Orajärvi fault. To the east, it is truncated by the folded, mylonitic Ellitsa thrust (described in the next section). The southern boundary of the Martinvaara thrust sheet is marked by the unexposed, NW-trending Martinvaara fault which truncates structural trends and aeromagnetic anomalies on either side (Figs 1c, 2) and juxtaposes rocks of the Sodankylä Group in the Martinvaara thrust sheet against metavolcanic rocks of the Onkamo Group in the Leviäaapa thrust sheet. Southward vergence of an overturned fold near the western part of the fault and repetition of stratigraphy across the fault implies it is a thrust (Fig. 2). Outcrops are prevalent in the western part of the thrust sheet, which is dominated by an anticline containing a small amount of older, Onkamo Group volcanic rocks in its core. Andalusite is common in the lower sections of the Ellitsanvaara Formation schists in the north of the Martinvaara thrust sheet.

4.d. Ellitsa thrust sheet

The Ellitsa thrust sheet is dominantly underlain by relatively undeformed and well-preserved metasiltstones of the Ellitsanvaara Formation and the gabbro sill mentioned earlier. A thin slice of Orakoski Formation quartzites crops out in the core of an anticline near the southwestern boundary of the Ellitsa thrust sheet. The folded Ellitsa thrust marks the western and southern boundaries of the Ellitsa thrust sheet. To the north, the Ellitsa thrust sheet is separated from the Rahkavaara domain by the NW-trending Rahkavaara fault. Bedding is locally transposed near smaller NW-trending faults cutting the gabbro sill in the nose of the southern syncline (Fig. 2). Formations of the Ellitsa thrust sheet are sharply truncated by the unexposed Kitinen fault to the east. The Ellitsa thrust sheet is significantly less deformed and metamorphosed than the other thrust sheets in the study area and experienced a different tectonic evolution than the others (discussed in more detail in sections below).

4.d.1. Rahkavaara domain of the Ellitsa thrust sheet

The Rahkavaara domain is composed solely of NE-trending metasiltstones from the Ellitsanvaara Formation and the gabbro sill described above. These metasiltstones are relatively undeformed, preserving several primary sedimentary structures such as ripples and graded bedding. Younger units of the Ellitsanvaara Formation in the southeastern corner of the Rahkavaara domain contain andalusite and chloritoid porphyroblasts attesting to their relatively high aluminium content. They can be followed into the Ellitsa thrust sheet to the south, however, they have been sinistrally offset along the late Rahkavaara fault that represents the southern boundary of the Rahkavaara domain. A late NW-trending fault marks the end of outcrops and aeromagnetic patterns in the eastern part of the thrust sheet. The northern boundary of the Rahkavaara domain is the Oratunturi thrust.

4.e. Leviäaapa thrust sheet

The Leviäaapa thrust sheet is made up almost entirely of non-magnetic greenstones of the Onkamo Group. A sliver of conglomerate-bearing Orakoski quartzite is found near the Martinvaara fault in the west. Pebbles from volcanic conglomerates in the west underwent D_2 deformation and are stretched in a shallow NE-plunging direction. The Martinvaara and Ellitsa faults form the northern boundary of the Leviäaapa thrust sheet. The western boundary of the Leviäaapa thrust sheet is marked by the Kitinen fault. Further south it follows the Kitinen River continuing eastwards and marking the southern boundary of the Onkamo Group. It then bends northwards following the Härkäjoki River and enters the eastern side of the study area to form the eastern boundary of the Leviäaapa thrust sheet. On aeromagnetic maps, this fault can be traced as a boundary between two contrasting domains (Fig. 1b). The northern domain consists of the southward-verging thrust sheets described above and is referred to here as the Kelujärvi nappe. Therefore, the Kitinen fault may be interpreted as the southern boundary and sole thrust of the Kelujärvi nappe. In the southwestern corner of the area, a small piece of Archaean basement (Porttikoski) separates the Kelujärvi nappe from the Pyhätunturi nappe on the western side of the basement. The Aska fault marks the western boundary of

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the Archaean Porttikoski window in the Sodankylä area. This fault continues southward as the roof thrust of the Pyhätunturi nappe (Fig. 1b).

4.f. Luirojoki autochthon

The Luirojoki autochthon is not exposed in the study area, however, it exhibits a distinctive, chaotic, worm-like pattern on aeromagnetic maps (Fig. 1b). Korsman *et al.* (1997) classified the lithologies as volcanic and calc-silicate rocks, but this area is yet to be mapped in any detail. This supracrustal package probably lies unconformably atop Archaean Belomorian basement exposed further east. In the study area, the Luirojoki autochthon is bounded to the west by the unexposed continuance of the Kitinen fault (Figs 1b, 2).

5. Deformation history

5.a. S_0 bedding

Bedding is well preserved in all of the tectonostratigraphic domains throughout the study area, excepting the schists of the Oratunturi thust sheet. This allowed the determination of over 200 younging directions derived from observations of graded bedding and cross-bedding (Fig. 4) in the quartzites and graded bedding and ripples in the siltstones (Fig. 5).

5.b. D_1 southward-verging thrusts and folds

All structural measurements representing the first deformation event (D_1) recorded in rocks of the Sodankylä area are presented in Figure 7. D_1 is the strongest deformation event in the area and is characterized by a marked consistency in E–W fabric orientations within and between different thrust sheets. Apart from the Ellitsa fault, most of the major faults bounding the thrust sheets are unexposed. Instead, they are usually represented by significant topographic depressions. These faults are interpreted as N-dipping thrusts based on truncation of aeromagnetic anomalies and structural trends, repetition of stratigraphy, vergence of folding, transposition of foliations within 1 km of the faults, and in the case of the Ellitsa fault, mylonitic fabrics with kinematic indicators. The Ellitsa thrust, however, has been strongly folded by later D_2 deformation. Exposures of the thrust in the area reveal a thin zone of shallowly dipping protomylonitic–mylonitic fabrics that are folded into upright folds with a shallowly southward-dipping enveloping surface (Fig. 2). This surface effectively covers the earlier D_1 thrusts. Shear-sense indicators show thrusting along this plane to the south (Fig. 8), consistent with the southward vergence of earlier D_1 structures. Therefore, the Ellitsa thrust is considered a late D_1 structure.

Schists of the upper Ellitsanvaara and Tepsaniemi formations in the Oratunturi, western Orajärvi, western Martinvaara, and Rahkavaara domains were most affected by D_1 deformation. Bedding in the Oratunturi and Martinvaara thrust sheets is folded into simple, tight, 10 km wavelength, southward-verging folds as demonstrated by bedding and younging direction measurements (Fig. 2). Asymmetric folds at lithological boundaries indicate some flexural slip occurred during this folding. S_1 foliation and macro-meso-microscopic fold axial planes dominantly dip moderately–steeply to the north. S_1 is mesoscopically and microscopically folded about a number of generations of subparallel, subhorizontal E–W-trending axes (Fig. 9). These elements are noted as F_1, F_{1a} and F_{1b}, where F_{1a} crenulated S_1 schistosity axial planar to F_1. Axial planes to F_{1a} crenulations then developed into S_{1a} schistosity, which in turn was crenulated by F_{1b}. This system of crenulations can be followed approaching the summit of Oratunturi from the west, and in all cases original F_1 axes and subsequent F_{1a} and F_{1b} axes are sub-parallel to each other (Fig. 7a,b).

Rocks of the Oratunturi thrust sheet display at least three similarly oriented generations of southward-verging, subhorizontal E- or W-plunging folds with wavelengths varying from map scale (1 km) to microscopic crenulations (< 1 cm) (Figs 7b, 10). The internal structure of the western part of the Orajärvi block (Fig. 7c) and Martinvaara thrust sheet (Fig. 7d,e) is characterized by a penetrative E–W-trending foliation that has been crenulated several times along mutually subparallel axes in a manner similar to the Oratunturi thrust sheet. In the Martinvaara thrust sheet this penetrative foliation is axial planar to an upright, shallowly E-plunging, F_1 anticline (Figs 2, 7). This steeply N-dipping, E–W-trending S_1 foliation and F_1 crenulation is weakly developed in some of the more pelitic units of the Ellitsanvaara Formation in the Rahkavaara domain (Fig. 7f), but appears to have unaffected bedding trends (Fig. 2). Small garnets associated with contact metamorphism from the gabbro sill are also aligned parallel to this foliation in the Rahkavaara domain. D_1 structures and high grade metamorphism are virtually absent in the Ellitsa thrust sheet (possible reasons are discussed in sections below).

5.c. D_2 upright NE-trending folds

All structural measurements representing the second deformation event (D_2) recorded in rocks of the Sodankylä area are presented in Figure 10. Evidence of D_2 deformation is preserved in all of the structural domains, but is best exemplified by macroscopic folds in the Ellitsa thrust sheet. The gabbro sill within the Ellitsa thrust sheet is an excellent marker layer tracing out a gently NE-plunging syncline/anticline/syncline sequence easily visible on aeromagnetic maps (Figs 1b, 2). The D_1 Ellitsa thrust was also folded along with the gabbro sill and the Ellitsanvaara Formation. This

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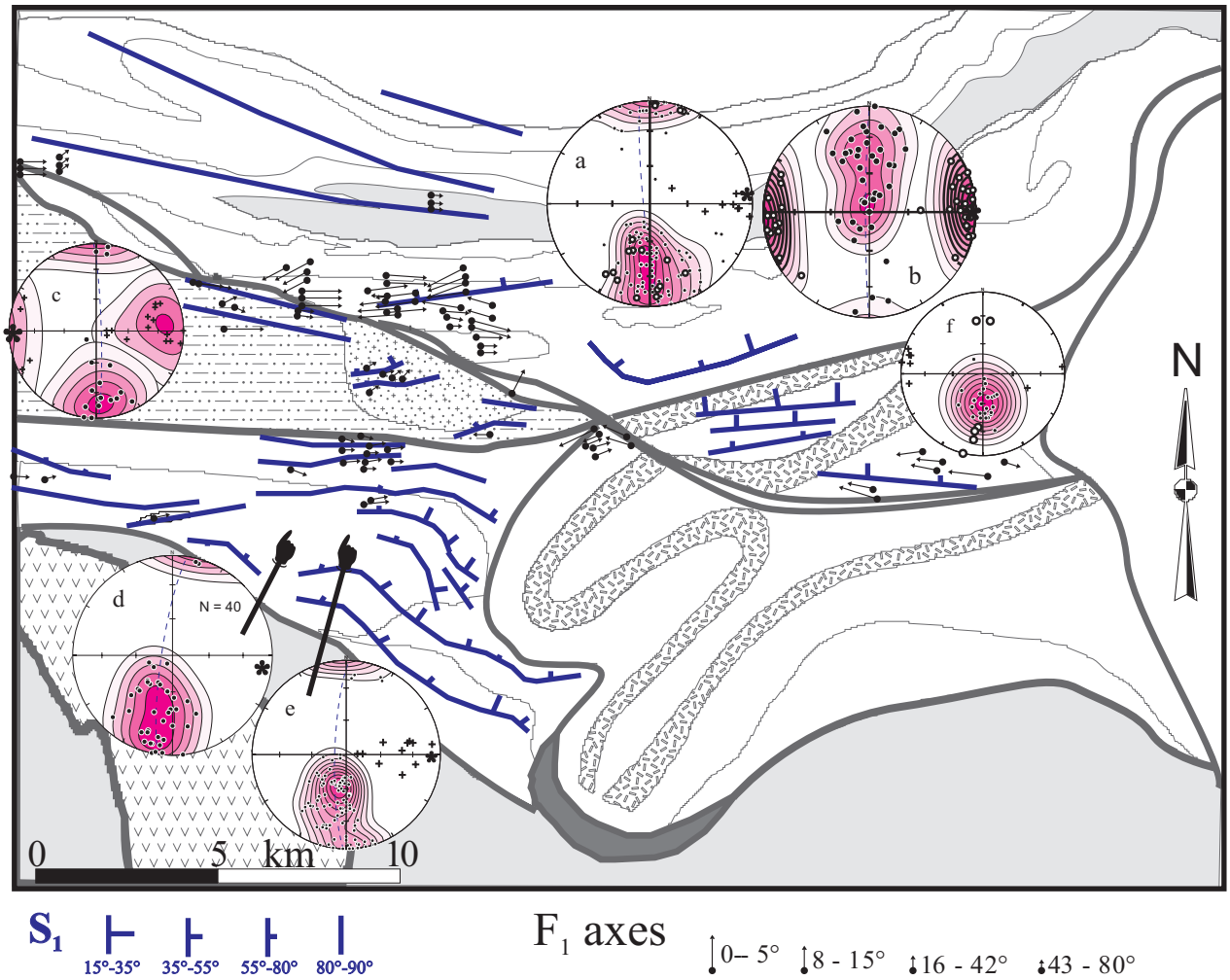


Figure 7. Map of S_1 foliation trajectories and F_1 axes in the Sodankylä area with stereonet inserts depicting various D_1 structures within their respective domains. All fabrics are plotted on lower hemisphere equal-area stereonets, and all contours are drawn at 2σ intervals. Girdle and cluster percentages are calculated according to Vollmer (1989). Measurements within 500 metres of the main faults were not included. Net (a) Oratunturi thrust sheet: Contoured poles to moderately N-dipping S_1 foliation (dots, N=105) form a 56% cluster at 356°/63° (dip direction/dip for all planar measurements). They define a weak 24% girdle giving an F_{1a} axis (asterix) at 84°/5°. Poles to S_0 (open circles, N=18) define a 71% cluster centred at 11°/68° showing that bedding has been transposed parallel to S_1. Shallowly E-plunging S_0/S_1 intersection lineations (crosses, N=9) form a 78% cluster at 91°/23° showing near coaxiality between F_1 and F_{1a}. Net (b) Oratunturi thrust sheet: Contoured poles to S_{1a} foliation and F_{1a} crenulation axial planes (dots, N=49) define a 48% F_{1b} girdle plunging 90°/2° (asterix). Contoured S_0/S_{1a} intersection lineations, and F_{1a} crenulation axes (open circles, N=42) form a 81% cluster at 85°/3° suggesting that these schists have experienced at least three generations of folding along subparallel shallow E-plunging axes (compare to net a). Net (c) Orajärvi block: Contoured poles to steeply N-dipping S_1 (dots, N=18) form a 67% cluster at 357°/72°. They define a weak 24% girdle giving an F_{1a} axis (asterix) at 269°/5°. Shallowly E-plunging S_0/S_1 intersection lineations (crosses, N=20) are weakly 47% clustered about 85°/22° showing near coaxiality between F_1 and F_{1a}. Net (d) Martinvaara thrust sheet: Contoured poles to steeply N-dipping bedding form a 61% cluster at 12°/70° and define a weak 26% F_1 girdle plunging shallowly to the east at 98°/9° (asterix). Net (e) western part of the Martinvaara thrust sheet: Contoured poles to shallowly N-dipping S_1 (dots, N=98) form a 57% cluster at 14°/28°. They define a weak 33% girdle giving a shallow E-plunging F_{1a} axis at 92°/10°(asterix). More steeply plunging S_0/S_1 intersection lineations (crosses, N=11) form a 74% cluster at 86°/41°. Net (f) Rahkavaara domain: Contoured poles to shallowly N-dipping S_1 and F_1 axial planes (dots, N=28) form a 86% cluster at 356°/29° in schistose layers of the upper Ellitsanvaara Formation. Poles to S_{1a} and F_{1a} axial planes (open circles) are similarly oriented. F_{1a} axes (crosses) plunge shallowly westwards forming an 81% cluster.

large-scale F_2 folding was accompanied by the formation of a subvertical, NE-trending axial planar S_2 crenulation cleavage and weak schistosity which was progressively folded upon itself at all scales during continued compression in a manner similar to D_1 in the Oratunturi thrust sheet (Figs 10g, 11). This produced macroscopic F_{2a} folds with axes parallel to F_2 axes and a fanning S_{2a} axial planar cleavage (Fig. 10). Locally this S_{2a} axial planar cleavage was folded again into similarly oriented F_{2b} folds (Fig. 10g).

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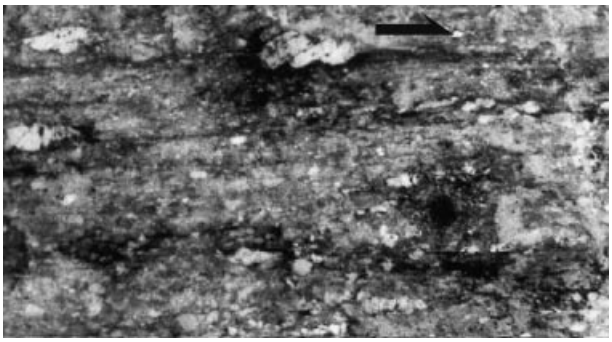


Figure 8. Fractured and dextrally rotated feldspar from a mylonite in the Ellitsa fault. Outcrop surface is perpendicular to foliation and parallel to lineation. Width of view is 6.8 cm.



Figure 9. Folding of S_{1b} in schists of the upper Ellitsanvaara Formation in the Oratunturi thrust sheet. The fold axis is subparallel to F_1, F_{1a} and F_{1b}. Hammer head is 15 cm long.

In the eastern part of the Orajärvi block a later, steep NE-trending S_0/S_2 axial planar cleavage intersection lineation marks the axes of a large (5 km wavelength) shallowly NE-plunging syncline/anticline pair (Figs 2, 10d). In the eastern Martinvaara thrust sheet a later NE-trending, shallowly plunging crenulation accompanied by a well-developed, shallowly NE-plunging lineation, overprints the earlier E–W fabric (Fig. 10e). Here the Orakoski and Ellitsanvaara formations are folded into a shallowly NE-plunging syncline/anticline pair (Fig. 2). Bedding in the Rahkavaara domain strikes NE and is folded around horizontal, NE-trending anticlinal/synclinal F_2 axes (Figs 2, 10f). Pebbles from volcanic conglomerates in the Leviäaapa thrust sheet underwent D_2 deformation and are stretched in a shallow NE-plunging direction (Fig. 10j). Shallowly NE-plunging F_2 crenulations occur locally in the Oratunturi thrust sheet (Figs 10a, 12).

The D_2 event occurred after intrusion of the folded, 2060 ± 2 Ma (Patchett *et al.* 1981) gabbro sill and before deposition of the undeformed < 1860 Ma Kumpu Group (Hanski *et al.* 2000) that unconformably overlies all of the rocks in the Kittilä area. However, the < 1860 Ma (Hanski *et al.* 2000) Lainio Group (75 km to the west of the area) is folded in a similar manner and orientation, therefore D_2 could be very young. Tectonic analyses based on geophysics from the Sattasvaara area to the northwest inferred a late NW–SE compressional stage (Lehtonen*et al.* 1998; Airo, 1999) in the region possibly related to southeastward thrusting of the Kittilä Greenstone Belt. This late compressional stage may have been responsible for the formation of D_2 structures in the Sodankylä area.

5.d. D_3 late NW-trending folds and sinistral faults

D_3 is represented by the major Rahkavaara fault, several minor NW-trending faults and local, NW-plunging, open folds. Kinematics of the NW-trending Rahkavaara fault have been derived from measuring its sinistral displacement (2–3 km) of the gabbro sill on either side of it (Fig. 2). The presence of asymmetric, S-crenulations near the fault confirms its sinistral nature. The western half of the Oratunturi fault was reactivated by the Rahkavaara fault to form a broad NW-trending zone characterized by the presence of scapolite. In the Ellitsa thrust sheet, bedding is locally transposed near smaller, NW-trending faults cutting the gabbro sill in the nose of the southern syncline (Figs 2, 10i). Late, moderately NW-plunging, open F_3 folds are found locally in the Oratunturi thrust sheet (Fig. 10c), while F_2 fold axes are warped about a shallowly NW-plunging F_3 axis (Fig. 10h). Sinistral NW-trending faults are known to displace *c.* 1.8 Ga intrusions throughout Lapland (Korsman *et al.* 1997) indicating that D_3 is a relatively late event.

6. Metamorphism

Schists in the upper part of the Ellitsanvaara Formation supply the only useful metamorphic mineral assemblages in the area. The assemblages present in the schists are chlorite–muscovite ± andalusite ± chloritoid ± staurolite ± kyanite. Chloritoids represent the only pre-tectonic porphyroblasts in the schists. They are found as subhedral crystals with abundant opaque inclusions. The crystals are surrounded and replaced by chlorite to form millimetre-sized round porphyroblasts. S_1 foliation defined by chlorite and muscovite wraps around these porphyroblasts attesting to their pre-tectonic nature (Fig. 13). Large, up to 5 cm randomly oriented, euhedral to subhedral, andalusite porphyroblasts overgrow both S_1 foliation and F_2 crenulations suggesting andalusite growth occurred after the main deformation events (Fig. 14). These andalusite porphyroblasts may contain euhedral to subhedral inclusions of both staurolite and

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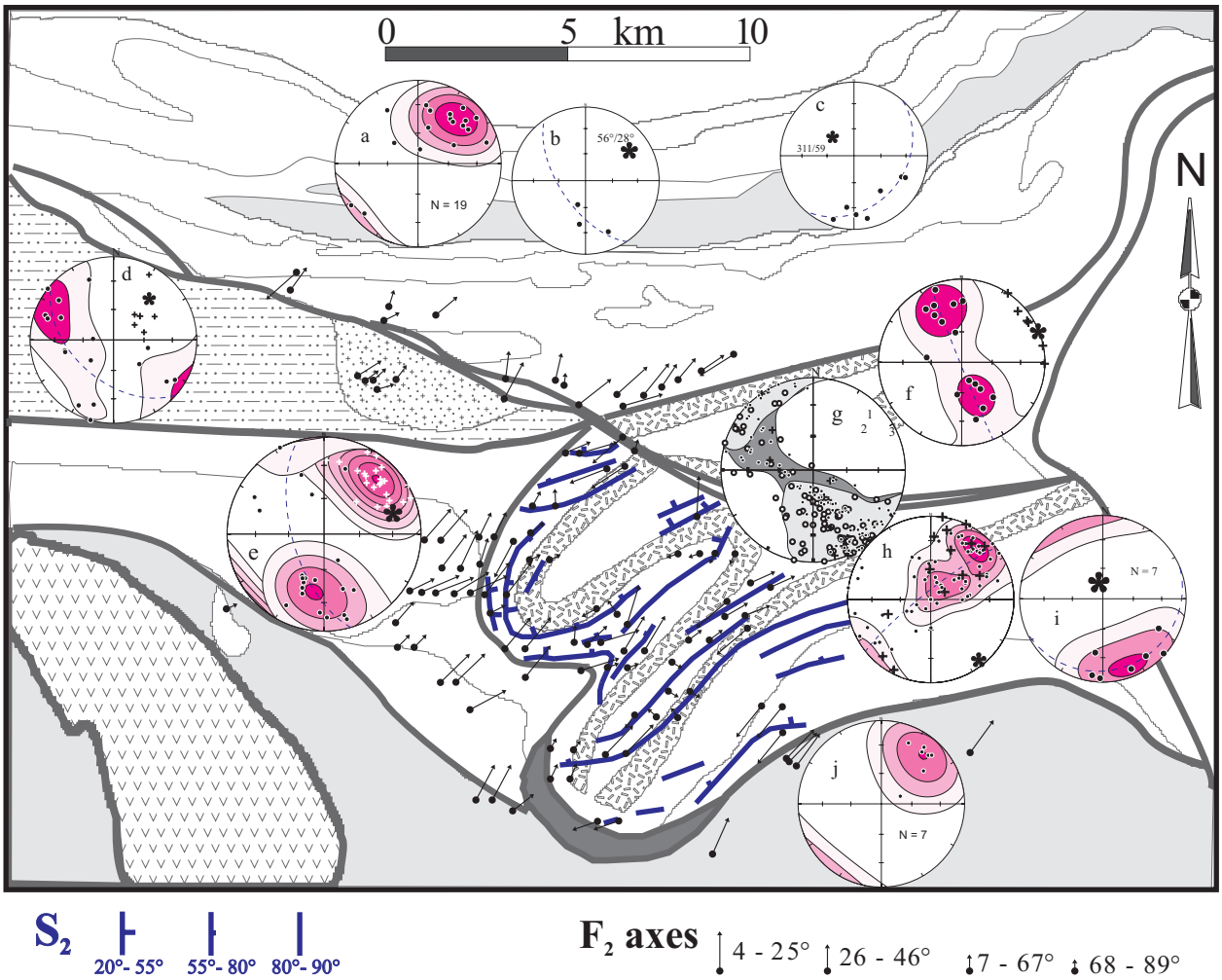


Figure 10. Map of S_2 foliation trajectories and F_2 axes in the Sodankylä area with stereonet inserts depicting various D_2 structures within their respective domains. All fabrics are plotted on lower hemisphere equal-area stereonets. All contours drawn at 2σ intervals. Girdle and cluster percentages calculated according to Vollmer (1989). Measurements within 500 metres of the main faults were not included. Net (a) Oratunturi thrust sheet: Contoured F_2 crenulation axial plane/S_1 intersection lineations and F_2 axes form a NE-plunging 44% cluster at 38°/34°, Net (b) Poles to S_1 (N=3) from a single outcrop in the Oratunturi thrust sheet define a NE-plunging F_2 girdle (asterisk). Net (c) Poles to S_1 (N=6) from another outcrop in the Oratunturi thrust sheet yielded a moderately NW-plunging F_3 girdle (asterisk). Net (d) eastern Orajärvi block: Poles to bedding (dots, N=17) define a weak, 40% NE-plunging F_2 girdle at 40°/42° for the Orajärvi syncline. S_0/S_2 intersection lineations and mesoscopic F_2 axes (crosses, N=6) also plunge moderately to the NE to form a 79% cluster at 49°/53°. Net (e) Martinvaara thrust sheet: Contoured poles to moderately NW-dipping S_2 foliation and F_2 axial planes (dots, N=21) form a weak 38% cluster at 10°/50° and a weak F_{2a} girdle plunging NE at 74°/27°(asterisk). Contoured S_0/S_2 intersection lineations (crosses, N= 26) also plunge shallowly NE forming a 73% cluster at 43°/27°. Net (f) Rahkavaara domain: Contoured poles to bedding (dots, N=16) clearly form a F_2 girdle plunging shallowly NE at 68°/1° (asterisk) with measurement clusters on the fold limbs. Contoured S_0/S_2 intersection lineations and mesoscopic F_2 axes (crosses, N= 6) also plunge shallowly in the NE quadrant forming a 73% cluster at 61°/5°. Net (g) Ellitsa thrust sheet: Contoured (dark grey) poles to bedding (dots, N=79) define a 56% girdle whose pole (marked 1) represents the shallow NE plunge 47°/20°of the major folds' F_2 axes. Contoured (light grey) poles to S_2 (open circles, N=91) also define a reasonable 38% girdle with a similarly plunging 45°/30° F_{2a} axis (marked 2). Poles to F_{2a} axial planes and crenulation axial planes (crosses, N=13) also define a girdle (55%) with a NE 64°/5° plunging F_{2b} axis (marked 3). The similarity between calculated fold axes 1–3 suggests all of the structures plotted were due to the same progressive event. Net (h) Ellitsa thrust sheet: Contoured mesoscopic F_2 axes and S_0/S_2 intersection lineations (dots, N=65) define a subvertical 42% girdle with a shallowly SE 142°/8° plunging F_3 pole (asterisk). F_{2a} mesoscopic and crenulation axes (crosses, N=14) are distributed in a similar manner. Net (i) Tight folding adjacent to late D_3 faults in the Ellitsa thrust sheet is characterized by steeply NW 337°/75° plunging axes (N=7). Net (j) Leviäaapa thrust sheet: Pebbles from a volcanic conglomerate display a strong (80% cluster), shallow NE 41°/24° plunging D_2 stretching lineation.

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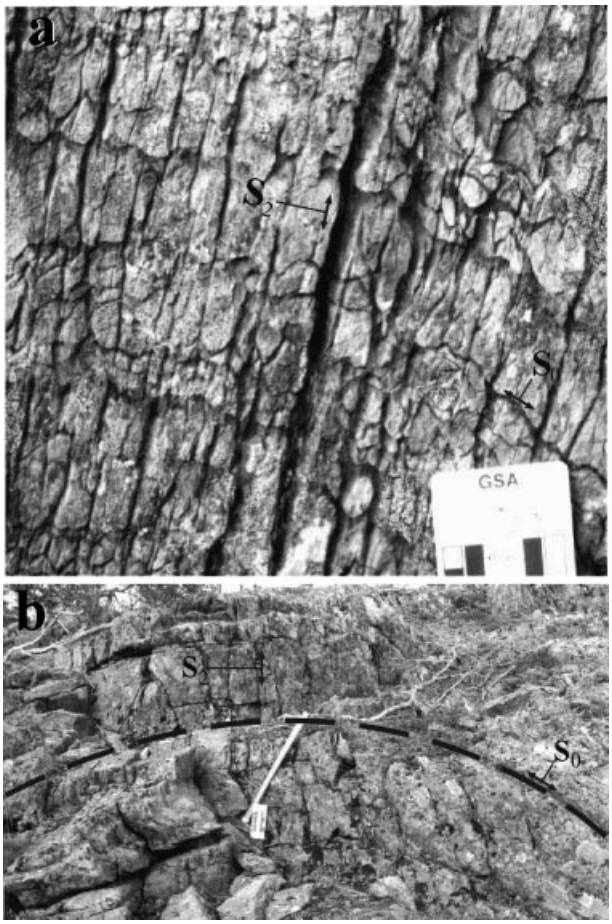


Figure 11. Relationships between S_0 and S_2 in the Ellitsa thrust sheet. (a) Spaced S_2 cleavage cutting S_0 in the centre of an anticline. Width of view is 28 cm. (b) Vertical S_2 cutting warped S_0 from a nearby locality. Note that S_2 (left of the hammer) is warped along an axis subparallel to F_2. Hammer head is 15 cm long.

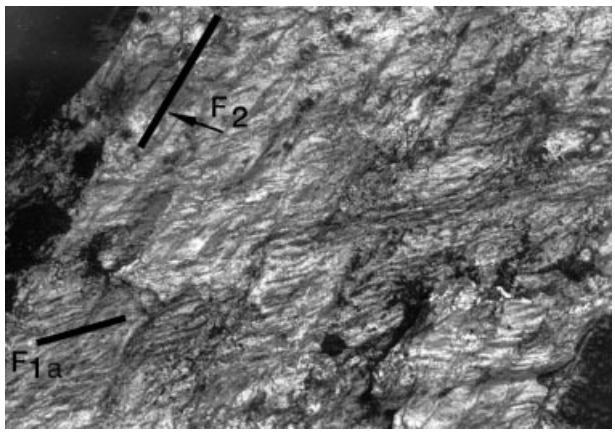


Figure 12. Multi-crenulated schist from the upper Ellitsanvaara Formation in the Oratunturi thrust sheet. Spaced, NE-trending F_2 crenulation axial planes intersect the F_{1a} crenulated S_1 surface. Width of view is 10 cm.

kyanite. When viewed separately both staurolite and kyanite are randomly oriented and appear to overgrow both S_1 and F_2 crenulations suggesting their growth also occurred after the main deformation events. Textural equilibrium between kyanite, staurolite and andalusite in these rocks constrains metamorphic conditions to 4.5 to 7 kbar = 17–26 km depth and 530–660 °C (M. Rask, unpub. M.Sc. thesis, Univ. Helsinki, 1978). Detailed metamorphic studies on similar schists northeast of the area determined the following prograde metamorphic sequence: kyanite to staurolite to andalusite at the expense of kyanite (M. Rask, unpub. M.Sc. thesis, Univ. Helsinki, 1978). These metamorphic assemblages mainly occur in the schists of the Oratunturi thrust sheet to the north with minor occurrences in the Martinvaara thrust sheet and Orajärvi block to the south. The lack of these assemblages in the Ellitsa thrust sheet indicates that the former domains experienced significantly higher temperatures and pressures than the Ellitsa thrust sheet. This discrepancy may be explained by the burial of the Oratunturi thrust sheet, Orajärvi block and Martinvaara thrust sheet by the southward-thinning Ellitsa thrust sheet.

As mentioned earlier, local contact metamorphism from an intruding gabbro produced small millimetre-sized garnets in metasiltstones of the Ellitsanvaara Formation. Late, low-grade metasomatism and metamorphism triggered the growth of scapolite along the western half of the Oratunturi fault and the Rahkavaara fault.

7. Relationship between D_1 and D_2 structures

From Figures 7 and 10 it becomes apparent that the Ellitsa thrust sheet is lacking D_1 structures, whereas the majority of D_2 structures are found in the Ellitsa thrust sheet. Based on the similar deformation styles of progressive folding in D_1 and D_2 and their similar shallow plunges, one might come to the conclusion that the D_2 structures in the Ellitsa thrust sheet are simply anticlockwise-rotated versions of the D_1 structures in the surrounding thrust sheets. However, observations along the Ellitsa thrust fail to provide evidence of any strike-slip movement. Furthermore, folds in the Rahkavaara domain of the Ellitsa thrust sheet are parallel to those in the rest of the Ellitsa thrust sheet, despite being on either side of the only fault (Rahkavaara fault) that could allow rotation of these structures. Overprinting relationships between E–W-trending D_1 fabrics and NE-trending D_2 fabrics in all of the other domains as well as along the Ellitsa thrust are the most conclusive argument for the distinction of D_1 and D_2 events. We interpret the structures in the Ellitsa thrust sheet to represent a later D_2 event based on the following observations: (1) similarly oriented NE-trending crenulations folding D_1 structures in the

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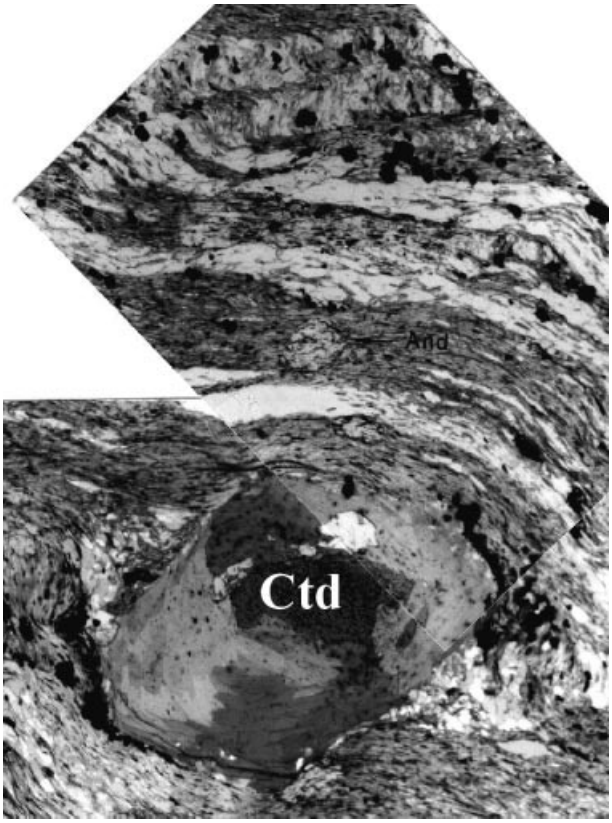


Figure 13. S_1 wraps around a chloritoid-cored chlorite porphyroblast. Note the post-S_1 andalusite porphyroblast and F_2 crenulation near the top. Width of view is *c.* 3 mm.

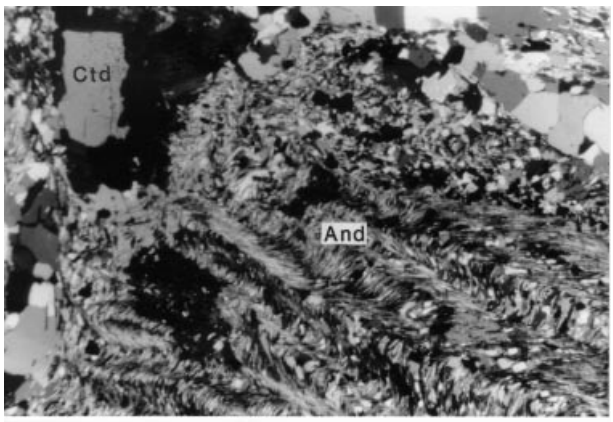


Figure 14. A large andalusite porphyroblast overgrows F_2 crenulation in schist from the Oratunturi thrust sheet. Note the chloritoid porphyroblast to the upper left. Width of view is *c.* 4 mm. Crossed nicols.

other thrust sheets; (2) similarly oriented, NE-trending foliations and folds found elsewhere in the Central Lapland Greenstone belt (Lehtonen *et al.* 1998; Airo, 1999) truncating earlier E–W-trending fabrics (Fig. 1b); (3) later, F_2 folding of the D_1 Ellitsa thrust; and (4) the difference in intensity of tectonic fabric and metamorphism between the Ellitsa thrust sheet (weaker fabric, lower metamorphic grade) and its surroundings (stronger fabrics, higher metamorphic grade).

The question remains as to how the interior of the Ellitsa thrust sheet escaped stronger D_1 deformation seen in the surrounding domains. Tectonic lenses that have escaped deformation are common features on all scales due to deformation partitioning (Andersson *et al.* 1999; Bell, 1985). However, they usually differ rhealogically from their surroundings. Since the Ellitsa thrust sheet is composed of the same lithologies as its surroundings, it is unlikely that it acted as a rigid lens in which a penetrative D_1 fabric could not develop. One explanation for the lack of D_1 structures in the Ellitsa thrust sheet is that it was at the front of the Sodankylä thrust stack, and therefore further from the core of the orogen during the D_1 event. As D_1 progressed, rocks closer to the core of the orogen were more strongly folded and metamorphosed and subsequently emplaced as thrust sheets (Oratunturi and Martinvaara thrust sheets) behind the Ellitsa thrust sheet. On a larger scale, this deformation pattern is manifest as a decrease in metamorphism and deformation intensity from core to foreland across orogenic belts throughout the world. However, the lower degree of deformation and metamorphism in the Ellitsa thrust sheet suggests it was at a higher level than and thrust over the Oratunturi and Martinvaara thrust sheets. The most likely scenario for the structural evolution of the Sodankylä area involves southward thrusting along the Oratunturi and Martinvaara thrusts during early D_1 orogenic thickening. During this stage, the Ellitsa thrust sheet was either (1) passively transported in the upper sections of the Kelujärvi nappe (surfing the nappe) and was emplaced in front of the other thrust sheets during late-D_1 deformation producing a complex thrust duplex similar in style to those of the northern Appenines (Boccaletti & Sani, 1998, figs 10, 11) or (2) later transported from atop the uplifted core of the orogen to the foreland of the orogen via gravitational collapse (e.g. Aerden, 1998). Subsequent D_2 southeastward compression then folded the thrust. Aeromagnetic maps reveal that the major sole thrusts of the Kelujärvi and Pyhätunturi nappes were also folded along N- to NE-trending axes during D_2 and NW axes during D_3 (Fig. 1b).

8. Regional implications

As mentioned earlier, the tectonic evolution of the Central Lapland Greenstone belt is poorly understood in terms of collisional tectonics. The structural observations from the Sodankylä area presented above may be extrapolated across the belt to better understand its internal structure. In Figure 1b, the boundary between the chaotic pattern of magnetic anomalies in the Luirojoki autochthon and E–W-trending belts of Karelian quartzites, schists, and greenstones represents the thrust boundaries of the Kelujärvi and Pyhätunturi nappes. Structural observations in the Sodankylä area

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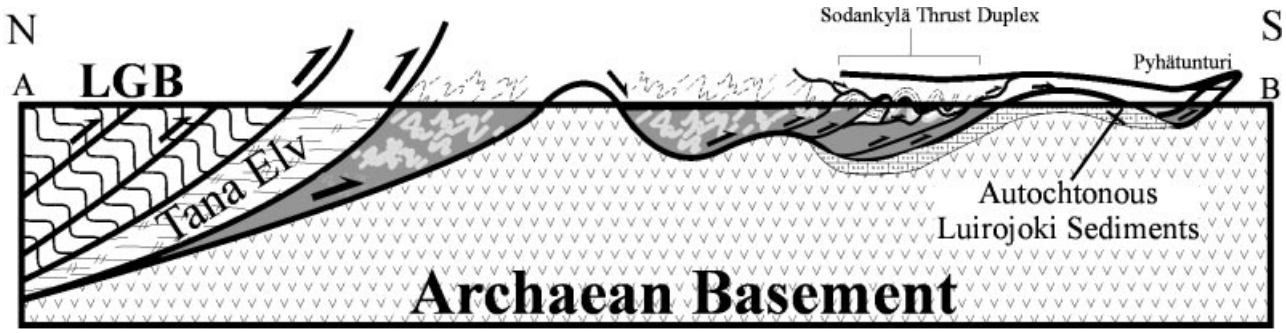


Figure 15. Schematic cross-section along line AB in Figure 1a through the Central Lapland Greenstone belt. Lithological fill-patterns correspond to those labelled in Figure 3.

highlight the role of thrusting within these nappes. During D_1, rocks in this domain were thrust over Luirojoki calc-silicates and Belomorian Archaean basement into their current position as the Kelujärvi nappe to the north, and its southern re-entrant, the Pyhätunturi nappe. The Kumpu Group conglomerates located on the northern side of the Pyhätunturi roof thrust may have been deposited during thrusting to form a thrust-sheet-top-basin (e.g. Evans & Elliot, 1999). This D_1 thrusting is also evident in the N–S-trending continuance of the Central Lapland Greenstone belt known as the Karasjok Greenstone belt. Here, D_1 thrusting was followed by D_2 folding and crenulation along axes oblique to D_1 thrusts (Braathen & Davidsen, 2000). The angular relationship and style of deformation between D_1 and D_2 from the Karasjok Greenstone belt matches those of the Sodankyla area presented above.

A cross-section from the Lapland Granulite belt across the Central Lapland Greenstone belt is presented in Figure 15, combining the structural data from this study and interpretations from the aeromagnetic map in Figure 1b. Here, the belt is depicted as a southward-verging classic foreland fold and thrust belt with the Archaean Inari block and allochthonous Lapland Granulite belt representing the hinterland and orogenic core respectively (an idea originally hypothesized by Sorjonen-Ward (Sorjonen, 1993)). N-verging structures, including the shallowly S-dipping Sirkka Line, have been reported by other researchers along the southwestern border of the Central Lapland Greenstone belt (Berthelsen & Marker, 1986; Sorjonen, 1993; Sorjonen, Nironen & Luukkonen, 1997; Hölttä & Väisänen, 2000). Sorjonen-Ward (Sorjonen, 1993; Sorjonen, Nironen & Luukkonen, 1997) proposed that these, along with the N- to NE-trending folds throughout the Central Lapland Greenstone belt, were formed by interference between deformations caused by the coeval Svecofennian orogeny to the south and the Lapland–Kola orogeny to the north.

The geometry and age of the Cape Smith belt of the Trans-Hudson orogen in northern Canada is strikingly similar to that of the Central Lapland Greenstone belt (compare Fig. 15 to fig. 2 from St-Onge *et al.* 1999). Similarly shaped nappes may also be found in the notably younger Montagne Noire region of the Variscan belt in France (Aerden, 1998). The geometry of the latter was explained by a sequence of crustal thickening via bulk shortening due to deep, listric thrusts. Subsequent transversal collapse with associated gravity thrusts was then followed by a second bulk shortening folding event (Aerden, 1998, fig. 7). This model implies moderate to large orogenic wedge growth (Braathen, Bergh & Maher, 1999). We propose a similar model for the structural evolution of the Central Lapland Greenstone belt.

9. Conclusions

The Central Lapland Greenstone belt can be divided into a number of nappes, two of which are presented here (the Kelujärvi and Pyhätunturi nappes) and one of which has been recognized by earlier researchers (Kittilä nappe: Lehtonen *et al.* 1998). The Sodankylä area represents a complex thrust duplex composed of the Oratunturi, Martinvaara, Ellitsa and Leviäaapa thrust sheets within the Kelujärvi nappe (Figs 2, 15). In the Sodankylä area, an early D_1 schistosity wraps around chloritoid porphyroblasts in mica schists in the northern part of the area. It is axial planar to at least three coaxial generations of southward-verging, sub-horizontal E–W-plunging D_1 folds with wavelengths ranging from 1 km to < 1 cm. This folding accompanied major southwards thrusting marked by metre-scale protomylonitic zones. In the southern part of the area, a relatively thin veneer of lower grade versions of the schists were thrust southwards over the schists during the latter stages of thrusting. This southward compression is related to *c.* 1870 Ma thrusting (Marker, 1988) from the north during the Lapland–Kola orogeny. Southeastward-directed compression (D_2) formed broad, map-scale, upright, NE-trending folds. Staurolite-grade metamorphism represented by post-tectonic andalusite + staurolite + kyanite assemblages occurred after D_2 folding. Later D_3 deformation was limited to local NW-trending folds and faults.

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The Central Lapland Greenstone belt lies directly south of the deeply rooted Lapland Granulite nappe. In view of the fold, thrust and nappe-like internal geometry of the belt, we propose that it represents a foreland fold and thrust belt to the Lapland Granulite belt and Lapland–Kola orogeny.

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