Early Proterozoic (c.2000-1900 Ma) crustal structure of the northeastern Baltic Shield: tectonic division and tectogenesis.

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Recent structural investigations in the Precambrian of northern Finnish Lapland and Norwegian Sørvaranger and their extrapolation into the neighbouring Kola Peninsula have established that the northeastern part of the Baltic Shield can be divided into several tectonic units consisting of Archaean to Early Proterozoic crust. The tectonic units are separated by Early Proterozoic, Svecokarelian linear thrust zones with clear evidence of deep-seated, high ductile strain deformation. From northeast to southwest, the units are: the Murmansk unit, the Sørvaranger unit, the Kola suture belt, the Inari unit, the Granulite belt, and the Tanaelv belt. The structural work combined with recently published petrological and geochronological results provides new evidence for the interpretation of the Svecokarelian crustal structures in the northeastern part of the Baltic Shield in terms of a plate tectonic model. The Kola suture belt is considered to mark the site of a continent-continent collision suture, which was formed by the closure of a former Kola ocean. The metaflysch sequence of the Granulite belt is interpreted as having been deposited in a back-arc basin to the southwest of the Kola ocean. This basin was floored by attenuated, partly oceanized continental crust (now the Tanaelv belt). As a result of the collision between the Sørvaranger and Inari units and the closure of the Kola ocean, the Granulite and Tanaelv belts were thrusted upon the southern foreland.

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Introduction

Recent regional mapping and structural investigations in the Precambrian of northern Finnish Lapland and Norwegian Sørvaranger (Fig. 1) have established that regional thrust tectonics played an important role in both the Archaean and Proterozoic crustal evolution of the northeastern part of the Baltic Shield. Until recently, tectonic studies in this part of the shield have been limited, and apart from early studies in the 1930's, when the southwestward thrusting of the Lapland Granulite belt was recognized (Kranck 1936, Sahama 1936), later investigators have mainly focused on petrological and geochemical subjects. These studies have led to important new results that have stressed the need for renewed tectonic investigations and combined tectonic-petrological analyses. Therefore, when the Polar DSS Profile (executed in August 1985, Fig. 3) of the European Geotraverse Project (EGT) was planned in 1982 (Berthelsen 1982), it was agreed that prepatory structural investigations should be carried out in northern Finnish Lapland and Finnmark in collaboration with colleagues from the Nordkalott project.

On this basis, the present study was initiated in 1983. The investigation has been performed by means of structural mapping (i.e. the mapping of contact relations, linear and planar elements, rock textures, etc.) of key areas selected on the basis of available lithological maps. Along with this, compilatory studies have been carried out by using the new structural information on the lithological maps and combining this with available information from the literature. Early in the investigation it became evident that the mapping of zones of high ductile strain was particularly important in the effort to separate the major tectonic units. Most of these zones are gently dipping, and thus they provide reliable evidence for large-scale displacements of the crustal segments along low-angle thrusts. In addition to being well suited for the separation of tectonic units, the recognition of ductile strain belts is chronologically important because these supply the most reliable information on the main stages in the formation of crustal structures. Some of the thrust belts are difficult to detect using published geological maps because systematic structural investigations have rarely been an integral part of the survey mapping. Therefore, it is essential that systematic strain mapping is also performed as part of the structural investigation so that a tectonic map can be

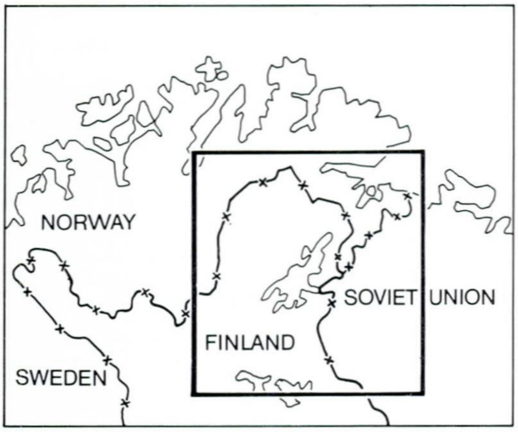

Fig. 1. Location map showing the investigated area. The framed area indicates the limits of Fig. 3.

prepared on a much better basis.

By the methods outlined above, it has been possible to prepare a tectonic map for the region and to establish major tectonic subdivisions of the northeastern part of the Baltic Shield (Figs. 2 and 11). General geological maps from Finland (Meriläinen 1965, Mikkola 1941), Norway (Bugge & Iversen 198å, b) and the Soviet Union (Gorbunov 1980, Kozlovsky 1984) form the basis for the investigation.

The discovery of major thrust belts within the Baltic Shield has led many workers to propose tectonic interpretations for the formation of the Precambrian crustal structures which are very similar to Phanerozoic plate tectonic models. The present work also provides evidence for a plate tectonic interpretation. From the western part of the shield, plate tectonic models have been proposed for the Sveconorwegian mobile belt by Berthelsen (1978, 1980), Falkum & Petersen (1982) and Falkum (1983), and from the Svecokarelian part by Hietanen (1975), Rickard (1979), Gaòal (1982, 1985), Park (1984) and Bowes et al. (1984). Recently, plate tectonic models have also been proposed for the Early Proterozoic evolution of the northeastern part of the shield by Berthelsen (1981, 1984, 1985), Barbey et al. (1984), Berthelsen & Marker (1985) and Krill (1985b, this volume).

Tectonic division

Based on the new structural evidence, the northern Finnish Lapland-Sørvaranger area has been divided into five major NW-SE trending units (cf. Fig. 3) comprising Archaean to Early Proterozoic crust. Each of the tectonic units is separated by and often itself forms part of a zone of high ductile strain which, as discussed later, on the basis of published geochronological evidence, can be shown to be of Early Proterozoic, Svecokarelian age, with one possible exception.

Using this division and field data from the northern Finnish Lapland-Sørvaranger area, the established units have been extended eastwards into the neighbouring Kola Peninsula by Berthelsen & Marker (1985), as shown in Fig. 2. North of what has been denoted the South Lapland-Karelian craton (Barbey et al. 1984) of high-grade Archaean gneisses and low-grade Archaean to Lower Proterozoic greenstone associations, six main tectonic units have been differentiated (Fig. 2). From northeast to southwest, these are: the Murmansk unit, the Sørvaranger unit, the Kola suture belt, the Inari unit, the Granulite belt and the Tanaelv (West Inari Schist zone, Tana river) belt. On the Kola Peninsula (Bylinski et al. 1977), the Murmansk unit corresponds to the Murmansk segment, the Sørvaranger unit to the Central-Kola segment, and the Kola suture belt to the Pechenga-Imandra-Varzuga zone. The trends, both of the southwestern part of the Granulite belt and of the Tanaelv belt, roughly coincide with the trend of the 'Main White Sea deep fault' (Bylinski et al. 1977).

In the following, the general characteristic features of the tectonic units will be described.

The Murmansk and the Sørvaranger units

In the Murmansk and the Sørvaranger units, both the crust and the main crustal structures are of Archaean age. They are separated by a northeast-dipping thrust zone, matching with the Keiv-Porosozero zone on the Kola Peninsula (Bylinski et al. 1977), which most probably is of Late Archaean (or possibly Early Proterozoic?) age as it cuts the older Archaean structures on each side (cf. Gorbunov 1980). An influence of this zone may have caused the high degree of deformation which is observed in the easternmost part of the Jarfjord group at Grense-Jakobselva in Sørvaranger (Bugge & Iversen 1981b).

The Kola suture belt

The Kola suture belt consists of Lower Proterozoic (2400 - 2000 Ma), Jatulian volcano-sedimentary formations of epicontinental to deep-

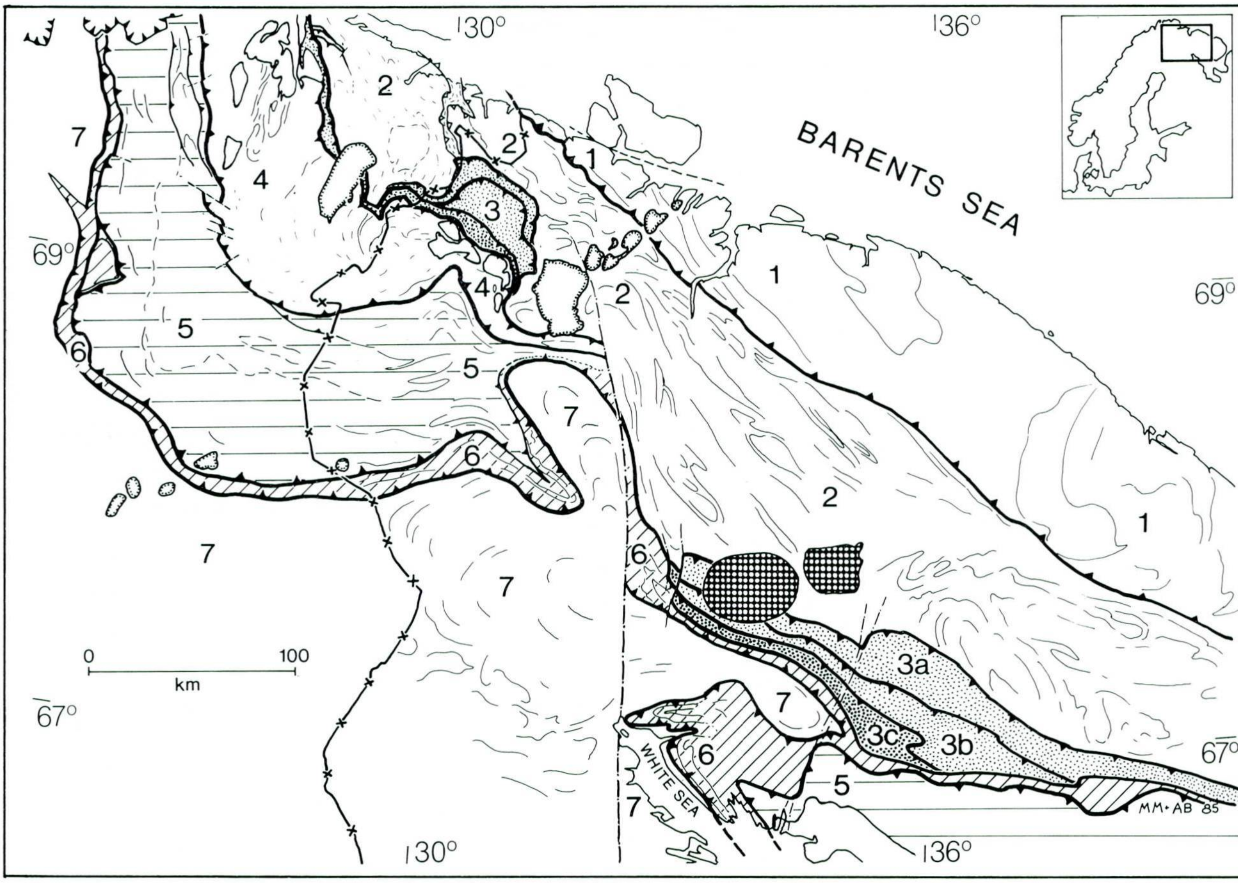

Fig. 2. Tectonic map of the northeastern part of the Baltic Shield with structural trends indicated; based on Berthelsen & Marker (1985). The differentiated tectonic units are: 1: The Murmansk unit; 2: the Sørvaranger unit; 3(dotted): the Kola suture belt with supposed island arc terrain shown by heavy dots (3c); 4: the Inari unit; 5(horizontally ruled): the Granulite belt; 6(obliquely ruled):the Tanaelv belt; 7: the Southern Foreland (South Lapland-Karelia craton). Post-orogenic granites (c. 1790 Ma) are shown with dotted rims. Cross-ruled: Palaeozoic alkaline complex. The Soviet/Finnish/Norwegian international border is indicated by the line with crosses.

-water provenance (Bugge 1980, Negrutsa 1979,, Zagorodnyi 1980), as well as a discontinuous island arc terrain to the southwest. The oldest epicontinental formations and a basal conglomerate lie on the previously deformed Archaean crust of the Sørvaranger unit. In the Kirkenes area, the basal conglomerate (the Neverskrukk conglomerate) overlies the thrust-bounded Archaean Bjørnevatn group (Bugge & Iversen 198å, b), showing that thrust tectonics was prominent even in the formation of Archaean structures within the Sørvaranger unit (Berthelsen 1984). As shown in Fig. 2, the southern Kola suture belt notably contains abundant andesitic volcanic rocks (Zagorodnyi 1980, Gorbunov 1980), and this part of the belt seems to continue into the Pasvik Valley in Norway, where the low-grade southern half of the Petsamo-Pechenga group includes metavolcanites of andesitic affinity (Bugge 1980, Bugge & Iversen 198å).

The Kola suture belt consistently dips in a southwesterly direction, and its contacts clearly cut off older structures of the neighbouring units (Figs. 2 and 7). Further, the contacts are commonly accompanied by broad zones of mylonitic rocks, which together with the highly discordant nature of the boundaries show that thrust tectonics was very important in the tectonic evolution of the belt. The age of the thrusting is Svecokarelian because in Finland the belt is cut by the 1790 Ma old Vainospää granite (Haapala & Front 1985).

The Kola suture belt is considered to contain a major Svecokarelian continent-continent collision suture, which was formed by the closure of a former Kola ocean (Berthelsen 1981, 1985), and the andesitic southern part of the belt is thought to represent the remnants of a primitive island arc, which was formed by early southwestward subduction of Kola oceanic lithosphere (Berthelsen & Marker 1985).

The Inari unit

The Inari unit, which consists of high-grade Archaean crust (Meriläinen 1976), represents a median massif or microcontinent squeezed between the Kola suture belt to the northeast and the Granulite belt to the southwest. The boundary with the Granulite belt is formed by a thrust zone, as is the boundary with the Kola suture belt, which generally dips moderately to the northeast. Part of it is more steeply dipping, as in the southern Inarijärvi area. As shown by the map (Fig. 2), the Inari unit disappears towards the southeast on the Kola Peninsula, where the Kola suture belt and the Granulite/Tanaelv belts are found in contact.

The major structures within the Inari unit were probably formed in the Archaean, and as it appears from the maps (Figs. 2 and 7) their trends are generally north-south with a distinct angle to the boundary thrusts, most convincingly seen towards the Kola suture belt. The northeastern part of the Inari unit is intruded by several calc-alkaline plutons (Barbey et al. 1984) that have been dated at c. 1900-1950 Ma (Meriläinen 1976).

The Granulite Belt

The Granulite belt forms a wide arch of high-grade metasedimentary and meta-igneous gneisses that can be followed from the Caledonian front in Finnmark, through Finnish Lapland, and about 100 kilometres into the Kola Peninsula, where the belt almost disappears (Fig. 2). Along the northern shore of the White Sea, the Granulite belt reappears, again forming a wide belt (cf. Gorbunov 1980), and this configuration can be explained by a complex fold culmination structure in the underlying basement gneisses between the Lapland area and the White Sea (Berthelsen & Marker 1985, and in prep.).

The southwestern border of the Granulite belt is a major thrust zone which dips gently to the northeast, with the direction of thrusting towards the southwest, at right-angles to the general trend of the belt (Kranck 1936, Sahama 1936, von Gaertner 1964). During thrusting, the southwestern part of the Granulite belt itself was transformed into a wide movement zone of highly strained blastomylonites, which during this event acquired a strong penetrative, gently northeastward-dipping, mylonitic foliation (Fig. 3).

As demonstrated by Bernard-Griffiths et al. (1984), the rock sequence which makes up the Granulite belt must be of Early Proterozoic age, and during the Svecokarelian event at about 2000-1900 Ma ago (about 1950 Ma according to Bylinski et al. (1977)), the sequence was metamorphosed into granulite-facies gneisses. The thrusting of the Granulite belt to the southwest most probably occurred closely after about 1900 Ma ago because field evidence demonstrates that the migmatitization of the granulites preceded their mylonitization. Further, in Finnish Lapland the blastomylonites are cut by the c. 1770 Ma old Nattanen granite (Haapala & Front, 1985).

The Tanaelv belt

The Tanaelv belt is another high-grade tectonic unit which dips gently northeastwards below the Granulite belt, forming a comparatively narrow zone along its entire length. It consists of a banded sequence of garnetiferous amphibolites, hornblende gneisses and light quartz-feldspar gneisses, some of which are believed to be derived from mainly tholeiitic magmatic ancestors (Hörmann et al. 1980, Barbey et al. 1980). The Tanaelv belt is further characterized by a large number of small concordant bodies and lenses of metamorphic gabbroic, anorthositic and ultramafic rocks (Mikkola & Sahama 1936, Hörmann et al. 1980, Barbey et al. 1980, Efimov et al. 1977), in addition to a few occurrences of highly aluminous rocks formed at elevated pressures (Haapala et al. 1971). From the Kola Peninsula, eclogite-like rocks have been reported (Bylinski et al. 1977) which probably also belong to the Tanaelv belt. The largest plutonic body found within the belt in Lapland is the Vaskojoki anorthosite (Fig. 3), which has been dated at 1906 Ma (Bernard-Griffiths et al. 1984). The Vaskojoki anorthosite is tectonically emplaced (Barbey et al. 1984), and this is probably also the case with most of the small bodies

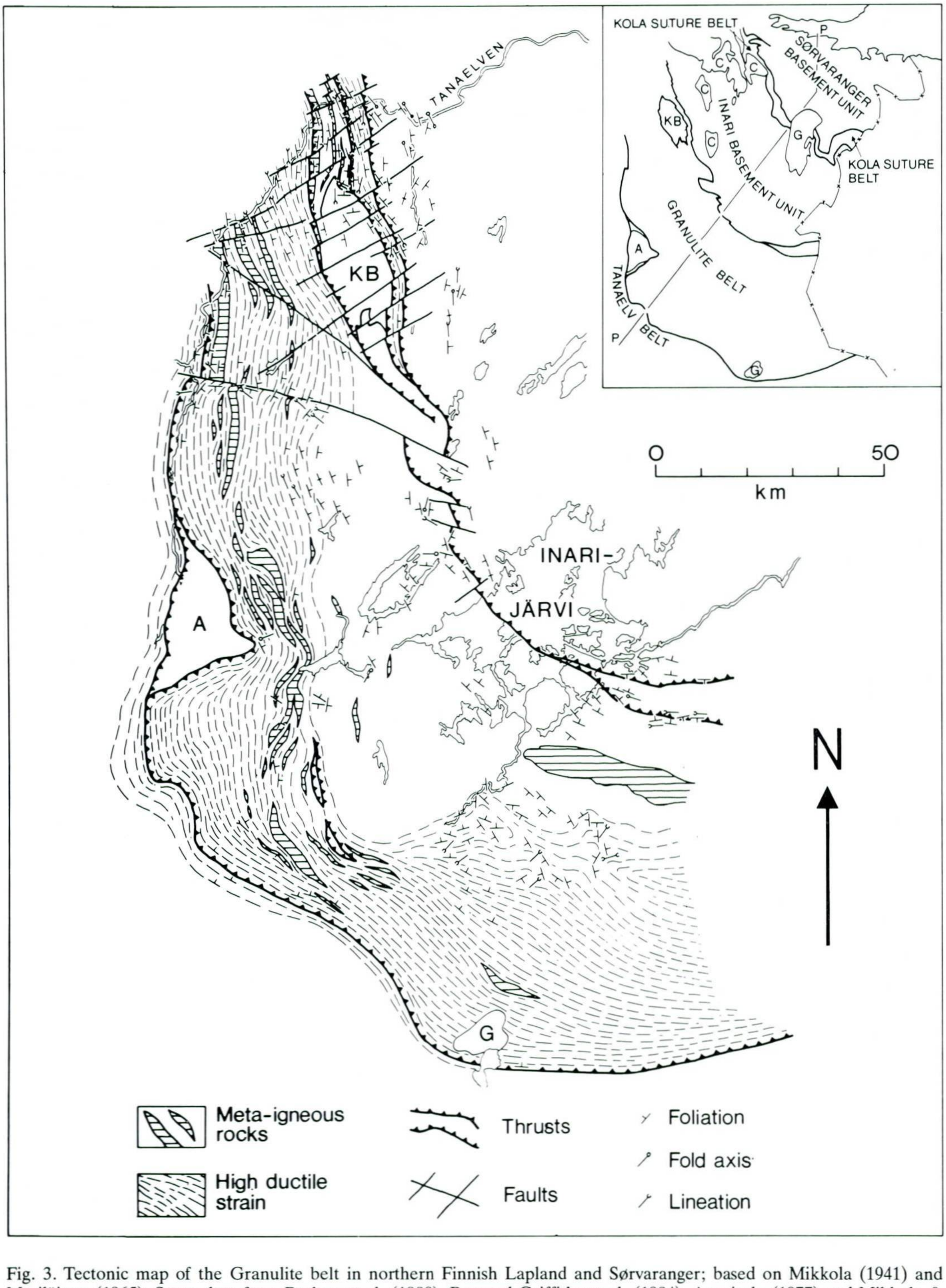

Fig. 3. Tectonic map of the Granulite belt in northern Finnish Lapland and Sørvaranger; based on Mikkola (1941) and Meriläinen (1965). Some data from Barbey et al. (1980), Bernard-Griffiths et al. (1984), Aarnisalo (1977) and Mikkola & Vuorela (1977) have been incorporated. Inset map shows the tectonic division of the northern Finnish Lapland-Sørvaranger area. KB: Kevo basement area; A: Vaskojoki anorthosite; C: calc-alkaline plutons; G: Nattanen-type granites; P-P: Polar Profile. For further explanation see text.

mentioned above, as indicated by the fieldwork to the west of the Granulite belt. The Tanaelv belt is in part metamorphosed under granulite-facies conditions, and shows invertd metamorphic zonation away from the contact with the overlying Granulite belt. This inversion is interpreted as having been caused by the overthrusting of the Granulite belt (Krill 1985, and 1985b this volume).

Tectonically the Tanaelv belt forms a highly strained ductile shear zone, the structural evolution and age of which are comparable to that of the Granulite belt. As in the Granulite belt, migmatitization preceded the shearing. During the ductile shear movements, the rocks of the Tanaelv belt were transformed into a strongly banded sequence in which the original, more irregularly distributed neosomes form an integral part of the penetrative banding (Fig. 4). Reported ages on the rocks from the Tanaelv belt vary from about 1900 Ma (Bernard-Griffiths et al. 1984) to 2360 Ma (Meriläinen 1976), which indicates that apart from Lower Proterozoic intrusives highly strained reworked Archaean gneisses may be an important ingredient of the Belt.

The granulite belt and the Kola Suture Belt in northern Finnish Lapland and Sørvaranger

A more detailed account will now be given on the Granulite belt and the Kola suture belt on the basis of new field data from northern Finnish Lapland and Sørvaranger. Both of these Early Proterozoic belts, the first the most extensive regional thrust belt, the second considered to include a continent-continent collision suture, contain the key structures in the plate tectonic model (cf. Berthelsen & Marker 1985) which will be presented at the end of this paper.

The tectonic setting of the Granulite belt

Lithologically, the Granulite belt consists of a thick, rather homogeneous flysch-like metagreywacke sequence (Khondalite suite of Barbey et al. 1985a) with impersistent layers of orthopyroxene-bearing meta-igneous rocks concentrated in at least two main levels in the tectonostratigraphic sequence (see Fig. 3, and Meriläinen 1976). These meta-igneous rocks have a tholeiitic to calc-alkaline geochemistry (collectively called the Charnockite complex by Barbey et al. 1982b), and they were probably intruded into the metagreywacke sequence at different times, with those of calc-alkaline trends as the latest intrusions (Barbey et al. 1982b). Their intrusive ages fall in the range of 1900-2000 Ma (Bernard-Griffiths et al. 1984). The latest intrusions were probably emplaced more or less contemporaneously with the peak of the granulite-facies metamorphism and the plastic fold deformation of the entire sequence

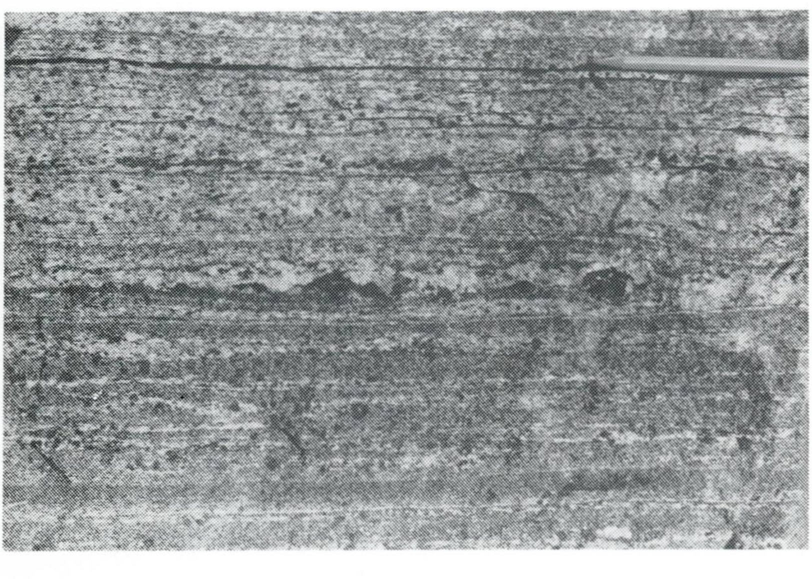

Fig.4. Highly ductile, strained sequence from the Tanaelv belt, with a strong penetrative banding of thin garnetiferous amphibolite bands and sheared noesomes in grey gneiss (6 km N of Karigasniemi, Finland).

(author's unpublished observations).

Only one prolonged metamorphic event is recorded in the Granulite belt (Hörmann et al. 1980, Barbey et al. 1984, Krill 1985a), and by this event the metasedimentary precursors to the granulites were transformed into rather coarse-grained garnet + sillimanite + biotite/garnet + cordierite + sillimanite + biotite-bearing migmatites during prograde metamorphism and gradual dehydration (Krill 1984, author's unpublished observations). The migmatites which make up the northeastern part of the belt show a fairly high degree of melting, and their dominant neosomes are typically diffuse or irregular in shape, often giving the rock a rather granitic appearance. This structure contrasts completely with the structure of the strongly foliated, fine-grained blastomylonites with platy quartz, which make up the western and southwestern part of the Granulite belt.

The distribution of low-strained migmatitic and highly strained blastomylonitic granulites within the Granulite belt are shown on the map (Fig. 3). This distribution roughly coincides with the distribution of cordierite on the map of Meriläinen (1965), in which the cordierite-bearing areas correspond to the low-strained migmatitic area in Fig. 3. An investigation of the border zone between the two texturally defined areas clearly showed that the blastomylonitization everywhere postdates the migmatitization. The irregularly oriented neosomes in the migamtitic granulites are gradually made parallel towards the blastomylonitic zone, and in the transition zone the rock attains a porphyroclastic texture with porphyroclasts of feldspar and garnet. In the blastomylonitic zone, platy quartz appears and finally is dominant in the texture of the rock. At this stage, feldspar porphyroclasts diminish in number and size, cordierite disappears, and the rock acquires a new distinct, planar, mylonitic foliation, mainly defined by platy quartz. Close to the trasition zone, cordierite may still occur, but only within small lenses of previous neosome material. In addition to this general pattern, areas with both lower and higher strain indications may be found within the blastomylonitic zone. Apart from a couple of small-scale rootless intrafolial folds, folds have not been observed in the blastomylonitic zone and, besides a sporadic sillimanite lineation, the platy quartz lineation (rodding) is the only linear fabric element that can be measured in the field.

The meta-igneous granulites show a similar tectono-metamorphic development to that shown by the metasedimentary part of the granulite belt.

The textural evidence clearly establishes that migmatitization predates the thrusting and formation of blastomylonites, and not the inverse, as argued by Hörmann et al. (1980) and Barbey et al. (1984) from petrological considerations. Besides, it is also difficult to understand how water could have percolated into the dry blastomylonites, as suggested by these authors, and subsequently have caused the uniform, high degree of melting which is characteristic of the migmatite zone.

As seen from mineral parageneses,the thrusting of the Granulite belt occurred under granulite-facies conditions, and the absence of cordierite in the blastomylonites is a consequence of higher shear stresses and somewhat higher pressures.

It has already been mentioned in the previous section that the Granulite belt is bordered by thrust contacts on both sides of it. As can be deduced from the map (Fig. 3), the most extensive development of blastomylonites took place in the basal part of the belt during its thrusting to the southwest at about 1900 Ma ago.

The northeastern thrust boundary of the Granulite belt towards the Inari unit basement gneisses is built up somewhat differently and is generally exposed as a rather wide zone of several, parallel or convergent thrusts of more restricted width. These thrusts may be localized both in the Granulite belt and in the Inari unit basement gneisses. In the best exposed northern part of the thrust boundary, exemplified by the Paistunturit area in Finland (Fig. 5), the strongly sheared, platy quartz textured, metasedimentary granulites dip about 45° to the northeast below the basement of the Inari unit. Towards the boundary, the Inari basement gneisses become increasingly sheared, as convincingly shown by the deformation of amphibolite inclusions in the gneisses. At the boundary, these inclusions are sheared to cm- to mm-thick bands in a strongly banded rock with a gneiss matrix that shows platy quartz texture (cf. Fig. 6). The shearing at the boundary may often be traced up to 1 or 2 kilometres into the basement gneisses.

Equivalent relations are observed between the basement gneisses of the Kevo area and the granulites which surrond them (Fig. 5). On earlier maps, the Kevo basement area has been connected to the Inari unit basement to the east

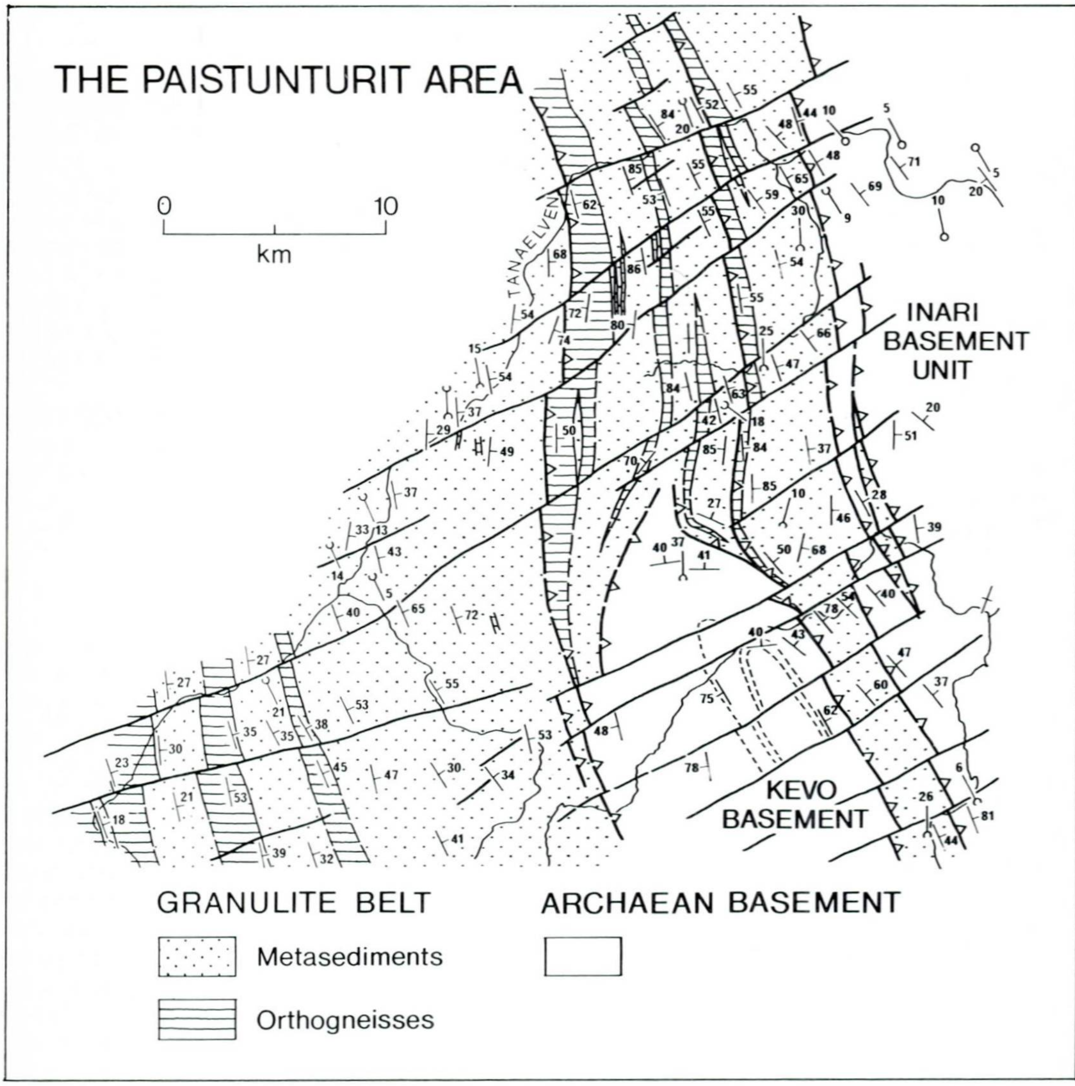

Fig. 5. The geological structure in the Paistunturit area of the northern part of the Granulite belt. The northernmost part of the map (in Norway) is based on Krill (1985, this volume). For explanation see text.

by a folded structure (i.e. Meriläinen 1965), but the new mapping clearly disclosed that the Kevo basement is entirely separated from the Inari unit basement by a zone of blastomylontitic metasedimentary granulites, which dip to the northeast without any indications of folding.

The tectonic interpretation of the Finnish part of the northern Granulite belt is shown in Fig. 3. The Kevo basement area forms a tectonic slice of basement gneisses within the granulite belt, and is separated from the basement of the Inari unit to the northeast. Originally, however, the Kevo basement must have formed part of this basement, because the rock types in both basement areas are identical. Most probably, the Kevo basement was initially developed as a dome-shaped antiformal fold structure, as suggested by the structural readings on the maps, but was later disrupted and transformed into a major tectonic slice during the thrusting of the Inari unit to the southwest over the Granulite belt. At this stage the thrust boundaries no longer followed the boundary between the Kevo basement and the granulites, but continued to

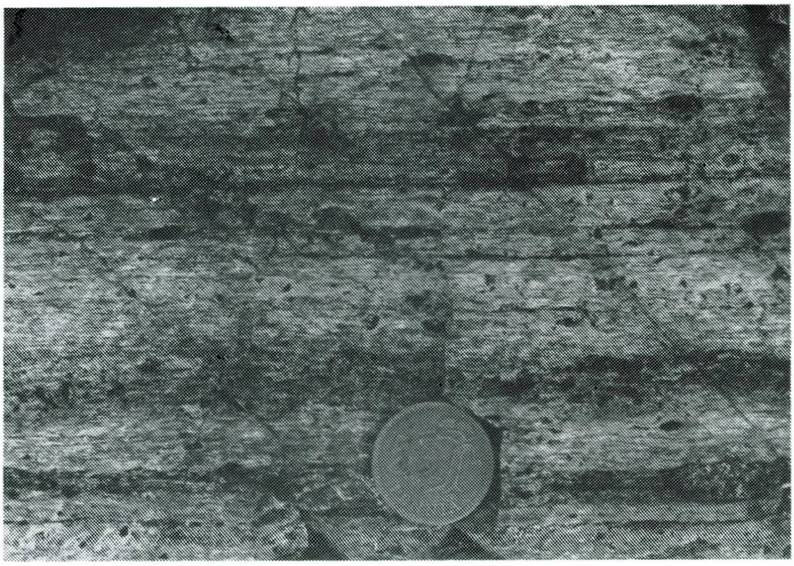

Fig. 6. Strongly mylonitic, amphibolite-banded basement gneiss from the eastern part of the Kevo basement area at the high -strained border with the Granulite belt. Originally irregular amphibolite inclusions are sheared to thin bands in a light gneiss with a strong platy quartz texture (Paistunturit area, Finland).

the northwest and southeast into the rocks of the Granulite belt (Fig. 3); the metasedimentary granulites, which lie between the bordering thrust of the Kevo basement gneisses, are rather unaffected by the mylonitization and contain cordierite. The southern termination of the Kevo basement has not yet been mapped, and has been inferred from the map of Meriläinen (1965).

The boundary between the Granulite belt and the basement gneisses is transected by a prominent set of NE-SW trending steep faults, which consistently show a right-lateral component of displacement (Fig. 5). This set is parallel to one of two prominent regional fault systems (cf. Aarnisalo 1977 (Fig. 11) and Mikkola & Vuorela 1977 (Fig. 2)). The complementary set trends NW-SE, and observed flexures around meso-scale faults of this orientation suggest that they have left-lateral displacements. As shown on the maps (Figs. 5 and 3), these faults have influenced the course of the thrust boundaries which they displace. Most of the faults were probably established soon after the thrusting since very high CO_2 cordierite-bearing parageneses, attributed to a late stage of the granulite metamorphism, developed in some of them (cf. Ambruster et al. 1982). Judging from the sense of displacement, they may have been established as a conjugate fault system formed in response to late-stage east-west oriented compression, in contrast with the main stage northeast-southwest oriented compression.

Outside the northern area the exposure is generally bad, and it is more difficult to obtain a coherent picture of the northeastern Granulite belt boundary. From preliminary investigations, the thrust boundary in the area south of Inarijärvi seems to consist of several rather steeply-dipping separate thrusts which cause basement slices to alternate with granulites in a wide thrust zone. It is suggested that most of the northeastern marginal zone of the granulite complex (Meriläinen 1976) should be interpreted as alternating basement and granulite gneiss due to thrusting. Mica gneisses are the most important constituent of the supracrustal intercalations in the basement gneisses, and are very similar to the metasedimentary granulites of the Granulite belt.

The tectonic setting of the Kola suture belt

The rocks of the Kola suture belt belong to the Petsamo-Pechenga group. Apart from the southern low-grade part of the belt in the Pasvik area, which consists of varied lithologies of both metasediments and mainly andesitic metavolcanites (Bugge 1980, Bugge & Iversen 1985a, b), the rocks of the Kola suture belt consist of a rather monotonous series of medium-grade greenstones or, more strictly speaking, fine-grained amphibolites. In places, as in the Polmak area in Norway, intercalations of felsic metavolcanic rocks appear. Thin, minor inter-

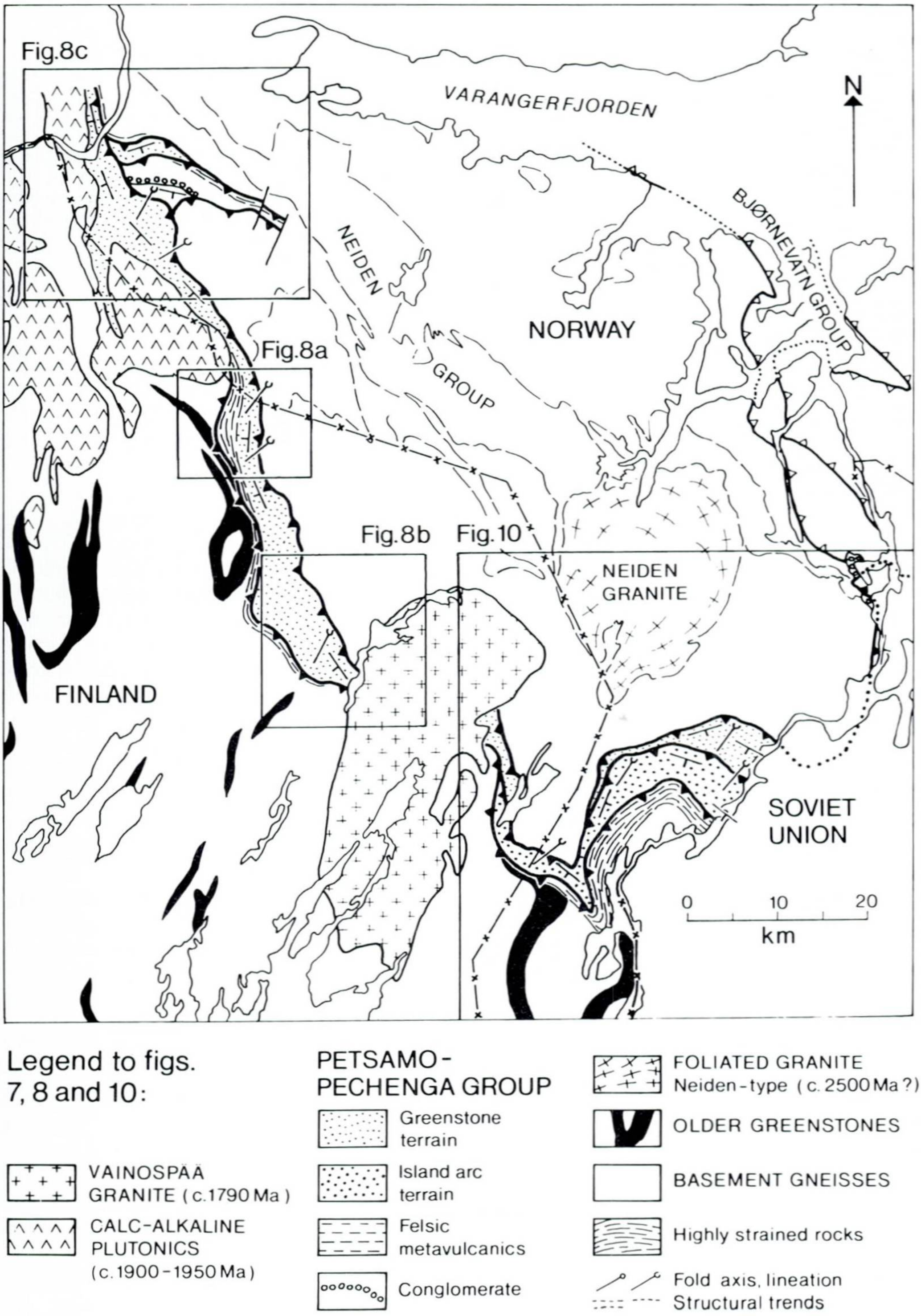

Fig. 7. The Kola suture belt in northern Finnish Lapland and Sørvaranger; based on Meriläinen (1965) and Bugge & Iversen (1981a). The locations of Figs. 8, b, c and 10 are indicated.

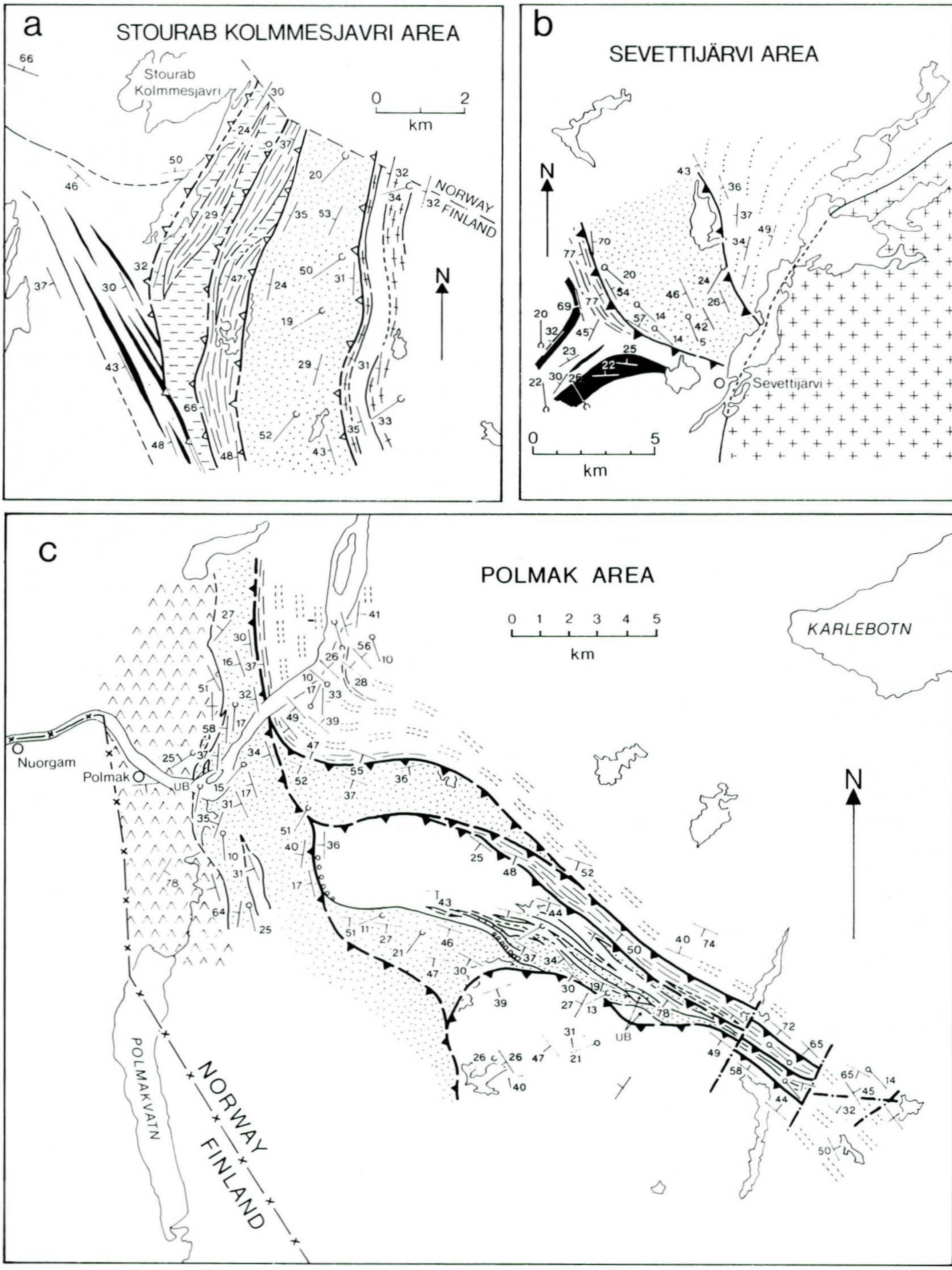

Fig. 8. The structure of the Kola suture belt in the Stourab Kolmmesjavri, Sevettijärvi and Polmak areas. See Fig. 7 for legend and location. UB: ultrabasic rock.

calations of chert and a conspicuous garnet- and staurolite-rich schist have also been found in the axial part of the northern half of the belt.

The contacts between the Kola suture belt and the basement gneisses to the northeast and to the southwest are mostly strongly sheared and mylonitic. Along the entire length of the belt, the contacts on both sides dip in southwesterly directions. In many places along the border, thin intercalations of greenstone are found alternating with highly sheared basement gneisses, and almost everywhere the trends and structures within the basement gneisses are cut off and deflected along the border with the Kola suture belt forming high-angle structural discordances (Fig. 7). Both features clearly demonstrate the tectonic nature of the boundary.

The structure of the Kola suture belt has been investigated in four selected areas (Fig. 7). In the Stourab Kolmmesjavri area (Fig. å), the Kola suture belt is bordered by strongly blastomylonitic metagranites to the east, whereas to the west it cuts off the structures of the basement gneisses, including a series of older greenstones. The western part of the Kola suture belt consists of light-coloured felsic metavolcanites without greenstone intercalations. These felsic metavolcanites, which continue further to the north into Norway (Bugge & Iversen 1985a, b), are in part strongly sheared into a mylonitic rock of phyllonitic appearance. The boundary between these rocks and the greenstones to the east is also highly sheared, with thin bands of greenstones alternating with sheared felsic metavolcanics and, as can be seen in Fig. 8, several internal thrusts can be distinguished within the belt. The thrusts generally dip about 30-35° to the west with a prominent southwest-plunging amphibole lineation in the greenstones, which probably reflects a direction of thrusting to the northeast.

In the Sevettijärvi area further to the southeast (Fig. 8b), similar relations exist between the greenstones of the Kola suture belt and the basement gneisses. Along the southwestern border, typical phyllonites are found, which in places may contain kyanite, suggesting that higher pressures could have prevailed in the mylonitic rocks than in the surroundings. It is also seen how the structures of the basement gneisses to the southwest are cut off and sharply bent at and towards the boundary with the Kola suture belt. As in the Stourab Kolmmesjavri area, older greenstones to the southwest are cut by the Kola suture belt (compare with Fig. 7). The greenstones also contain a southwest-plunging hornblende lineation, which like the main foliation, overprints an older phase of small-scale, tight to isoclinal folds with fold axes that generally plunge gently in directions which are subparallel to the belt.

The northwestern part of the Kola suture belt, i.e. the Polmak area in Norway (Figs. 7 and 8c), shows a more complicated structure. It appears that the northeastern part of the thrust boundary is divided up into several southwest-dipping minor thrusts whose southeastern continuation is as yet unknown. Most probably, these thrusts rejoin the Kola suture belt further to the south. These thrusts delineate thrust slices consisting of either basement rocks, greenstones of the Petsamo-Pechenga group, or both (Fig. 8c). The basement gneisses in a zone up to 1-2 kilometres from the thrust have been affected by the thrusting, and towards the contact, they have commonly been transformed into strongly sheared, fine-grained, light-coloured rocks that often display a platy quartz texture. Sometimes the sheared border zone contains layers of greenstones which may be interpreted as highly strained tectonic fragments of Petsamo-Pechenga group greenstones. Phyllonites are found at various places along the northeastern thrust boundary of the Kola suture belt, as shown in Fig. 8c.

Of particular interest is the second northern thrust slice that contains strongly sheared basement rocks in its northern part and greenstones in its southern part (Fig. 8c). Along the boundary between the two, a deformed, often highly strained conglomerate is found, which in one locality has survived in an isolated undeformed enclave. There it consists of rounded boulders of granitic rocks and some subordinate biotite gneisses/schists and quartz-rich rocks set in a light grey matrix (Fig. 9). In the highly strained conglomerates, only the remnants of the two last-mentioned boulder types can be identified, sheared out into schlieren. It is most probable that this conglomerate, the Polmak conglomerate, corresponds to the Neverskrukk conglomerate, which overlies the Bjørnevatn group south of Kirkenes (cf. Bugge & Iversen 1985a, b), and that it represents the basal conglomerate of the Petsamo-Pechenga group which originally rested unconformably on the basement to the northeast of the Kola suture belt.

Also in the Polmak area, a prominent southwest-plunging amphibole lineation overprints tight to isoclinal folds of an earlier phase, and this again indicates a direction of thrusting towards the northeast.

The western part of the Kola suture belt in the Polmak area is cut by calc-alkaline plutons which have been dated at c. 1900-1950 Ma by Meriläinen (1976). These plutons are themselves foliated, and this indicates that they were intruded while deformation was still occurring in the Kola suture belt.

In the southeastern part of the Kola suture belt of Finland and Norway, structural relations that correspond to those described above are observed between the belt and the basement gneisses on either side. In the Pasvik area in Norway (Fig. 10), the Kola suture belt is divided into the Tundra series and the Petsamo-Pechenga group. As mentioned earlier, the Petsamo-Pechenga group in the Pasvik area can be divided into two parts, which are separated by a thrust. This thrust can be continued into Soviet territory (cf. Väyrynen 1938 and Kozlovsky 1984; see Fig. 11) and separates rocks showing different lithologies, metamorphic facies and degree of deformation. The southern low-grade part consists of variable lithologies including serpentinites and metavolcanites of andesitic affinity (Bugge 1980, Bugge & Iversen 1985a), whereas the northern part consists of greenstones metamorphosed at medium grade. The Tundra series is made up of muscovite-, biotite- and occasionally garnet-bearing phyllonites with some bands of amphibolite. The phyllonites are identical to those found in the Sevettijärvi area at the same structural position, and they may represent highly sheared basement gneisses which formed along the southern boundary of the Kola suture belt during the upthrusting of the Inari unit to the northeast.

The basement gneisses to the north of the Kola suture belt are made up of uniform, somewhat migmatitic banded, light grey Svanvik gneisses with a few scattered amphibolite bands. As can be seen in Fig. 10, structures within the Svanvik gneisses are cut at an high angle along the northern thrust boundary of the Kola suture belt. Near this boundary, the foliation of the gneisses is commonly bent into a flexure, as was also observed in the Sevettijärvi area. The northern thrust boundary turns to the east into Soviet territory and reappears in the northeastern part of Fig. 10, where it cuts off the Bjørnevatn group. The basement area to the south of the Kola suture belt is badly exposed, but the map by Bugge & Iversen (1985a) shows similar stural relations between the belt and the basement gneisses.

Fig. 9. The Polmak conglomerate at the base of the Jatulian formations in the Kola suture belt. (13 km ESE of Polmak, Norway).

As shown in Fig. 10, the greenstones of the Kola suture belt in the Pasvik area show a consistent southwest-plunging amphibolite lineation similar to that in other parts of the belt.

Tectonics of the northeastern part of the Baltic Shield

The structural examination of the northern Finnish Lapland-Sørvaranger area, and the extension of this examination on to the Kola Peninsula, provides a new opportunity to interpret the crustal evolution of the northeastern part of the Baltic Shield.

From the record presented above, the northeastern part of the Baltic Shield, north of the South Lapland-Karelia craton (cf. Barbey et al. 1984), can be divided into six main tectonic units. These units are displaced by, and often form part of, major linear thrust zones of Lower Proterozoic age. Even though the crustal age and internal structure in some units, i.e. the Murmansk, Sørvaranger and Inari units, are Archaean, these units were highly involved in Lower Proterozoic Svecokarelian tectonics.

In accordance with previous investigations, the Granulite belt forms a major thrust belt which has been thrusted to the southwest over the South Lapland-Karelia craton of Barbey et

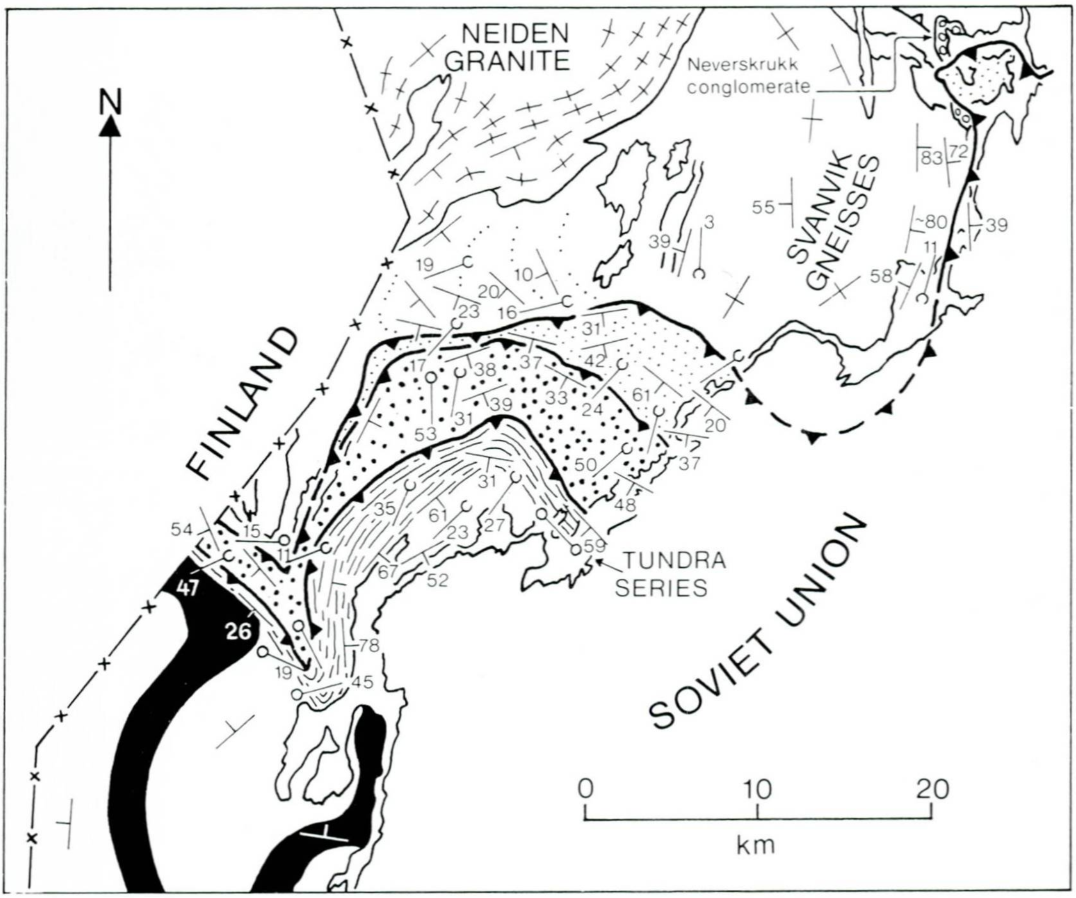

Fig. 10. The structure of the Kola suture belt in the Pasvik area. See Fig. 7 for legend and location.

al. (1984), with the formation of a wide high-strain zone at its base. From the present investigation, it may be concluded as well that the Inari unit was thrusted upon the Granulite belt during the same event, and that additional thrusts were formed within the Granulite belt itself. A further conclusion is that the Tanaelv unit achieved its highly strained structure during the thrusting of the overlying Granulite belt.

The Kola suture belt is considered to present key evidence for an understanding of the tectonic evolution of this part of the Baltic Shield, as first suggested by Berthelsen (1981). It is concluded above that the belt must be interpreted as a major southwestward-dipping regional thrust belt, which thrusted towards the northeast, normal to the general trend of the belt. This interpretation is further reinforced by new results from the Kola superdeep bore hole on the Kola Peninsula (Kozlovsky 1984), which disclose that the contact between the Petsamo-Pechenga group and the underlying Archaean basement gneisses of the Sørvaranger unit consists of a 1-2 kilometres thick zone of highly strained mylonitic rocks.

The tectonic environment of the Kola suture belt is summarized in Fig. 11. It is particularly striking to see how the belt cuts across the various Archaean rock units and structures of the Sørvaranger unit, and as described above the same applies for the relation to the Inari unit to the southwest. The map also shows the position both of the c. 1900-1950 Ma old calc-alkaline plutons that intrude the Inari unit to the southwest of the Kola suture belt, and of the cross-cutting 1790 Ma old Vainospää granite and associated granitic intrusions on the Kola Peninsula.

Most of the tectonic and igneous features now recognized in the Precambrian of the northeastern part of the Baltic Shield show a striking

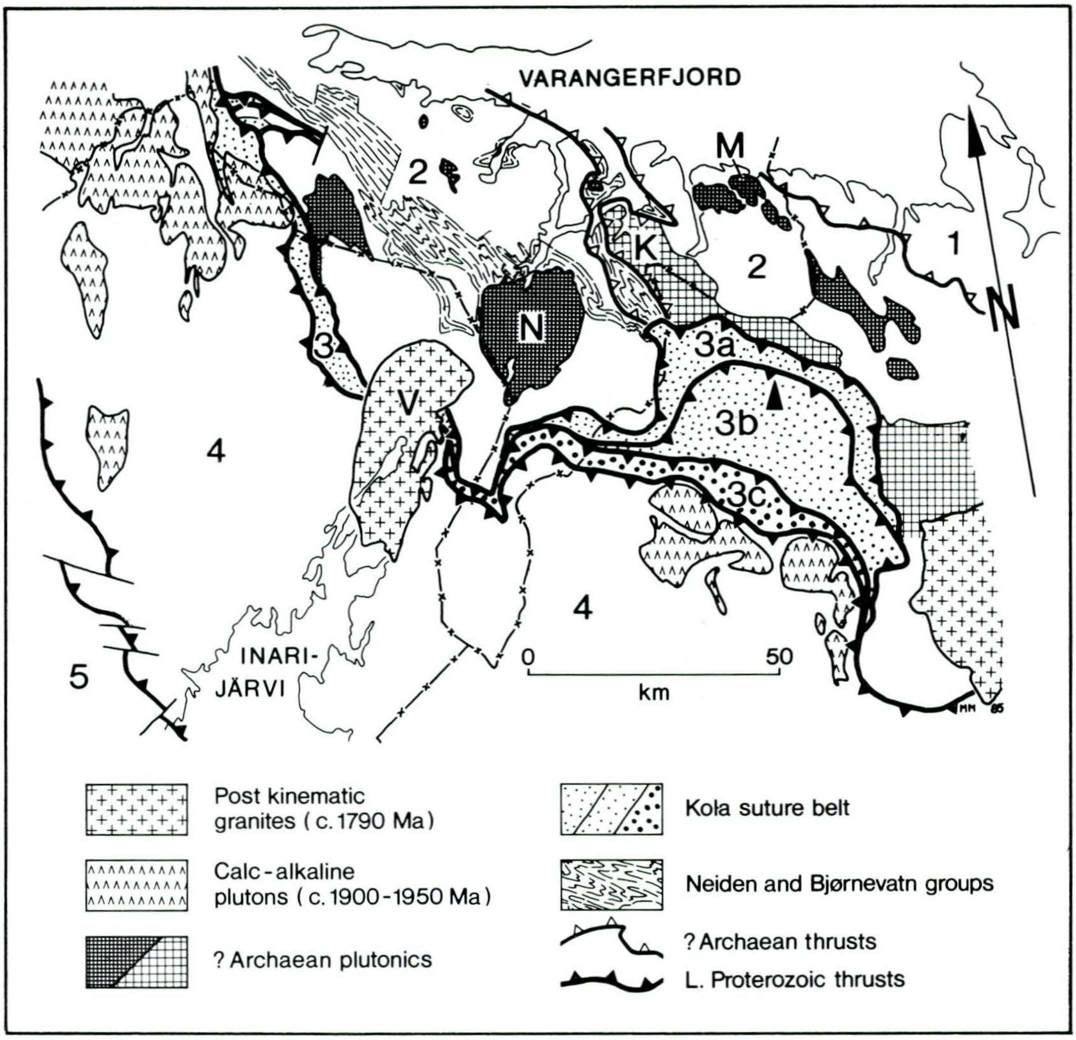

Fig. 11. Tectonic map showing the continuation of the Kola suture belt into the Kola Peninsula; based on Meriläinen (1965), Bugge & Iversen (1985a) and Kozlovsky (1984). The solid triangle shows the position of the Kola superdeep bore-hole. Tectonic units: 1: the Murmansk unit; 2: the Sørvaranger unit; 3: the Kola suture belt (3 and 3b northern continental margin of the Kola ocean; 3c: supposed island arc terrain); 4: the Inari unit; 5: the Granulite belt. (V: Vainospää granite, N: Neiden granite, K: Kirkenes tonalite, M: Mangerite intrusions in the Jarfjord gneisses).

similarity to those that are fundamental to the establishment of Proterozoic plate tectonic models. In particular, this applies to the recognition of major linear thrust belts and the determination of the type and spatial distribution of the magmatism. These discoveries have recently led to plate tectonic interpretations by Berthelsen (1981, 1984, 1985), Barbey et al. (1984) and Krill (1985b, this volume), with subduction zones located within the Kola suture belt, within the Granulite belt, and within the Karasjok greenstone belt (west of the Tanaelv belt), respectively.

On the basis of new structural evidence from the northern Finnish Lapland-Sørvaranger area, a revised and refined plate tectonic model for the Svecokarelian crustal evolution of he northeastern part of the Baltic Shield can now be outlined (Berthelsen & Marker 1985). In this model (Fig. 12), the Kola suture belt is interpreted to contain a continent-continent collision suture and a concealed arc-continent collision in the southwest. The suture was formed by the closure of an earlier Kola ocean at about 1900

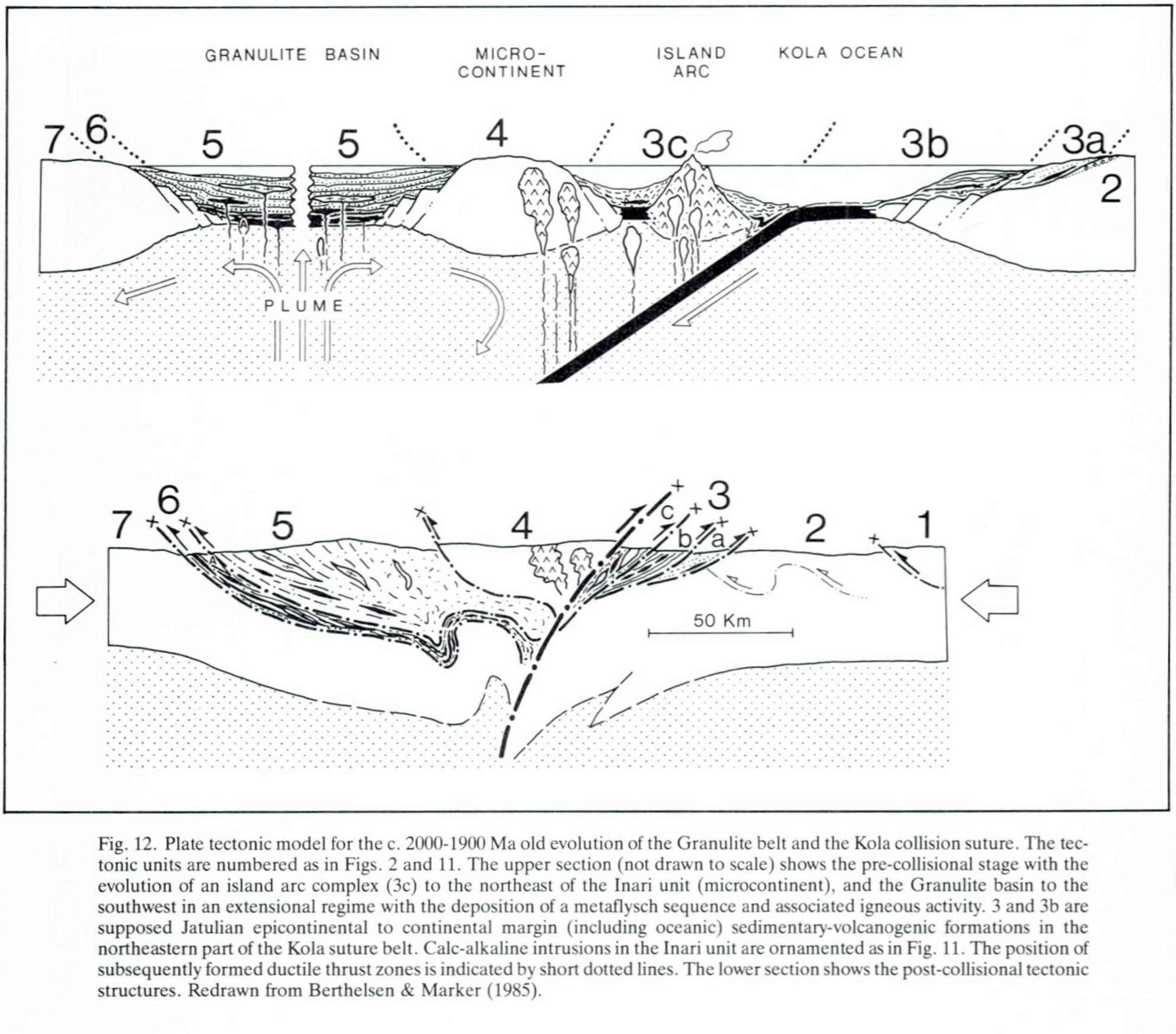

Fig. 12. Plate tectonic model for the c. 2000-1900 Ma old evolution of the Granulite belt and the Kola collision suture. The tectonic units are numbered as in Figs. 2 and 11. The upper section (not drawn to scale) shows the pre-collisional stage with the evolution of an island arc complex (3c) to the northeast of the Inari unit (microcontinent), and the Granulite basin to the southwest in an extensional regime with the deposition of a metaflysch sequence and associated igneous activity. 3 and 3b are supposed Jatulian epicontinental to continental margin (including oceanic) sedimentary-volcanogenic formations in the northeastern part of the Kola suture belt. Calc-alkaline intrusions in the Inari unit are ornamented as in Fig. 11. The position of subsequently formed ductile thrust zones is indicated by short dotted lines. The lower section shows the post-collisional tectonic structures. Redrawn from Berthelsen & Marker (1985).

Ma ago, while the metagreywacke sequence of the Granulite belt is interpreted as having been deposited in a back-arc-like, largely ensialic basin, which came into existence to the south of the Inari unit.

The early and pre-Svecokarelian evolution is depicted in the upper part of Fig. 12. The evolution was initiated by the rifting and formation of an ensialic basin between the Inari unit and the Sørvaranger unit. During the rifting stage, which may have initiated as early as 2400 Ma ago (Negrutsa 1979, Zagorodnyi 1980), the lower part of the Jatulian formations were deposited on the southwestern margin of the Sørvaranger unit, beginning with an epicontinental sequence with basal conglomerates (Bugge 1980, Zagorodnyi 1980). Owing to further extension and attenuation, the basin deepened, and subsequently, a Kola ocean opened between the Inari and the Sørvaranger units, with widespread extrusion of tholeiitic basalt in addition to komatiite (Suslova 1976).

During the early contraction stage in the evolution of the Kola ocean, oceanic lithosphere was subducted southwestwards, and a primitive island arc developed off the Inari unit at the same time as an attenuated back-arc-like basin came into existence to the southwest between the Inari unit and the South Lapland-Karelia craton. During continued extension and subsidence of the basin, the metaflysch sequence of the Granulite belt was deposited, accompanied by basic tholeiitic volcanism, now represented by the orthophyroxene-bearing meta-igneous layers in the metasediments. It is uncertain whether part of the metaflysch basin was actually floored by oceanic crust as argued by Barbey et al. (1984), but it appears likely that the basin was floored mainly by attenuated Archaean continental crust, which during attenuation was intruded/extruded by tholeiitic basaltic melts (cf. Hörmann et al. 1980) of the same age as the tholeiitic volcanites in the metasedimentary granulites (Bernard-Griffiths et al. 1984). The regional tectonic setting suggests that the attenuated, possibly partly oceanized continental crust beneath the Granulite basin is now represented by the Tanaelv belt. The lower crustal provenance of the Tanaelv belt is further suggested by the presence in this unit of ultrabasic, gabbroic and anorthositic inclusions, which may represent disrupted parts of upper mantle rocks and their differentiates and cumulates (anorthosites).

The subduction of Kola ocean lithosphere north of the Inari unit (or microcontinent) led to the formation of a volcanic arc along the southwestern margin of the Kola ocean, which is now represented by the discontinuous andesitic zone of the Kola suture belt (Figs. 2 and 11). The calc-alkaline plutons, which now outcrop within the Inari unit to the southwest of the Kola suture belt, were generated in a more distal environment in relation to the subduction zone (Figs. 3 and 11).

As mentioned earlier, the tholeiitic basic volcanic rocks in the Granulite and Tanaelv belts have been dated at c. 2000-1900 Ma (Bernard-Griffiths et al. 1984), and the calc-alkaline plutons in the Inari unit at c. 1900-1950 Ma (Meriläinen 1976), and these age relations suggest that the southwestward subduction of Kola oceanic lithosphere initiated close to 2000 Ma ago. It is likely that the deposition of the metaflysch sequence of the Granulite belt initiated at about the same time, since deposition of similar sequences in orogenic belts elsewhere occurs not too long before their deformation (Harris et al. 1978, Yardley et al. 1982, Condie 1982).

The final orogenic stage of the Svecokarelian evolution in the northeastern part of the Baltic Shield is summarized in the lower part of Fig. 12, which represents the tectonic structure as it appears today. During closure of the Kola ocean, the Inari unit first collided with the primitive island arc and then with the Sørvaranger unit. During this collision, the Kola suture belt was thrusted to the northeast over the Sørvaranger unit, causing the former volcanic arc to be located just below the overriding Inari unit. As a result of the collision, the Inari unit acted as a resistent massif that was welded to the northeastern continent, causing southwestward thrusting of the Granulite and Tanaelv belts upon the southern foreland of the South Lapland-Karelia craton by continued compression. Thrusting of the Granulite and Tanaelv belts probably ended close to 1900 Ma ago as indicated by the ages of synorogenic meta-igneous rocks that show calc-alkaline trends in the Granulite belt (Bernard-Griffiths et al. 1984).

As demonstrated from the textural evidence, high-grade metamorphic conditions were reached before the main thrusting, with extensive formation of migmatites within the Granulite and Tanaelv belts. Barbey et al. (1984) proposed that a mantle-derived thermal anomaly must have been located beneath the depositional basin of the metasedimentary granulites in order to explain the observed high dT/dP gradient that prevailed in the Granulite belt during its metamorphism. As shown in Fig. 12 this thermal anomaly could have been generated due to a convective back-flow system in the mantle caused by the southwestward -directed subduction zone northeast of the Inari microcontinent. It is probable that the dry granulite-facies conditions in the Granulite belt were brought about by carbonic metamorphism (cf. Newton et al. 1980), with the escape of CO_2 vapour from a mantle plume or ridge rising beneath the Granulite basin resulting from this mechanism. During the subsequent thrusting event granulite-facies conditions still prevailed as indicated from the mineral parageneses in the blastomylonites.

The discovery of calc-alkaline trends in the meta-igneous rocks within the Granulite belt has recently led Barbey et al. (1984) and Krill (1985b this volume) to argue for a possible collision suture formed by northeastward subduction of oceanic lithosphere within the Granulite belt and the Karasjok greenstone belt (west of the Tanaelv belt), respectively. Both solutions may be questioned when the tectonic structure and configuration in the northeastern Baltic Shield (Fig. 2) are compared with those of Phanerozoic orogenic belts, such as the Himalayas, where the suture is situated well to the north of the major south-directed thrust zone that came into existence by continued post-collisional compression of India and Asia (Le Fort 1975, Allégre et al. 1984, Matthews & Hirn 1984). By comparison, the Kola collision suture corresponds closely to the Indus-Tsangpo suture, while the thrust sheets of the Granulite and Tanaelv belts correspond to the Main Central and the Main Boundary Thrusts of the Higher and Lesser Himalayas further to the south. Other examples of similar plate tectonic configurations can be quoted from the British Caledonides (Watson & Dunning 1979) and the Appalachians (Hatcher & Odom 1980), where the closure of Iapetus by westward subduction of oceanic lithosphere led to the overthrusting of crustal segments of Laurentian provenance onto the western foreland. In both of these cases, back-arc-like ensialic basin evolution is involved, formed within the Laurentian margin and later overthrusted to the west or northwest during the collisional phase. The interpretation of the Kola suture belt as an arc-continent, continent-continent collision suture fits readily with this plate tectonic pattern.

The limited volume of calc-alkaline, synorogenic intrusions/extrusions in the Granulite belt is not considered compelling evidence for the existence of a major northeastward-directed subduction zone located within the Granulite belt; but the possibility that local sea-floor spreading and related subduction regimes (cf. the Mediterranean area) may have been operating within the back-arc basin should naturally be kept open.

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