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Basement control of the Caledonian orogen along the Torneträsk section, northern Sweden

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Abstract

The Scandinavian Caledonides are dominated by orogen-parallel and orogen-transverse structures that have the same strike as old fault zones in the basement of the orogenic foreland. The close correspondence of the rhombohedral fault pattern in the Proterozoic basement with lithologic, structural, and metamorphic discontinuities in the Caledonian nappes suggests that reactivated fault zones in the basement played a major role in the structural evolution of the Scandinavian Caledonides. The orogen-parallel trend is defined by two discontinuous chains of large basement culminations (e.g., Rombak-Sjangeli, Nasafjäll, and Grong-Olden), which are terminated to the north and south against orogen-transverse fault zones.

The NW–SE striking Torneträsk Mega-Lineament (TML) in northern Sweden is one of these orogen-transverse fault zones in the basement. Geologic sections on the northern and southern shore of Lake Torneträsk, parallel to the southeastward directed Caledonian thrusting, differ significantly in occurrence and behavior of the various tectonostratigraphic units. For instance, to the south of TML, the basement is intensely imbricated to form a huge antiformal stack, now exposed in the Rombak-Sjangeli basement culmination, and the thrust sheets of the Lower Allochthon are voluminous. In contrast, to the north of TML, the much smaller Kuollejokk window is much closer to the erosional thrust front and the rest of the Lower Allochthon units are only little developed. Similar lithologic differences persist also in tectonostratigraphically higher units, where sandstone-dominated units with rifting-related mafic dikes are voluminous on one side of orogen-transverse fault zones in the basement, whereas they are absent on the other side. Such lithologic contrasts in corresponding tectonostratigraphic units on different sides of orogen-transverse disturbances are often also associated with contrasting styles of deformation and differing metamorphic evolution.

Keywords: Scandinavian Caledonides, basement culmination, basement fault, tectonic evolution, Torneträsk, Sweden.

Introduction

The Scandinavian part of the Caledonian orogen forms an almost 1800 km long mountain belt along the western margin of the Baltic craton (Fig. 1, inset). The Caledonian nappes were thrust in late Silurian / early Devonian times in a piggyback style southeastwards onto the margin of the former continent Baltica. An often underestimated aspect of the interpretation of the Caledonian orogeny is the behavior of the basement during all phases of the Caledonian diastrophism. For instance, the interaction of the lower nappes with the underlying basement has been strongly disputed since the early geological investigations of the Scandinavian Caledonides (TÖRNEBOHM, 1901; HOLMQUIST, 1903). Among the extreme positions were those of KULLING (e.g., 1964) and ASKLUND (1938). Kulling advocated an immobile basement and considered the basement culminations (Fig. 1: Rombak-Sjangeli, Nasafjäll, Grong-Olden) as autochthonous. Thrusts described by KAUTSKY and TEGENGREN (1952) were thought by Kulling to be only of local importance. Such an immobile basement would have required very large amounts of thrusting for the various

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nappes: palinspastic reconstructions on this basis indicate that the Lower Allochthon, which is exposed at the erosional thrust front, would have to be thrust at least 100 km onto the foreland. Tectonostratigraphic higher units require increasingly larger amounts of thrusting. GEE (1975) and BJÖRKLUND (1989) suggested 500 km of thrusting for the upper tectonostratigraphic units. In contrast, ASKLUND (1938, 1946) considered the basement windows (Fig. 1) to be highly imbricated sections of the Baltic Shield that became involved in the Caledonian orogeny. ASKLUND (1938) claimed considerable thrust movements underneath the present erosional level in the tectonic Grong-Olden Culmination (see Fig. 4 in ASKLUND, 1951) and assumed a similar situation for the Rombak-Sjangeli Window (ASKLUND, 1946). Assuming an allochthonous character of the basement culminations yields minimum thrusting distances for the Lower Allochthon of about 50 km, i.e., about half the amount required by an immobile basement. The model of an immobile basement with thrusting up to 100 km for the Lower Allochthon came, however, to dominate (e.g., KULLING, 1964; GEE and ZACHRISSON, 1979). Subsequently, the Caledonian orogen was widely considered to be a typical example of a thin-skinned orogen (e.g., ANDRESEN, 1985).

The basement windows form topographic highs and expose Proterozoic granitoids and supracrustal rocks. These culminations were interpreted as passive domes of the basement due to the gravitational instability caused by the thrusting of the Caledonian nappes onto a less dense granite-dominated basement (RAMBERG, 1980). In recent years, however, detailed field work (e.g., LINDQVIST, 1987; BAX, 1984, 1986, 1989) confirmed former field evidence in favor of a mobile basement (HOLMQUIST, 1903; VOGT, 1922) and added new evidence, mainly from the Nasafjäll, Rombak-Sjangeli, and Kuokkel basement culminations (Fig. 1), for large scale basement mobilization. Recent vibroseismic investigations in the Central Scandinavian Caledonides also provide evidence for a Caledonian imbricated and mobile basement (HURICH et al., 1989; PALM et al., 1991). The basement culminations are now interpreted as antiformal stacks that formed during the final stages of crustal shortening, when the continental blocks of Baltica and Laurentia collided (e.g., BAX, 1989; HURICH et al., 1989; PALM et al., 1991).

We present data from the Torneträsk area (Figs 1 and 2) and show that the basement blocks north and south of the Torneträsk Mega-Lineament (TML) had different histories during the Caledonian orogeny. South of Lake Torneträsk, the basement became intensely imbricated and forms a large duplex, whereas the corresponding basement segment north of the TML was little involved in the Caledonian crustal shortening. Tectonostratigraphically corresponding nappes on both sides of TML differ in their lithologic, metamorphic and deformational record. We argue that old structural features in the basement controlled the tectonic evolution of the Caledonides in the Torneträsk area as well as the Caledonian orogenic belt as a whole.

The Caledonides of northern Scandinavia

The Caledonian nappe pile is divided into four major tectonostratigraphic units (GEE and ZACHRISSON, 1979): Lower, Middle, Upper, and Uppermost Allochthon. These four major units occur all along the orogen. Nevertheless, they do not represent lithologically and petrologically continuous thrust sheets. Instead, they are along the strike of the orogen variably developed. The various units are on some segments very voluminous and on the adjacent segments only poorly developed or absent. All units consist of lithologically and metamorphically distinct assemblages that often form internally imbricated nappe complexes, which show significant lateral variation in thickness and have an overall tendency to become thinner towards the hinterland. The tectonostratigraphic subdivision is mainly based on lithological and metamorphic criteria, but the repetition of partly similar basement-cover relationships in units of the Lower and Middle Allochthon makes it in many cases almost impossible to assign a mapped association to a specific tectonostratigraphic level. In areas dominated by quartzofeldspatic mineral assemblages, where metamorphic index minerals are lacking, only detailed mapping on a regional scale can help to differentiate between nappe units.

The Lower and Middle Allochthon include basement gneisses which are overlain by arkoses, sandstones, siltstones, graphitic schists, and greywackes, which are probably to be correlated with autochthonous Vendian to early Cambrian shelf deposits (Dividal Group), mainly preserved adjacent to and underneath the nappe pile. The rocks of the Lower and Middle Allochthon units are derived from the former margin of Baltica. In contrast, the Upper and Uppermost Allochthon consist of rocks that mostly formed outboard from the continent Baltica (Iapetus ocean and Laurentian margin). The Upper Allochthon consists of medium to high-grade schists, amphibolites, and migmatitic gneisses (Seve Nappes) overlain by a low-grade sedimentary sequence and volcanic rocks of arc affinity (Zachrisson, 1973). In several places the Seve Nappes include low-grade sedimentary successions that are intruded by rifting-related dolerite dikes. The Uppermost Allochthon units are again of continent-marginal provenance and show Laurentian affinity.

Metamorphic grade increases from the basement though the Lower and Middle Allochthon to reach a maximum in the Upper Allochthon (Bryhni and Andréasson, 1985). It is generally assumed that the time of peak metamorphism also varies in the different units. Units of the Upper Allochthon reached metamorphic peak conditions before ca 460 Ma (most data fall in the range 480 to 510 Ma, see Dallmeyer et al., 1985; Mørk et al., 1988; Sturt and Roberts, 1991), whereas metamorphic and thrusting ages in the Lower and Middle Allochthon fall in the range of 400 to 430 Ma (e.g., Claesson, 1987; Page, 1993). However, new U–Pb data from monazites from the Seve nappe (Upper Allochthon) fall in the range 435–440 Ma (Gromet et al., 1993) and lend no support to the published higher ages that were interpreted to demonstrate Early Ordovician ("Finnmarkian") tectonothermal activity (Sjöström and Bergman, 1994). The geographic distribution of metamorphic grade requires that the thrusting occurred in a piggy-back style (e.g., Bax, 1986, 1989; Kathol, 1989; Page, 1993), after peak metamorphic conditions.

Proterozoic basement of northern Sweden

The Palaeoproterozoic basement of northern Finland, Sweden and Norway consists of four major tectonic areas (Fig. 1, inset). The northern and northeastern part of the Baltic Shield is dominated by Archaean rocks (A in Fig. 1). 1.9–1.8 Ga old rocks of the Svecofennian region (Fig. 1, inset: SF, T), including island arc volcanic suites separated by sedimentary basins, were accreted to the Archaean craton and subsequently intruded by voluminous granitoids. Granitoids in the arcs and in the destroyed basins each have a bimodal distribution of age and chemical character. Those with magmatic arc affinity are 1.89–1.87 Ga old, whereas granites younger than ca 1.875 Ga have a distinctly more mature chemical composition (Skiöld et al., 1993). The granitoids that intruded the former sedimentary basins were crustal melts that formed after the crustal thickening. They followed arc accretion and continental collision and range in northern Sweden from 1800 to 1780 Ma in age (Romer and Smeds, 1994). The border between the Svecofennian domain and the Archaean craton is defined to the east by the Raahe-Ladoga zone (e.g., Vaasjoki and Sakko, 1988), a major crustal-scale strike-slip shear zone. Westwards, this border becomes increasingly less well defined, as geological, geochemical, and geophysical arguments used to define the border yield diverging results. In Sweden, the northernmost definition of the Archaean-Proterozoic boundary (e.g., Pharao and Pearce, 1984) reaches the Caledonides in the Torneträsk area (see Fig. 1). The southernmost definition is based on the similarity of volcanic rocks and massive sulfide deposits along the Raahe-Ladoga Line and in the Skellefte district (e.g., Guggisberg and Berthelsen, 1987). This boundary reaches the Caledonides in the Arjeplog area (Hornavan Lineament, Fig. 1). Another definition of the boundary between the Svecofennian domain and the Archaean area (inset Fig. 1: PKZ) that is based on gravity and geochemistry (e.g., Öhlander et al., 1993) falls between these two estimates. The westward widening zone between the two extreme estimates of the Archaean-Svecofennian boundary is treated here as a transitional zone, consisting of Proterozoic rocks with southward decreasing influence of Archaean crustal components (see Öhlander et al., 1987; Skiöld and Öhlander, 1989). These three estimates of the position of the paleo-margin of the Archaean craton coincide with major northwest-striking fracture zones. The projection of these zones into the Caledonides shows that two of them coincide with the margins of the major basement culminations (Fig. 1). The northern border of the transition zone coincides with the northern margin of the Rombak-Sjangeli culmination, i.e., the Torneträsk Mega-Lineament, whereas the southern border of the transition zone aligns with the northern margin of the Nasafjäll basement culmination (Fig. 1).

The three major crustal segments of the basement in northern Scandinavia, i.e., the Archaean crust, the transition zone, and the Svecofennian magmatic arcs, are to the west intruded by the north-south striking ca 1.70–1.79 Ga Transscandinavian Igneous Belt (TIB), which in part is concealed beneath the Caledonides (Fig. 1, inset). The geographic extent of TIB rocks is inferred from aeromagnetic correlation (Eriksson and Henkel, 1983) and is confirmed by geochronologic work (Johansson, 1988; Romer et al., 1992). The TIB rocks have a similar bimodality in age and geochemical character as the arc-related granitoids in the Svecofennian domain. However, TIB rocks are in average 50–100 Ma younger than geochemically corresponding Svecofennian rocks: Older TIB granitoids fall in the age range

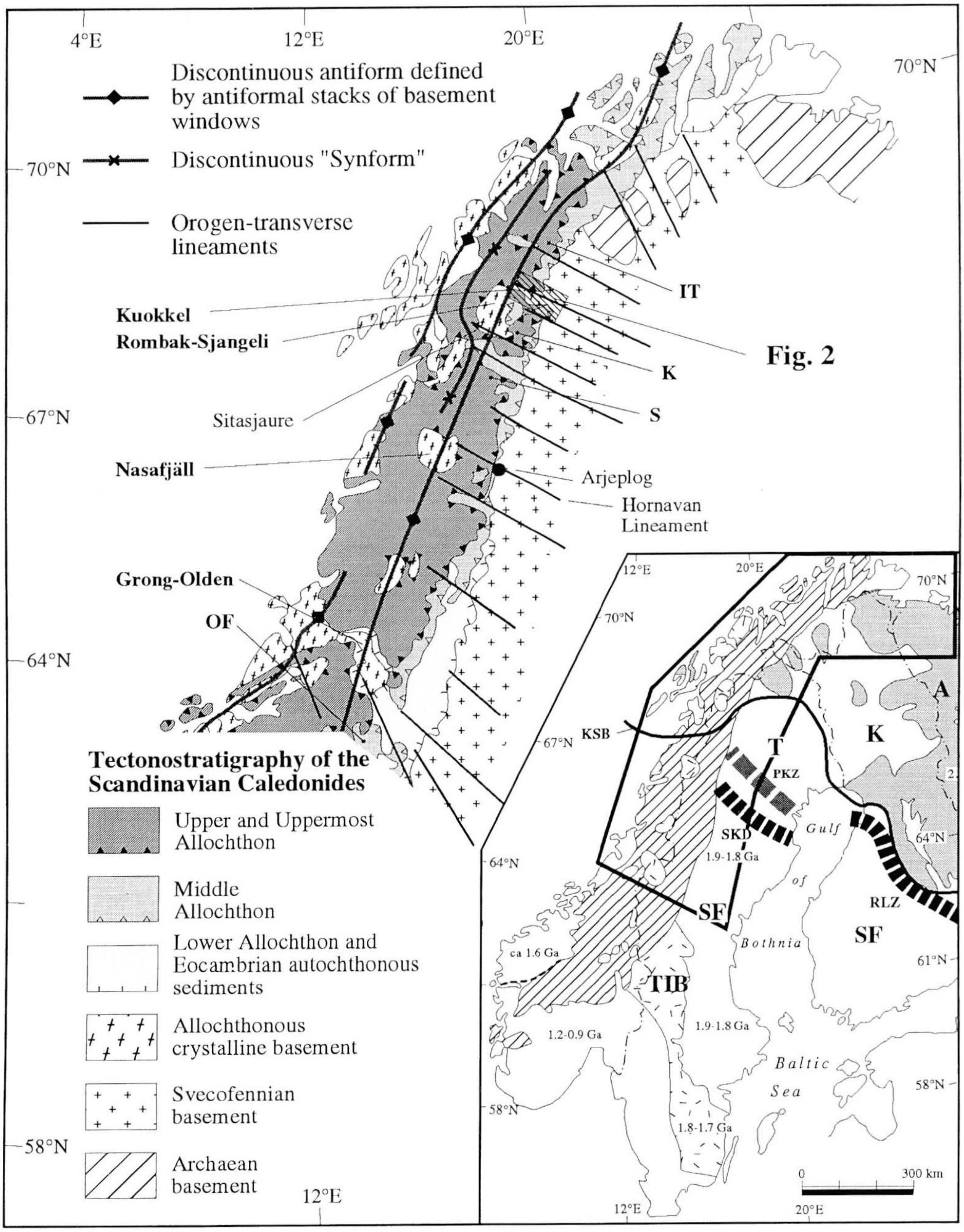

Fig. 1 Tectonostratigraphic map of the Caledonides of northern Scandinavia (after ROBERTS and GEE, 1985). Orogen transverse lineaments in the Proterozoic basement to the east of the Caledonides from HENKEL (1991) and aeromagnetic and geologic maps published at the Geological Survey of Sweden. Orogen-parallel antiforms and synforms after VOGT (1922) and RAMBERG (1980). Mafic dikes swarms in Caledonian nappes: IT = Indre Troms, K = Kebnekaise, OF = Ottfjäll, S = Sarek. Inset: Tectonic map of the Baltic Shield showing the geographic distribution of the Archaean basement (A) and its cover (K = Karelian), Palaeoproterozoic magmatic arc and sedimentary rocks (SF = Svecofennian), the westward widening transition zone (T) between them, and the Transscandinavian Igneous Belt (TIB). Suggested positions of Archaean-Proterozoic palaeoboundary: KSB (PHARAO and PEARCE, 1984), SKD and RLZ (GUGGISBERG and BERTHELSEN, 1987), and PKZ (ÖHLANDER et al., 1993).

1.79–1.76 Ga and younger ones fall in the range 1.73–1.70 Ga (ROMER et al., 1992).

The nature of the Torneträsk Mega-Lineament (TML)

The Torneträsk valley follows a major steeply dipping anastomosing shear zone of Precambrian age (ROMER and BAX, 1992). This broad zone of crustal weakness, here called Torneträsk Mega-Lineament (TML), is thought to have played an important role in the structural evolution of the area both before and during the Caledonian orogeny. Probably the most important parts of this dislocation zone are covered by the approximately 70 km long Lake Torneträsk (Fig. 2), which fills a WNW–ESE striking topographic depression and consists of several smaller basins, reaching its maximum depth (168 m = 173 m a.s.l.) in the central parts of the large sub-basin north of Abisko (EKMAN, 1957). The various basins are flanked by fault zones of which several branches have mapped on land, such as SE of Stordalen (LINDSTRÖM et al., 1985) or along the southwestern margin of the peninsula Pieskenjar-

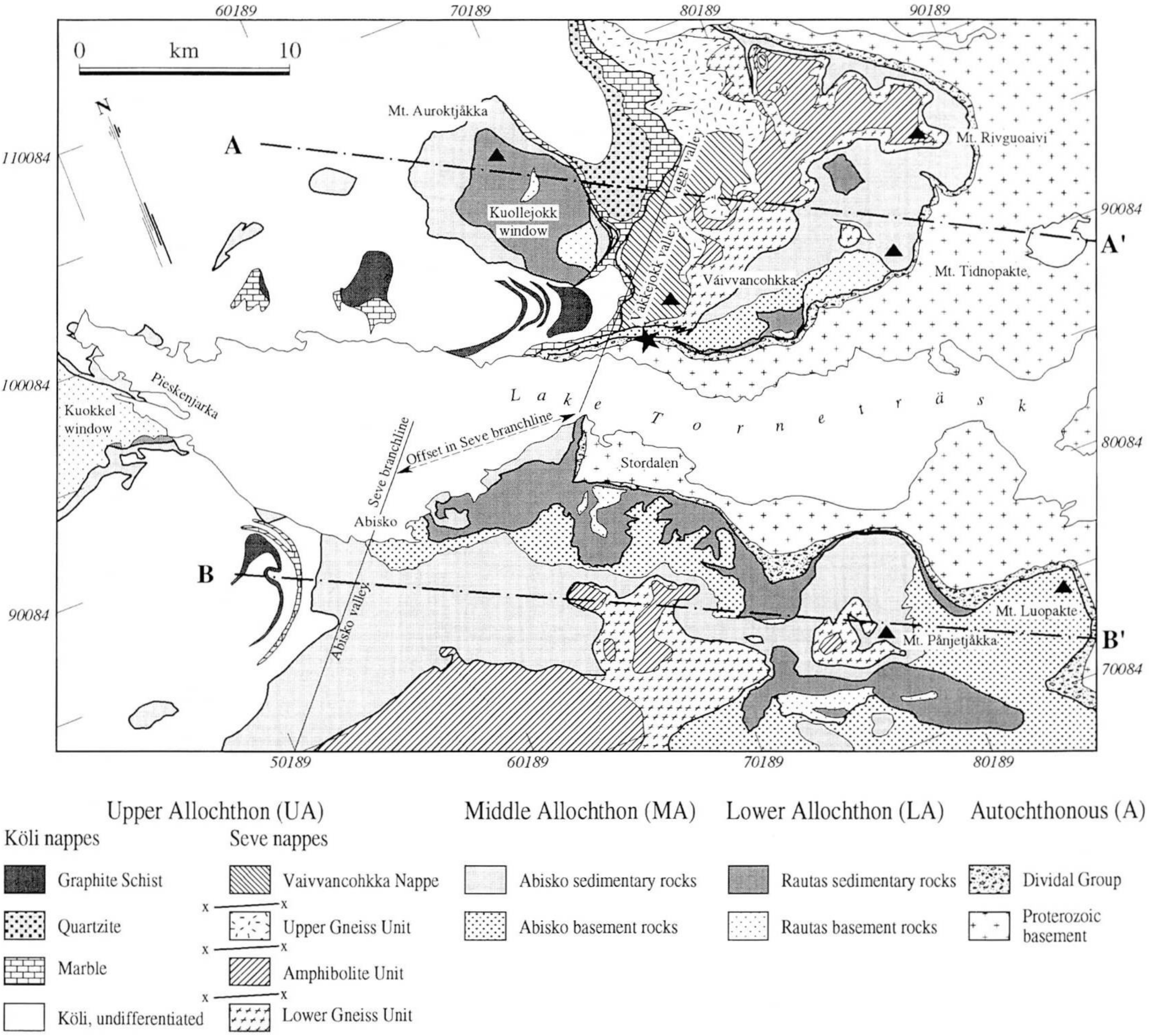

Fig. 2 Geology of the central parts of the Torneträsk area. Note the geological differences between the northern and southern shore of Lake Torneträsk covering TML. Compiled from LINDSTRÖM et al. (1985), BAX (1984, 1989), KATHOL (1985, 1990), and LINDSTRÖM (1987). The displacement of the Seve unit branchline along the TML is marked. Asterisk on northern shore of Lake Torneträsk marks occurrence of Vakkejokk breccia in the autochthonous basement cover.

ka (Gieb, 1986). In both cases a dextral strike slip component dominates (Fig. 2).

The northwestward continuation of the Pieskenjarka fault and the TML do not offset the nappe pile. Late-Caledonian shearing and thrusting slightly oblique to the strike of the Pieskenjarka fault and the TML has obliterated most structural evidence for a Caledonian activity of these faults. However, a continuation of the TML farther to the NW is required by abrupt lateral lithologic changes in nappes and basement cover that indicate movements along these faults before the final phases of thrusting. Such changes occur even in the far travelled upper nappe units (see below), which supposedly had formed outboard of the old continent Baltica.

Dividal group and Caledonian nappes along the Torneträsk section

The distribution of major geological units in the Torneträsk area is illustrated in figure 2. Not all units that were mapped during detailed field work are shown here. Instead, special attention is given to units that show significant differences on either side of the Torneträsk Mega-Lineament (TML). Many of these differences are even visible as changes of roughness in the terrain along the profiles north and south of TML (Fig. 3). The topography of the Torneträsk area is dominated by two main lineament trends. The first set of topographic lineaments is represented by the NW–SE-striking TML and smaller subparallel lineaments, all of which are composed of several shorter, slightly differently oriented segments, which results in an anastomosing appearance of the lineament. The variability of directions is illustrated by the trends of the shorelines of Lake Torneträsk (Fig. 2) and minor lakes nearby. Examples for different lineament attitudes are the southeastern shore of Pieskenjarka peninsula and the shoreline of Lake Torneträsk along the Kuokkel window (Fig. 2). The second set of topographic lineaments includes NNE-striking zones that coincide with valleys and the eastward termination of the various nappes, such as at Vaggi valley (Fig. 2). These NNE-striking lineaments show distinct offsets along the NW-striking lineaments, suggesting that the thrust sheet fronts and fault zones do not continue undisturbed across the latter. Mobility of the NW-striking lineaments, such as the TML, is also indicated by contrasting lithologies that reflect lateral changes of sedimentary environments in the autochthonous Dividal Group and in the Lower Allochthon (in the Torneträsk area: Rautas Complex).

DIVIDAL GROUP (AUTOCHTHONOUS ROCKS)

The Dividal Group, which rests with depositional contact on the Proterozoic basement, reaches a maximum thickness of about 190 m (Fricke, 1984) in some parts of the area. In its lower part, Vendian basal conglomerates and arkoses dominate. These terrigenous sediments are overlain by an alternating succession of sandstones and shales. Locally, even the very distinctive Middle Cambrian Alum Shale, which occurs in the upper part of this succession, is preserved. This nonmetamorphic succession becomes thinner towards the west, where often only the basal conglomerate is preserved underneath the floor-thrust of the Lower Allochthon. Earlier workers mainly focussed on the similarities of the stratigraphic sequence in the Dividal Group and correlated the various units along the orogen (Vogt, 1922, 1967; Føyn, 1967; Thelander, 1982). Variations in thickness and facies, the occurrence of channels, basal conglomerates, and regoliths, however, reflect the locally highly variable depositional environment of the terrigenous sediments and to some extent the palaeotopography of the sub-Cambrian peneplane. Locally, very restricted breccias, such as the Vakkejokk breccia (Stodt, 1987), which includes blocks in meter size (Kulling, 1964), occur. However, these cannot have originated from lateral and local variations of the depositional environment on a stable continental platform. The Vakkejokk breccia (Kulling, 1930, 1960) reaches significant thickness north of the TML (asterisk in Fig. 2), whereas correlative units are insignificant or absent to the south of the TML. The Vakkejokk breccia is interpreted as a mass-flow deposit related to fault movements in the basement (Stodt, 1987) and indicates block movements during the deposition of the Dividal Group in Vendian time. Furthermore, the topographic position of the base of the Dividal Group is different north and south of the TML. On both sides, this surface dips gently (< 1°) to the NW. This horizon is situated at a higher level on the northern side of the TML and, therefore, it reaches the level of Lake Torneträsk farther to the NW than would be expected if this horizon continued undisrupted across Lake Torneträsk. Such offsets in the sub-Cambrian peneplane occur also on a local scale (Ljugner, 1943), as for instance in the Laisvall area (ca 300 km south of the Torneträsk area).

RAUTAS COMPLEX (LOWER ALLOCHTHON)

The Rautas Complex consists of Palaeoproterozoic granitoids and their sedimentary cover.

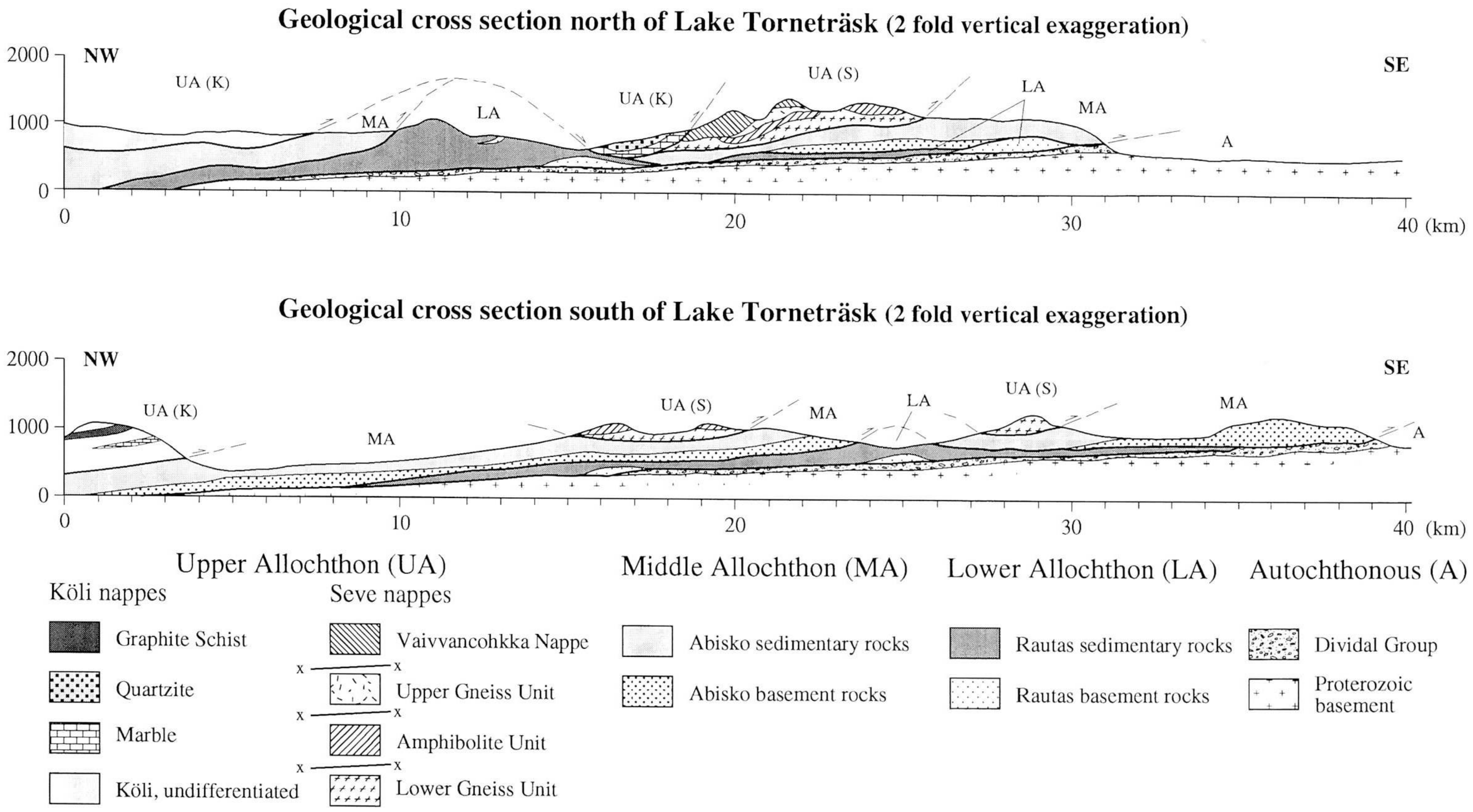

Fig. 3 Geological profiles north and south of Lake Torneträsk. Both profiles run parallel to TML, and hence are more or less parallel to the main thrusting direction. Double vertical exaggeration. Same geological subdivision as in figure 2.

These rocks were intensely deformed during the southeastward thrusting. Rocks derived from crystalline basement are imbricated and the various segments are separated from each other by a thin veneer of their former (Late Vendian to Early Cambrian) sedimentary cover. Volume and lithology of former basement rocks and their sedimentary successions in the Rautas Complex differ to both sides of the TML (Fig. 3). Textural and structural contrasts, however, are in part erased by intense deformation during Late Caledonian thrusting.

The Lower Allochthon south of Lake Torneträsk (Rautas Complex) mainly consists of intensely folded sedimentary rocks that lithostratigraphically resemble the underlying autochthonous succession of the Dividal Group (LINDSTRÖM et al., 1985). Slices of monzonites and granites, derived from the Proterozoic (Precambrian) basement, occur in the lower part of the Rautas Complex. For instance south of Stordalen (Fig. 2), they occur as up to 250 m thick blocks that are separated by deformed sedimentary sequences. The base of these blocks is cut by the essentially smooth sole thrust of the Lower Allochthon (LINDSTRÖM et al., 1985). The crystalline rocks display cataclastic, gneissose, and blastomylonitic fabrics that are interpreted as Caledonian (Lindström et al., 1985).

North of Lake Torneträsk no monzonites were found (KAMLAGE-OLGUN, 1987; KATHOL, 1987, 1989). The granites are less deformed than their southern counterparts. They are often massive to thickly parted and the original granoblastic texture is well preserved. According to the classification scheme of HIGGINS (1971), they are microbreccias. The crystalline rocks of the Lower Allochthon form a ca 200 m thick antiformal stack close to the Caledonian thrust front (Fig. 3). This stack contains a strongly deformed slab of Palaeoproterozoic calcite-bearing pelitic schists (KATHOL, 1989), which are not known from the southern side of Lake Torneträsk, and it is directly overlain by rocks of the Middle Allochthon (Figs 2 and 3). Sedimentary rocks of the Lower Allochthon occur as a relatively thin veneer mainly to the northwest of the crystalline antiformal stack.

Both, the roof and the sole thrust of this part of the Lower Allochthon do not reach the level of Lake Torneträsk, and the branchline is situated ca 12 km to the east of the area where the roof thrust of the corresponding southern part of the Lower Allochthon reaches the level of Lake Torneträsk (ca 2 km ENE of Abisko).

About 5 km north of the TML and to the west of Vaggi valley (Fig. 2), the Rautas Complex forms a large antiformal stack exposed in the Kuollejokk window (MASLOWSKI, 1985; NEUHAUS, 1985; JUNK, 1987). This antiformal stack involves large slices of dolomite. The Rautas Complex in the Kuollejokk window reaches an elevation of 1157 m a.s.l. (Mt. Auroktjåkka [Ávrukvárri]), which is significantly higher than the level reached by the roof thrust of this unit to the south of Lake Torneträsk. Several kilometers towards the hinterland, above the thickest parts of the Rombak-Sjangeli antiformal stack, this nappe boundary reaches altitudes higher than 2000 m.

ABISKO NAPPE COMPLEX
(MIDDLE ALLOCHTHON)

The Abisko Nappe Complex (Fig. 2) consists of mylonitic Precambrian basement rocks overlain by strongly foliated, quartz-rich tectonites (hard schists or hårdskiffer; PETTERSEN, 1878). The distinctive floor thrust of the Abisko Nappe Complex was considered to be the "main thrust boundary" of the region by KULLING (1964). The contact between the Abisko Nappe Complex and the Upper Allochthon generally is not well defined as both tectonic units have similar lithologies. The two units differ, however, in tectonic fabric and metamorphic grade, which increases from biotite grade in the Abisko rocks to garnet or higher grade in the Seve rocks of the Upper Allochthon (KULLING, 1964). South of the TML, the roof thrust of the Abisko Nappe Complex reaches the level of Lake Torneträsk 3 km NW of Abisko, which is 10 km west of the correlative structural feature north of the TML (Fig. 2).

The whole Abisko Nappe Complex shows signs of intense shearing. Basement-derived mylonites to the south of Lake Torneträsk often form massive rocks that lack foliation and in many cases even lineation (LINDSTRÖM et al., 1985), whereas to the north of Lake Torneträsk, they show an anastomosing pattern of fine grained cataclasites (nomenclature after SIBSON, 1977) which surround coarser grained protomylonites to mylonites (nomenclature after HIGGINS, 1971), often showing relic igneous textures (KATHOL, 1989). Sedimentary protoliths in the upper part of the Abisko Nappe Complex are mostly strongly foliated and tectonically banded (hard schists) to the south of TML, whereas corresponding rocks to the north include both tectonically banded and homogeneous quartzitic rocks that generally are thickly parted (KATHOL, 1989). Furthermore, the quartzitic tectonites to the north do not overlie the basement-derived rocks (Fig. 3). Instead, they occur to the east of the basement-derived rocks (KATHOL, 1989).

South of the TML, the basement-cover sequence of the Abisko Nappe is tectonically duplicated around Mount Pånjetjåkka (Fig. 2; LINDSTRÖM et al., 1985). At Luopakte, the Abisko Nappe Complex is thrust over rocks of the Lower Allochthon (Rautas Complex). In contrast, north of TML, there is no tectonic duplication of the Abisko basement-cover sequence and the front of the floor thrust at Tidnopakte represents the sole thrust of the allochthonous units (KULLING, 1964; KATHOL, 1989), i.e., the Lower Allochthon is absent (Fig. 3).

SEVE AND KÖLI NAPPES (UPPER ALLOCHTHON)

The Seve-Köli Nappe Complex consists of a series of medium- to high-grade schists, amphibolites and migmatitic gneisses (Seve Nappes) tectonically overlain by the low-grade volcano-sedimentary sequence of the Köli Nappes (ZACHRISSON, 1973).

Seve Nappes. North of Lake Torneträsk, Seve rocks occur between Vaggi valley and the Caledonian thrust front at Mt. Rivguoaivi (Fig. 2). To the west, the Seve rocks are drastically thinned and either dip under rocks of the Köli Nappes or wedge out against rocks of the Lower and Middle Allochthon, which are exposed in the Kuollejokk window. The Seve rocks in this area are divided into four different thrust sheets (KATHOL, 1989). From below, these consist of psammitic to pelitic gneisses and schists (Lower Gneiss Unit), foliated amphibolites (Amphibolite Unit), psammitic to pelitic gneisses and schists containing retrograded eclogites (Upper Gneiss Unit), and dolerite-intruded psammites, pelites, and calc-silicates (Váivvancohkka Nappe).

Metamorphic grades within the lower three units increase stepwise to medium amphibolite facies at most within the Upper Gneiss Unit. In contrast, the Váivvancohkka Nappe only shows low-grade regional metamorphism. It is suggested that the lower three units were telescoped during an early Caledonian subduction at the outer margin of the continent Baltica, whereas the Váivvancohkka Nappe escaped early Caledonian subduction and high-pressure metamorphism (KATHOL, 1989).

Rocks corresponding to the Váivvancohkka Nappe and the eclogite-bearing gneisses are not known from south of Lake Torneträsk (Figs 2 and 3). The roof thrust of the Seve Nappes is situated within or on top of amphibolites that could correspond to the Amphibolite Unit from north of Lake Torneträsk (Fig. 3). The NNE–SSW striking Seve branchline (see ZACHRISSON, 1973; HOSSACK, 1983) shows a displacement of more than 12 km along the TML (Fig. 2).

Köli Nappes. The Köli Nappes include graphitic schists, marbles, phyllites, and mica schists. North of TML, there occurs additionally a succession of quartzites that is up to 140 m thick. The eastern limit of the Köli Nappes is approximately parallel to Vaggi valley (north) and Abisko valley (south). This results in an offset of the present eastern limit of the Köli Nappes of ca 12 km along the TML.

Results of the basement mobilization during the Caledonian orogeny

CRUSTAL THINNING DURING THE IAPETUS OPENING

The Vendian sediments, which form the Dividal Group and which were deposited at the margin of the Baltoscandian continent, show contrasting facies on different tectonic segments. The sediments are psammitic and conglomerate-dominated in some areas, whereas they are more pelitic in others. These differences reflect either topographic irregularities in the deeply eroded Baltic Shield or contrasting subsidence histories on adjacent crustal segments. Local debris flows indicate an unstable relief, which could originate from vertical movements along reactivated fault zones (STODT, 1987). Similarly, slump structures in shaley sandstones at Laisvall (GRIP, 1954) might reflect water-expulsion related to tectonic reactivation of old faults in the basement. The variable development of sedimentary sequences is also preserved in the Caledonian nappes of the Lower and Middle Allochthon. However, facies and thickness changes are generally difficult to demonstrate because of Caledonian deformation and metamorphism.

Clastic continent-marginal sediments, intruded by mafic dike swarms, are preserved in Upper Allochthon units. The mafic dikes have the same trace element patterns as rifting-related tholeiites (KATHOL, 1989) and they probably mark the former margin of the Baltic Shield (ANDRÉASSON, 1987; STØLEN, 1989). The dikes, which presumably were originally parallel to the two sets of old fault zones in the Proterozoic basement, are preserved only on a few segments. For instance, the Váivvancohkka Nappe to the north of Lake Torneträsk contains a clastic sequence, which is intruded by dolerite dikes, which almost completely escaped Caledonian metamorphism. In contrast, mafic dike swarms in Upper Allochthon units from the Kebnekaise and Sarek areas (SVENNINGSEN, 1987; ANDRÉASSON and GEE, 1989; Fig. 1) were metamorphosed under amphibolite facies conditions. The patchy preservation of these rifting-related mafic dikes and their contrasting metamorphism suggest that they formed at different positions along the margin of continent Baltica and that they later became differently involved into the Caledonian orogeny. The discontinuous distribution of mafic dikes along the margin of the Baltic Shield requires active faults in the basement. The rifting-related mafic dikes (e.g., Ottfjäll, Sarek, Torneträsk, Indre Troms) appear to have different ages in the various areas (see STURT and ROBERTS, 1991), which indicates that the crustal extension was diachronous and that different parts of the rift system were active at different times. The contrasting ages of rifting require that there were movements along the NW–SE striking fault zones within the Caledonian basement.

Reactivation of basement fault zones during crustal thinning, resulting in contrasting sedimentary environments along the margin, is demonstrated by comparison of fault zones in a recent continental margin with fault zones in the adjacent basement. Using detailed seismic stratigraphy in a segment of the Norwegian shelf (between 62°N and 68°N) and remote sensing lineament analysis of the adjacent onshore area, AANSTAD et al. (1993) demonstrated that faults confining the major plateaus and basins in the shelf have the same orientation as old faults in the crystalline basement onshore. Multiple reactivation of the offshore faults during opening of the Atlantic and the subsidence of the shelf resulted in variable thickness of sediments on adjacent segments as well as erosion (or non-deposition) on fault-bound ridges (AANSTAD et al., 1993). Similar to the inheritance of the structural grain of the basement in the present distribution of sedimentary environments on the Norwegian continental margin, such deep-rooted old basement structures may also have played a major role during the Iapetus opening and the evolution of the continent-marginal sediments now preserved in the Lower and Middle Allochthon of the Caledonides.

CRUSTAL THICKENING DURING CALEDONIAN THRUSTING

The involvement of Baltica basement during the Caledonian compressional phase is demonstrated on a local and regional scale by (1) the presence of Proterozoic basement rocks in the nappe complexes of the Lower and Middle Allochthon, (2) the presence of "rootless" horsts of basement blocks in the Lower Allochthon such as in the Torneträsk area, (3) lateral ramp folds in the thrust sheets (TILKE in BJÖRKLUND, 1989), (4) antiformal stacks of basement rocks in basement culminations (e.g., Rombak-Sjangeli, Nasafjäll, Grong-Olden; Fig. 1), (5) disturbed metamorphic gradients in the Vendian basement cover (e.g., ANDERSON, 1989), and (6) the geographic distribution of mafic dike swarms of the Middle and Upper Allochthon.

In the Torneträsk area, basement mobilization during the Caledonian orogeny occurred mainly along two sets of fault zones striking approximately NNE–SSW and NW–SE. Compressional movements along the NNE–SSW striking fault zones resulted in orogen-parallel horst structures. These horsts were initially sheared off and transported at the base of the Lower Allochthon to the SE. They occur now as isolated blocks of crystalline rocks in the Lower Allochthon. For instance south of Stordalen (Fig. 2), they occur as up to 250 m thick "beheaded" horsts that are separated by troughs, which are filled with sedimentary sequences. The base of these truncated horsts is the essentially smooth sole thrust of the Lower Allochthon (BAX et al., 1991). During the final stage of the collision of the continental masses Baltica and Laurentia, the basement horsts were no longer sheared off. Instead, they built up to antiformal stacks, that now form major basement culminations (BAX, 1989).

The basement culminations align along two orogen-parallel discontinuous chains in the interior of the orogenic belt (VOGT, 1922; RAMBERG, 1980) and they have the same strike direction as the dominant fault zones in the Proterozoic basement to the east of the Caledonides. The positioning of the basement culminations is controlled by old zones of crustal weakness, such as ductile lithologies and old faults, or changes in crustal character in the basement (ROMER and BAX, 1992). The present position of the culmination might correspond to sites where the character of the basement changes. For instance, it is possible that the basement to the east of the culmination was not thinned by the rifting event before the Caledonian orogeny. This segment would then have been more rigid during the collision than the imbricated crust farther to the west. Aeromagnetic correlation (ERIKSSON and HENKEL, 1983) indicates that the basement culminations mainly comprise of rocks from the Transscandinavian Igneous Belt (TIB). Limited geochronologic work support this suggestion (Jarl and Johansson, 1988; Romer et al., 1992). In southern Scandinavia, the TIB is related to a distinct change in crustal thickness (Korja et al., 1993). Such a step in crustal thickness might also have existed farther to the north beneath the present Caledonian orogen.

The basement culminations represent areas where larger volumes of crust were piled up to form duplexes, not present on adjacent blocks. The culminations could reflect areas, where the basal thrust cut deeper into the basement and thus "scooped-out" a larger volume. Alternatively, they may be due to a larger amount of crustal shortening on that segment. As the total amount of crustal shortening is the same on adjacent basement segments, such a locally variable amount of crustal shortening requires that the basement faults at the northern and southern margins of the culminations were tectonically active during the buildup of the culminations. These margins coincide with distinct orogen transverse NW–SE striking valleys that in the basement rocks of the Caledonian foreland coincide with distinct fault zones (compare topographic and magnetic lineament maps, e.g., Henkel, 1991).

Variations of metamorphic grade in correlated nappe complexes to both sides of the orogen-transverse fault zones also require movements along these fault zones. For instance, the Vendian sedimentary cover on the Proterozoic basement has contrasting metamorphic grade north and south of Lake Torneträsk (Anderson, 1989). Similarly, mafic dikes in the Upper Allochthon were metamorphosed to different grades. They were, therefore, lowered to different crustal levels before thrusting over Middle Allochthon rocks. Different metamorphic grades and contrasting depth of burial along the orogen, however, require that the orogen-transverse fault zones in the basement were mobile.

The syn-thrusting and syn-collisional mobilization of the orogen-transverse fault zones are most clearly illustrated by lateral ramp folds in the nappes (e.g., Sitasjaure [Fig. 1], Tilke in Björklund [1989]). The nappe transport was slightly oblique to the orogen-transverse faults. Vertical movements along these faults, therefore, resulted in the truncation of nappe units that became doubled near the fault or in lateral ramp folds in the nappes. Such structures are mainly concentrated to the northern and southern margin of the basement culminations (e.g., Tilke in Björklund [1989]; Bax, 1989).

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