# 2200 MILLION YEARS OF CRUSTAL EVOLUTION: THE BALTIC SHIELD

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The crustal history of the Baltic shield is interpreted in the light of the plate tectonic concept. Five tectonic cycles, each characterized by special lithological and structural features, are distinguished: The Early Archean (> 2900 Ma), the Late Archean (2900—2500 Ma) and the Svecokarelian (2100—1750 Ma) cycle, the Southwest Orogen (1750—1550 Ma) and the Sveconorwegian cycle (1200—1000 Ma). The Early Archean ensialic basement of Late Archean greenstone belts in the eastern-central part of the shield is alleged to have formed the nucleus, with new crustal addition to the east during the Late Archean cycle. During the Svecokarelian cycle a diversified geosynclinal system developed on a passive continental margin west of the Archean craton. New continental crust has been generated by accretion west of this margin during the Svecokarelian cycle and the Southwest orogeny by sub-duction of proto-oceanic crust. Considerable reactivation of the Archean craton during Early Proterozoic times is manifested by rifting, layered intrusions, continental volcano-sedimentary belts and granitoidic diapirism. The Sveconorwegian cycle has reworked crust formed earlier producing only minor amounts of juvenile crust. The position of the Baltic shield within the Precambrian of northern and eastern Europe and in the pre-Alpine crust of western Europe is reviewed.

Key words: Archean, low-grade terrain, high-grade terrain, Proterozoic, plate tectonics, continental margin, accretion.

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## Introduction

Significant progress has been achieved in Pre-cambrian geology during the past twenty years. We can confidently state that the major trends of Precambrian crustal evolution on a global scale are emerging; no longer are shield areas looked upon as unique formations that evolved under obscure conditions. Although continuous gradual changes in crustal processes with time are recognized, the concept of unitarism has proved to be a useful approach in solving problems of Precambrian geologic history. The most radical change came with the steady advance of the plate tectonic concept into the Precambrian time scale. With the recognition of global Precambrian pro-cesses our ideas about the early history of the Earth are being revolutionized. At this stage we need well studied and documented models on a shield scale, and for this the Baltic shield is an excellent case.

The other important reason for progress in

Precambrian geology stems from the new methodology of research. New techiques have been applied to shield areas and the integration of the results of studies in various geoscience branches offer new insight into ancient Earth-forming processes. Special mention should be made of the contribution of isotope geology, structural geology, metamorphic petrology, geochemistry and sedimentology.

The purpose of the present paper is to analyze the geologic history of the Baltic shield, focusing special attention on its central part. The geology of the Baltic shield is being studied in four countries, Finland, Norway, Sweden and the U.S.S.R., and all have published national reviews (*e.g.* Kratts *et al.* 1978; Lundqvist 1979; Oftedahl 1980; Simonen 1980). Nevertheless, there is an urgent need for developing diverse views on the Baltic shield as an entity. The fruitfulness of such synthetic views is demonstrated by papers among others by Salop (1969), Hietanen (1975) and Berthelsen (1980). The most efficient way of achieving this is by international cooperation, such as the ongoing joint Finnish, Norwegian and Swedish Nordkalott Project, and the scientific cooperation between Finnish and Soviet geologists. The geology of the Baltic shield has long been an international issue, as is seen in the reference list of the present paper. To be able to study the entire literature on the Baltic shield one should have command of seven languages. This and the enormous size of the literature on the subject severely hamper the creation of syntheses of the subject, and also makes any synthesis subjective in nature.

## Major tectonic units

The Baltic shield exhibits characteristic geochronological zoning, which, somewhat generalized, is expressed in the younging ages from east to west. The time span extends from the oldest isotopic age, 3100 Ma, in northern Finland to the youngest age, 900 Ma, in southern Sweden.

Within the 2200 Ma crustal evolution of the Baltic shield five tectonic cycles can be distinguished (Fig. 1).

(1) The Early Archean cycle (> 2900 Ma) is identified in the ensialic basement of the Late Archean low-grade terrain.

(2) The Late Archean cycle (2900—2500 Ma) has resulted in the development of a granitoid-greenstone belt association and the high-grade terrains of the Belomorian and Kolan gneisses.

(3) The Svecokarelian cycle (2100—1750 Ma) has been the major crust forming event in the shield. Elements of a Circum Pacific-type orogen can be recognized in the Karelides and Svecofennides with synchronous tectonic-magmatic reactivation of the Archean crust. The granulite complex of Lapland, a high-grade intracratonic collision belt, represents an early event of this cycle at 2200—1900 Ma.

(4) The Southwest Orogen (1750—1550 Ma) is a minor accretional event in the southwestern Baltic shield.

(5) The Sveconorwegian cycle (1200—900 Ma) reworked the rocks of the Southwest Orogen with minor crustal addition.

The western margin of the Baltic shield is concealed under the autochtonous units and far-traveled nappes of the Caledonides. The Phanerozoic reworking is slight or negligible and rocks of all five cycles are recognized in the Caledonides, indicating that the shield area extended far to the west before the beginning of Caledonian thrusting (Gorbatschev 1984).

## Archean crust

The unconformity between the Archean basement complex and its Proterozoic cover at the eastern margin of the Karelian schist belt is one of the most remarkable features of the geology of North Karelia, and already impressed the early pioneers of the geology of the Baltic shield. East of the unconformity line extends a typical Archean granitoid-greenstone belt terrain.
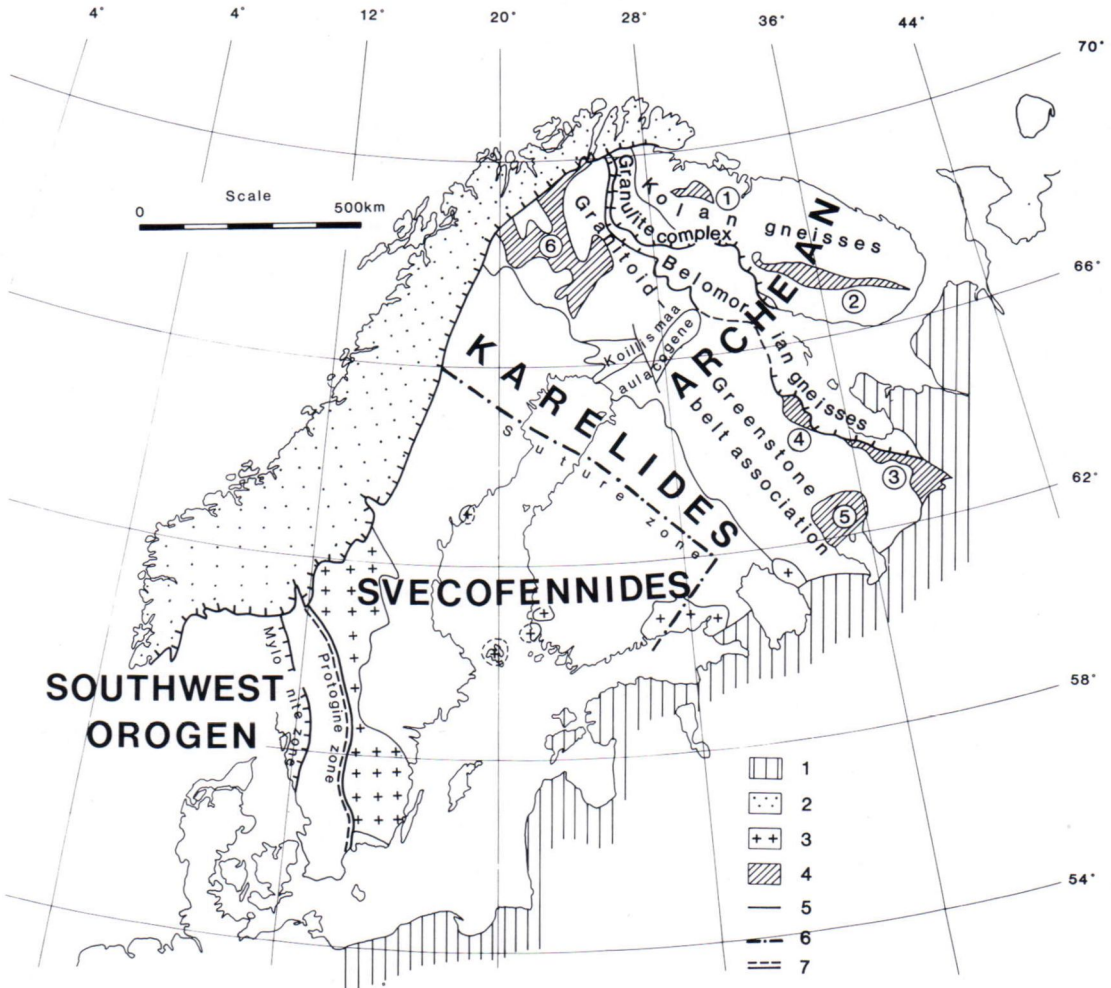
Fig. 1.  Major units of the Precambrian of the Baltic Shield. Explanations: 1. Phanerozoic platform cover, 2. Caledonides, 3. Rapakivi granites and porphyry belt, 4. Early Proterozoic greenstone belts: 1—6 (1. Petsenga, 2. Imadra — Varzuga, 3. Vetrenyy Poyas, 4. Central Soviet Karelia, 5. Suisaari, 6. Kiruna, 5. Exposed Archean — Proterozoic boundary, 6. Inferred western boundary of the Archean crust, 7. Protogine zone.

## Low-grade terrain: The granitoid-greenstone belt association

The western half of the Archean crust is a NW-trending, 300- to 350-km-wide and 1100-km-long zone consisting of various granitoids engulfing isolated low- to medium-grade metamorphosed greenstone belts. The major ones are Hauta-vaara, Manga, Jalonvaara, Himola, Koikari, Matkalahti, Sumozeri-Kenozero, South Vygozero, Bergaul, Parandova, Kostomuksha, Tiks-hozero, Paanajärvi and Kuolajärvi in the U.S.S.R., Ilomantsi, Tipasjärvi, Kuhmo, Suo-mussalmi, Jauratsi and Sodankylä in Finland, and Karasjokk in Norway (Fig. 2). Eastward, the zone is fault-bounded against the high-grade Be-lomorian gneisses thrust over the greenstone-belts to the west. The western margin of the Archean crust is concealed under both an autochtonous Early Proterozoic platform cover and alloch-tonous Karelidic nappes thrust to the east.

The greenstone belts in the northern part of

the Baltic shield are currently the subject of controversy. They have traditionally been regarded as Proterozoic in age, as part of the Svecokarelian cycle. More recently, Archean ages have been proposed for some of the greenstone belts in northern Finland (Mutanen 1976; Gaál *et al.* 1978; Silvennoinen *et al.* 1980). The suggestion seems to be well justified for the Sodankylä and Jauratsi greenstone belts, where supracrustals are intruded by the mafic layered complex of Koitelainen dated by the U-Pb method on zircons as 2450 Ma old (Kouvo 1976; Simonen 1980). These supracrustals form a typical Archean association with extensive intercalations of komatiitic volcanics (Räsänen 1983; Saverikko 1983). The same lithology continues into Norway in the Karasjokk belt (Wennervirta 1969), which could also be regarded as Archean. Doubts have been raised on the age of the western greenstone belts, *e.g.* the Kittilä greenstone belt and its analogies in northern Sweden known as the »older greenstones» of Kiruna. The above rock associations are tentatively asigned to the Early Proterozoic in age (Fig. 2). A similar problem is encountered in Vetrenyy Poyas in the U.S.S.R., where the boundary between Archean and Early Proterozoic has been drawn according to Belyaev *et al.* (1975) on Fig. 2.

## Granitoids

The granitoids range in age between 3100 Ma and 2500 Ma. The oldest geochronologically well-defined age presently known in the Baltic shield has been obtained from a tonalitic gneiss in northern Finland (Kröner *et al.* 1981). The granitoids in eastern Finland yielded zircon ages of 2800—2500 Ma (Gaál *et al.* 1978) whereas granitoids within and outside the greenstone belts of Soviet Karelia have been dated by U-Pb methods on zircons at 2740 ± 20 Ma (Tugarinov and Bibikova 1980). The Rb-Sr and Sm-Nd whole rock isochrone ages of 2860—2410 Ma for granitoids in eastern Finland do not compare well with the zircon ages (Martin *et al.* 1983a; Martin and Querré 1984). These Archean granitoids

have evolved in three stages, leading to three generations with average compositions corresponding to tonalite/trondhjemite, granodiorite and granite, respectively. Rb-Sr data suggest that the granitoids are a new addition to the crust through multi-stage development (Martin *et al.* 1983): First generation granitoids yielded 2860 Ma with $I_{Sr}$ 0.7023 and the second generation 2620 Ma with $I_{Sr}$ 0.7024. REE patterns suggest derivation by partial melting of basaltic crustal material. The third generation of granitoids has evolved by remelting of crustal material (Martin and Querré 1984).

## Greenstone belts

A generalized stratigraphic sequence similar to the classical model of Anhaeusser *et al.* (1969) has been suggested for eastern Finland, with a mafic-ultramafic unit at the base, an intermediary calc-alkalic unit, and a sedimentary unit at the top (Blais *et al.* 1978; Gaál *et al.* 1978; Martin and Querré 1984). However, detailed structural-stratigraphical studies lead to different results in the Tipasjärvi and Kuhmo greenstone belts, where calc-alkalic volcanics underlie the mafic-ultramafic unit (Hanski 1980; Taipale 1983). Also in Soviet Karelia some greenstone belts have calc-alkalic volcanics as the lowermost units, and the Hautavaara greenstone belt consists almost entirely of calc-alkaline volcanics. Only in the Sumozero-Kenozero belt has been komatiitic basalt reported at the base of the supracrustal sequence (Kulikov *et al.* 1984). An exceptional lithology is encountered in the Sodankylä greenstone belt, where a thick quartzite-conglomerate layer underlies the mafic-ultramafic unit (Silvennoinen *et al.* 1980; Kröner *et al.* 1982). Also in the U.S.S.R. basal conglomerate has been encountered in the Kolvitskaja structure (Kulikov *et al.* 1984). These observations indicate an unconformity below the greenstone belts and most researchers share the opinion that the supracrustal rocks deposited on an ensialic basement older than 2900 Ma (*e.g.* Blais *et al.* 1978; Gaál *et al.* 1978; Kröner *et al.* 1981).
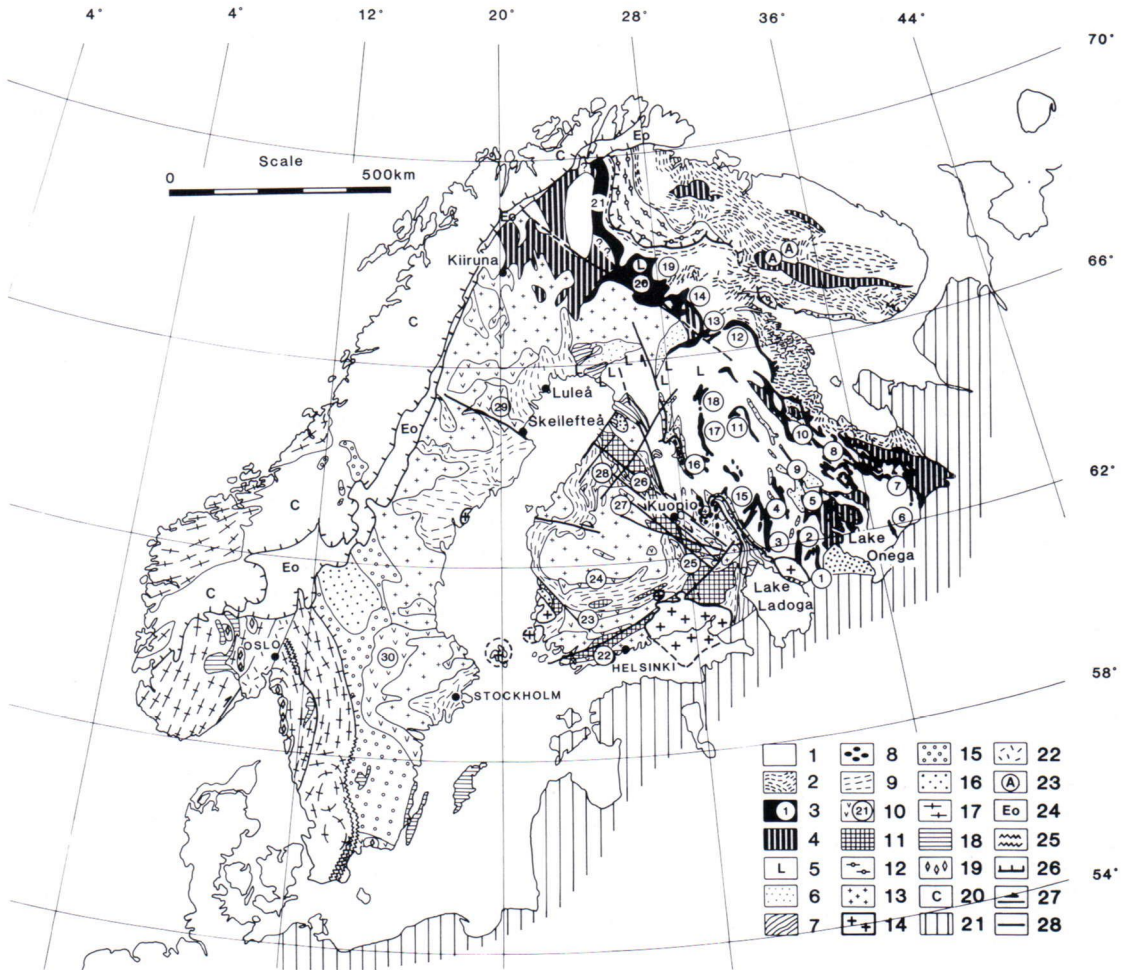
Fig. 2. The Precambrian of the Baltic shield. Explanations: 1. Archean granitoids, 2. Belomorian and Kolan gneisses, 3. Late Archean greenstone belts: 1—18 (1. Manga, 2. Hautavaara, 3. Jalonvaara, 4. Himola, 5. Koikari, 6. Matkalahti, 7. Sumozero-Kenozero, 8. South Vygozero, 9. Bergaul, 10. Parandova, 11. Kostomuksha, 12. Tikshozero, 13. Paanajärvi, 14. Kuolajärvi, 15. Ilomantsi, 16. Tipasjärvi, 17. Kuhmo, 18. Suomussalmi, 19. Jauratsi, 20. Sodankylä, 21. Karasjokk). 4. Early Proterozoic infracratonic greenstone belts, 5. Early Proterozoic mafic layered intrusions, 6. Platform cover (Jatulian and Sumi-Sariola groups), 7. Shelf sediments and proximal turbidites, 8. Ophiolite nappes, 9. Metagraywackes (micaschists and micagneisses), 10. Island arc volcanites and related sediments: 19—27 (22. Aijala-Orijärvi, 23. Hämeenlinna, 24. Tampere schist belt, 25. Haukivesi, 26. Kiuruvesi-Pyhäsalmi, 27. Pihtipudas, 28. Ylivieska, 29. Skellefteå, 30. Bergslagen province), 11. High-grade rocks (mostly metapelites), 12. Granulite complex of Lapland, 13. Synorogenic to postorogenic Svecokarelian granitoids, 14. Rapakivi granites, 15. Värmland-Småland porphyry granite, 16. Jotnian and Sub-Jotnian rocks, 17. Sveconorwegian gneisses, 18. Telemark suite, Dal group, Kapebo group, 19. Late Proterozoic granites, 20. Caledonides, 21. Sedimentary cover of the East European platform, 22. Oslo graben, 23. Paleozoic alkaline intrusions, 24. Eocambrian autochton, 25. Cataclastic zone, 26. Thrust fault, 27. Strike slip fault, 18. Fault in general.

On the basis of U-Pb ages of zircon, chiefly in granitoids in and around the greenstone belts, the deposition age of the greenstone-belt rocks has been bracketed in the range 2900—2700 Ma (Gaál *et al.* 1978; Tugarinov and Bibikova 1980). This view has been strengthened by more recent work on volcanics, whereby zircons in the felsic pyroclastics of the Kuhmo greenstone belt have

been dated at 2760 Ma (Taipale 1983). The 2500 Ma Rb-Sr age for the Kuhmo felsic pyroclastics given by Martin and Querré (1984) might represent a metamorphic event. Also the common lead age of 2500—2650 Ma for the ultramafic volcanics of the Kuhmo greenstone belt is inconsistent with the zircon ages (Vidal *et al.* 1980).

It is obvious that, despite the intensive work of the past ten years, we are still far from being able to establish reliable stratigraphic sequences within greenstone belts, and still further from being able to correlate the individual greenstone belts. A major reason is our imperfect knowledge of structures. The internal structure of the greenstone belts has been complicated by repeated deformation in three or four deformational phases (Sokolov *et al.* 1973; Gaál *et al.* 1976; Taipale 1983). It is suggested that the first deformation was probably dominated by recumbent folds, whereas at later stages subvertical movements brought about by diapirism of granitoids prevailed. It is also possible that lower parts of the supracrustal pile have been removed by stoping of the ascending granitoids. Further, hot granitoids might have been the primary cause of the metamorphic zonation typical of larger belts, as for example in the Hautavaara greenstone belt. Here greenschist facies metamorphism in the centre passes into high-grade amphibolite facies at the margins, where supracrustal rocks fade away as a result of granitization (Robonen *et al.* 1978).

## High-grade terrain: The Belomorian and Kolan gneisses

The high-grade gneisses of the northeastern part of the Baltic shield are traditionally subdivided into two tectonic units, the Kolan gneisses in the north and the Belomorian gneisses in the south. The two units are separated by the granulite complex of Lapland, thrust southward over the Belomorian gneisses (Fig. 1). The Belomorian gneisses in their turn are thrust to SE over the low-grade terrain of Soviet Karelia. The boundary is a mylonite and fault zone, indicated by seismic studies to be a low-angle thrust fault dipping to northeast (Akudinov *et al.* 1972). The age of this thrust is regarded as Lower Proterozoic.

The Belomorian gneisses on the western shore of the White Sea are of geosynclinal derivation, with garnet-biotite gneisses, often kyanite bearing, amphibolites and diopside-plagioclase rocks intruded by strongly deformed and metamorphosed granitoids. The rocks were deformed and metamorphosed in four deformational phases (Stenar 1972). During the first two phases high- to medium-pressure granulite-facies conditions prevailed. Recumbent folds formed first being followed by the development of NW-trending synforms and antiforms. During the next two phases, under retrograde amphibolite-facies conditions, first E-W-trending folds were formed and than NE-trending folds were superposed on the previous structures. The results are complex fold interference patterns typical of high-grade terrains. U-Pb ages on zircons indicate an event of intensive metamorphism and magmatism 2700 Ma ago and episodic loss of lead 1850 Ma ago, leading to the assumed depositional age of the supracrustal rocks of about 2900—2700 Ma (Tugarinov and Bibikova 1980).

The Belomorian gneisses continue in northern Finland in the high-grade metapelites of the Tuntsa-Savukoski formation (Mikkola 1941) grading into granite gneisses dated by the U-Pb method on zircons at 2600—2700 Ma (Geological Survey of Finland, Ann. Rep. 1969 and 1970). These granite-gneisses can be traced in strongly sheared form under the granulite complex as far as the Caledonian front in northern Norway.

The lithology, deformational and metamorphic history of the Kolan gneisses is similar to that of the Belomorian gneisses, as shown in detailed structural-metamorphic studies by Dobrzhinetskaja (1978). The Kolan gneisses forming the Kola nucleus were earlier regarded as the oldest part of the Baltic shield based on Early Archean ages

determined by the K-Ar method on hypersthene (Polkanov and Gerling 1960). Very high ages, in excess of 4000 Ma, were obtained by Ovchinnikov using the K-Ar method on biotite (1976). Since zircons in hypersthene-bearing tonalites and enderbites yielded 2790 ± Ma and in granite 2670 ± 30 Ma, it has been concluded that both granulite-facies and amphibolite-facies metamorphism occurred in the Kola region 2700 ± 50 Ma ago (Tugarinov and Bibikova 1980).

## Late Archean crustal evolution

Current geochronological evidence supports the view that, in both the low-grade and high-grade terrain, the supracrustal rocks deposited in the period between 2900 and 2700 Ma. There are also good indications for the existence of ensialic crust older than 2900 Ma in the low-grade terrain. The peak of paroxismal activity was reached during the final stage of deposition about 2750 ± 20 Ma ago and the main phase of deformation, metamorphism and magmatism affected the entire eastern part of the Baltic shield. It seems to be evident that the contrasting environments, low-grade terrain versus high-grade terrain, evolved synchronously and in juxtaposition. The greenstone-belt lithologies deposited in fault-bounded rift environments either on ensialic crust (Gaál et al. 1978; Robonen et al. 1978) or in a proto-oceanic rift system with oceanic crust of limited extent (Blais et al. 1978; Taipale 1983). The high-grade terrain is characterized by early recumbent folding and by high-pressure granulite-facies metamorphism affecting metapelites and associated rocks. The high pressure, in excess of 10 kbar (Stenar 1972; Volodichev 1972), indicates considerable crustal thicknening under the Belomorian gneisses. If we assume an average thickness of about 40 km for the Late Archean crust, the crust under the Belomorian gneisses was at least 70 km thick. Thus metamorphism and structural style imply that some sort of underplating mechanism was operating. On the other hand, the greenstone belts exhibit features suggestive of plate tectonic processes. Taipale (1983) proposed that the Finnish greenstone-belts developed in a back-arc rift environment. Farther east, in Soviet Karelia, the dominant calc-alkaline volcanism in greenstone belts indicates remnants of ancient island arcs.

In the light of the above analysis the application of the plate tectonic theory to the Late Archean seems feasible and a generalized model can be constructed as shown in Fig. 3. Archean ensialic crust older than 2900 Ma existed in the west, in the area now adjoining the Svecokarelian orogenic belt. This environment formed a protocontinent that could justifiably be named the nucleus of the Baltic shield. About 2900 Ma ago a geosynclinal system, underlain by

W

E

c.2800 Ma

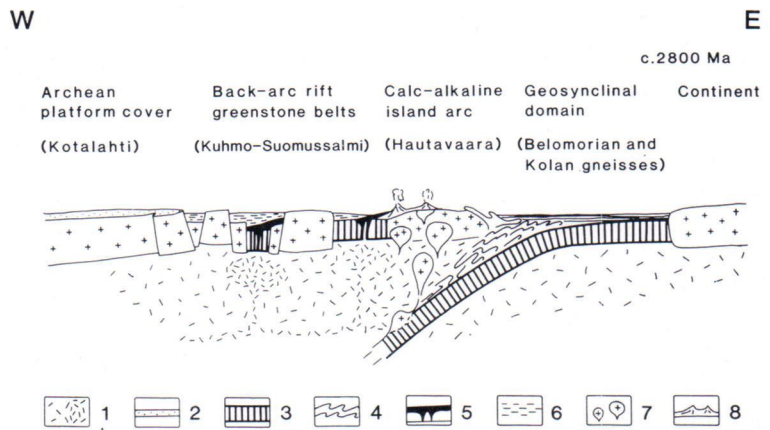| Archean platform cover | Back-arc rift greenstone belts | Calc-alkaline island arc | Geosynclinal domain | Continent |
|---|---|---|---|---|
| (Kotalahti) | (Kuhmo–Suomussalmi) | (Hautavaara) | (Belomorian and Kolan gneisses) | |



Fig. 3. Plate tectonic model for the Late Archean cycle of the Baltic shield c. 2800 Ma ago, not to scale. Explanations: 1. Upper mantle, 2. Archean platform cover, 3. Oceanic crust, 4. Geosynclinal sediments, 5. Komatiitic and tholeiitic volcanics, 6. Rift-stage sediments, 7. Granitoid diapirs, 8. Calc-alkaline volcanics.

a hypothetical oceanic crust, evolved on the eastern side of the protocontinent. The collisional stage might have started some 2800 Ma ago, resulting in the development of a subduction zone or a system of subparallel subduction zones dipping to the west or southwest. A N-NW-trending island arc system was formed with tholeiitic and calc-alkaline volcanism. In marginal basin environments komatiitic magma ascended from the upper mantle. The westernmost greenstone belts in Finland and Norway were generated in a back-arc rift system environment. Farther west the Archean protocontinent was covered by Archean platform-type sediments described in the Kotalahti area (Gaál 1981).

### Early Proterozoic history of the Archean crust

The Archean crust consolidated about 2500 Ma ago. The lower surface of the Archean crust was rapidly leveled by isostatic uplift and its upper surface has been peneplained by erosion. This consolidated landmass is called the »Jatulian continent» in Finland (Väyrynen 1933) and the »Karelian block» in Soviet Karelia (Kharitonov 1966). It is distinguished from some other Archean cratons, *e.g.* the Kapvaal craton and the Pilbara and Yilgarn block, by strong tectonic-magmatic reactivation during Early Proterozoic times. Immediately after the Archean consolidation, the crust was subjected to tensional stresses, and a period of rifting forming N-NW- and E-W-trending zones of block faulting started. One of the earliest indications of this activity are the mafic-ultramafic layered intrusions of the Kemi—Suhanko—Koillismaa belt in northern Finland, dated at 2440 Ma by the U-Pb method on zircon (Alapieti 1982). In this belt a tensional zone that originally trended E-W tapped the partially melted upper mantle. The mafic belt was later disrupted by dextral strike slip faults, one of them with a right-lateral separation of 90 km (Fig. 2). The early block faulting is also manifested by the widespread occurrence of terrestrial tholeiitic volcanics, fanglomerates and conglomerates of the Sumi-Sariola group 2500—2300 Ma ago (Sokolov *et al.* 1976; Meriläinen 1980; Marmo and Ojakangas 1984).

Where the Sumi-Sariolan tholeiitic volcanics overlie the Archean greenstone belts, as in Vetrenyy Poyas (Belyaev *et al.* 1975), the Archean-Proterozoic boundary has been obscured. Proterozoic terrestrial volcanism produced probably also the greenstone-belt lithologies in the northern part of the Baltic shield, *e.g.* in Finnmark, Norway, and in the Kiiruna area of Sweden. A similar geological setting is met with in the NW-trending Imadra-Varzuga-Petsenga belt in the Kola Peninsula. This belt has been interpreted to be the result of a continent-continent collision preceded by the development of a wide rift zone or Red-Sea type of ocean (Berthelsen 1984).

After the deposition of the Sumi-Sariola group a period of subaerial weathering prevailed followed by the deposition of the epicontinental sediments of the Jatulian group. The Jatulian group is subdivided into three formations, the Lower, Middle and Upper Jatulian (Sokolov 1976; Meriläinen 1980). Coarse epiclastic sediments predominate in the lowermost two formations, whereas dolomite, phyllite, and black schists, together with mafic volcanic intercalations and iron formation indicating shallow water marine environments prevail in the uppermost formation. The deformation of the platform cover is weak and characterized by faulting and open folding.

The Jatulian time terminated with extensive tensional fracturing giving way to the invasion of N-NW-trending diabase dikes and sills dated by the U-Pb method on zircons at 2000—2250 Ma (Sakko 1971; Kouvo 1976).

During the ensuing Svecokarelian cycle 1900—1700 Ma ago the Archean crust of the northern Baltic Shield was by numerous granitoidic diapirs (Witschard, 1984). The present author considers this magmatic reactivation to be associated with the subduction of oceanic crust towards NE under the Archean crust.

## The Svecokarelian cycle

The Early Proterozoic geosynclinal complex overlies the Archean crust in a 50- to 100-km-wide, NW-trending zone. This zone was earlier thought to form the Karelian orogen, as distinct from the adjoining E-W-trending Svecofennian orogen in the west (Eskola, 1963). Although these two orogens have since been shown to have evolved in a single event, the Svecokarelian orogeny (Metzger 1959; Simonen 1960), the terms »Karelian zone» and »Svecofennian zone» or their synonyms »Karelidic schist belt» and »Svecofennidic schist belt» have been retained (Kahma 1973; Simonen 1980).

Until a few years ago the entire Svecokarelian orogen was assumed to be floored by Archean ensialic crust (Salop 1977; Muratov 1980; Simonen 1980). Geochronological studies did not verify this view, since sofar no Archean ages have been obtained from the Svecofennides. Also the »Pregothides» in the western Baltic shield, thought earlier to be Archean in age, have now proved to be Proterozoic (Welin and Gorbatschev 1976). The western limit of the Archean basement has been delineated fairly reliably to run along a NW-trending line north of the Skellefteå belt in Sweden and south of the town Kuopio in Finland (Gaál et al. 1978; Adamek and Wilson 1979). Sm-Nd isotopes in the Svecokarelian indicate a predominantly mantle-derived juvenile crust (Patchett and Gorbatschev 1984). The new geochronological results give new sense to the old terms: the Karelides constitute the part of the Svecokarelian orogen that is underlain by Archean continental crust, and the Svecofennides have no Archean basement but form juvenile Early Proterozoic crust. The junction between the two units is a first-order crustal feature and has been called a suture (Burke et al. 1977; Koistinen 1981).

### Early Proterozoic continental margin: The Karelides

The initiation of the Svecokarelian orogen goes back to the time between 2250 and 2000 Ma when subparallel NW-trending diabase dikes invaded the Archean crust, marking the period of rifting under tensional stress directed NE-SW. Subsequently an ENE-trending rift zone was formed in the northern Baltic shield. This transversal rift zone formed a triple junction with the main rift zone located somewhere at the northern end of the Bothnian Bay. The continental crust split along a NW-trending line about 2100 Ma ago and the western part is thourought to have drifted away. The Svecokarelian geosyncline developed at a passive continental margin, and the Koillismaa aulacogen (Fig. 1) was formed on the failed arm of the triple junction (Gaál 1982, 1985 and Park et al. 1984).

At that eastern margin the Karelides are underlain by the platform sediments of the Jatulian group. The lowermost two formations of the Jatulian group are outsiders in the geosynclinal environment and are actually part of the basement complex. The Upper Jatulian formation, however, is indicative of shelf environment with deposition of carbonate rocks, carbonaceous metapelites, mafic volcanics, and Lake Superior type iron formations. The upper Jatulian is the oldest dated supracrustal rock assemblage of the geosynclinal complex: The carbonates yielded 2050 Ma and the iron formations 2080 Ma with the Pb-Pb method (Sakko and Laajoki 1975; Kouvo 1976).

The principal geosynclinal sediments of the Karelides are part of the Kalevian group, also known as the Ladogan group in Soviet Karelia. The Kalevian rocks can be divided into two tectonic-stratigraphic units, the external zone being in the east and the internal zone in the west (Gaál 1982). The external zone consists of more or less well preserved low- to medium-grade metaturbidites of the promixal type deposited on the continental margin above the Archean basement. The internal zone is made up of medium- to high-grade mica schists and gneisses interpreted as metamorphic derivates of distal-type metaturbidites. Especially typical of the internal zone is the Outokumpu association, a strongly deformed se-

quence of serpentinite, dolomite, calc-silicate rocks, cherty quartzite, black schists, and Cu-Co-Zn massive sulfide deposits. The association forms part of a large ophiolite nappe, an allochtonous unit deposited on oceanic crust and transported several tens of kilometers from the suture zone to the east (Koistinen 1981).

Mäkelä (1980) proposed a marginal basin underlain by transitional crust for the depositional environment of the Kalevian group. This concept was later supported by Gaál (1982) and Park (1984). The evolution of the marginal basin is presumably the consequence of the transformation of a passive continental margin into an active continental margin with subduction of oceanic crust under the Archean craton in the east.

*Suture zone: The Ladoga — Bothnian Bay — Skellefteå zone*

The western margin of the Archean is sliced and truncated by a fault system striking NW and NNW that separates the Karelidic schist belt from the Svecofennides. The special tectonic significance of this zone is expressed in its metallogenic features; it is in fact the most important metal-producing region in the Baltic shield. Its SE part, between Lake Ladoga and the Bothnian Bay in Finland, has been named the Main Sulphide Ore Belt (Kahma 1973) and its NE part, on the western side of the Bothnian Bay in Sweden, is known as the Skellefteå ore field. The special aspects of the Finnish side of the zone have been studied by several authors, *e.g.* Talvitie (1971), Gaál (1972, 1980, 1982, 1985), Brun (1980), Brun *et al.* (1981), Koistinen (1981), Neuvonen *et al.* (1981), Halden (1983) and Korsman *et al.* (1984).

A NW-trending belt of high-grade rocks of the low-pressure-high-temperature type within Svecokarelian metapelites fringes the SW margin of the Archean crust. Campbell (1980) suggested that the high-grade belt represents thickened crust uplifted by later isostatic movements. Korsman *et al.* (1984) emphasize the role of thermal domes but find tectonically thickened crust in southeastern Finland feasible.

At its southwestern margin the Archean basement is exposed in numerous mantled gneiss domes, indicating »softening» and remobilization of the Archean crust and leading to the diapiric rise of the granite-gneiss basement (Brun 1980).

The NW-striking faults are essentially dextral transcurrent faults (Gaál 1972, 1982, 1985; Halden 1983). They control the Kotalahti nickel belt, where synorogenic nickel-bearing mafic to ultramafic intrusions have been dated by the U-Pb method on zircons at 1982—1882 Ma (Neuvonen *et al.,* 1981). The Kotalahti nickel belt is characterized by a bimodal magmatic suite consisting of trondhjemites and tholeiitic intrusions. The environment is characterized by remnants of an eroded tholeiitic island-arc system generated by the early subduction of oceanic crust during the development of the marginal basin (Gaál 1982 and 1985). Scattered geochronological data along the suture zone indicate an interval 1930—1880 Ma (Helovuori 1979, Neuvonen *et al.* 1981 and Korsman *et al.* 1984) for the age of the development of the tholeiitic island-arcs. The system contributed comparatively little to the formation of new Proterozoic crust. The really effective crust-forming process culminated somewhat later, around 1880 Ma, when the extensive Svecofennian calc-alkaline island-arc system was formed farther west.

*Early Proterozoic island arcs: The Svecofennides*

The Svecofennides west of the suture zone are now widely accepted as ancient island arc environments (*e.g.* Hietanen 1975; Rickard and Zweifel 1975; Rickard 1979; Mäkelä 1980; Edelman and Jaanus-Järkkälä 1983). Well studied examples are the Skellefteå district (Rickard and Zweifel 1975) and the leptite zone of the Bergslagen district in Sweden, and the Aijala-Orijärvi zone (Latvalahti 1979), the Tampere schist belt, the Ylivieska area (Salli 1964), the Haukivesi area (Gaál and Rauhamäki 1971), the Pyhäsalmi-

Kiuruvesi area (Marttila 1976) and Pihtipudas (Aho 1979) in Finland.

The volcano-sedimentary belts are characterized by calc-alkaline felsic to intermediary volcanic rocks with predominant pyroclastic structures. Subordinately, tholeiitic volcanics with pillow lava structures occur. The volcanic centres are surrounded by sediments containing volcanic intercalations. The supracrustal rocks are often well preserved and exhibit low-to medium-grade metamorphism. They have been intruded by numerous granitoid stocks and batholiths dated by the U-Pb method on zircons at 1900—1850 Ma (Simonen 1980; Welin *et al.* 1980 a, b). Extensive submarine hydrothermal alteration and alkalimetasomatism has been described in connention with calc-alkaline volcanism (Lageblad and Gorbatschev 1984).

The characteristic sediments around the volcanic centers are proximal volcanogenic turbidites with well preserved primary structures. These rocks grade into mica schists, mica gneisses and migmatites, forming belts between volcanic zones. A geochronological study of the migmatites has shown that the major phases of deformation, metamorphism and migmatization, occurred within a short time span between 1885 and 1900 Ma (Hopgood *et al.* 1983).

An especially characteristic feature of the Svecofennides is the extensive and manifold plutonism. Numerous granitoid batholiths have ages close to those of the volcanics and associated gabbros and diorites. Both chemical characteristics and low $^{87}Sr/^{86}Sr$ ratios indicate I-type granitoids that could have been generated in connection with an Andinotype subduction zone (Wilson 1980, 1982; Nurmi 1984 and Nurmi *et al.* 1984). These results are corroborated by a study on hafnium isotope ratios in Svecofennic mafic plutonic rocks implying mantle origin (Patchett *et al.* 1981).

The Svecofennides are intruded by granitoids of the age group 1750—1550 Ma comprising rapakivi granites and the granite porphyry belt of the western Baltic shield. These rocks are encoun-

tered in an E-W-trending belt in which the $I_{Sr}$ values and the potassium content increases eastward. This zonation and other chemical variation indicate possible subduction eastward from a zone located somewhere west of the coast of Norway (Lindh and Gorbatschev, 1984).

### Intercontinental collision belt: The granulite complex of Lapland

The granulite complex is an arcuate belt composed of granulite-facies rocks extending from the Caledonides of northern Norway across Finnish Lapland into the western part of the Kola Peninsula, USSR. It reappears as an isolated patch on the northern shore of the Kandalashka Bay on the northern shore of the White Sea (Meriläinen 1976; Hörmann *et al.* 1980; Barbey 1982; Barbey *et al.* 1984). The belt is composed of high-grade metamorphosed derivates of a geosynclinal sequence consisting of graywackes and metapelites, the khondalite suite (Barbey *et al.* 1982), metavolcanites, and felsic to mafic plutonic rocks. In the south it is bordered by a low-angle thrust zone dipping N, NE and E. In the north it is bordered by migmatitic gneisses of the Archean basement in a zone with subvertical dips. The granulite complex was earlier thought to be Archean, or at least partly Archean, in age (Simonen 1980). Hörmann *et al.* (1980) ascribed the metavolcanics within the belt to a Lower Proterozoic subduction. Manifold geochronological work (U-Pb, Pb-Pb, Rb-Sr, Nd-Sm) indicates currently indisputable Proterozoic ages of between 1800 and 2200 Ma (Meriläinen 1976; Tugarinov and Bibikova 1980; Bernard-Griffiths *et al.* 1984).

Geochronological constraints and the present data on petrology and structure favor interpreting the granulite complex as a high-grade mobile belt that evolved as a result of continent-continent collision. A phase of rifting and deposition on oceanic crust was followed by a compressional phase 2000 Ma ago synchronous-

ly with the opening of the Svecokarelian geosyn-
cline resulting in a subduction zone dipping to
NE (Barbey 1982 and Barbey *et al.* 1984).

In the opinion of the present author several
problems remain unresolved in respect of the
granulite complex. The major problem is the
nature of the connection with the Late Archean
Belomorian gneisses. The thrust of the Belomo-
rian gneisses onto the low-grade terrain to the SW
in probably an Early Proterozoic event correlat-
able with the thrust of the granulites of Lapland
to the S, SW and W (Barbey *et al.* 1984).

*Early Proterozoic plate tectonic models*

Various plate tectonic models have been
applied to the Svecokarelides since the early
seventies (Hietanen 1975; Rickard 1979; Berthel-
sen 1980; Campbell 1980; Mäkelä 1980; Bowes
and Gaál 1981; Koistinen 1981; Gaál 1982a,
1982c; Walser and Einarsson 1982; Wilson 1982;
Edelman and Jaanus-Järkkälä 1983; Park *et al.*
1984). The initially large divergence of opinion
seems to have narrowed down during the last two
years to arrive at a model whose essential features
were stated by Hietanen in 1975. Unanimity exists
in assuming a general Circum Pacific-type colli-
sion model, although opinions differ as to the
direction of subduction, the role of microplates,
aulacogens, and some details of the mechanism.
Nevertheless, the Circum Pacific-type model has
the advantage that it explains features such as
transcurrent faults along the plate margin,
thrusts, magmatism, metamorphic zoning, and
metallogeny. There is no point in debating which
model is better or more elegant, and the time is
ripe for a comprehensive synthetic work integrat-
ing the wealth of geoscientific data that has ac-
cumulated in the course of regional surveys and
prospecting along the Ladoga — Bothnian Bay
— Skellefteå zone and in the Svecofennian
volcano-sedimentary belts.

Fig. 4. illustrates the plate tectonic concept out-
lined above. The first stage is characterized by
the development of the marginal basin and the

tholeiitic island-arc system on the active plate
margin. The second stage is envisaged along the
lines suggested by Hietanen (1985) with the ad-
dition of the ophiolite mappes and the suture
zone as well as with a more detailed view on the
generation depths of the various magma types.

**Mid-Proterozoic to Late Proterozoic cycles**

During Mid-Proterozoic to Late Proterozoic
times orogenic activity occurred in two cycles
restricted to the southwestern Baltic shield, west
of the Småland — Wärmland granite-porphyry
belt. The bulk of the crust was generated during
the Mid-Proterozoic Southwest orogen in the pe-
riod between 1780 and 1550 Ma (Gorbatschev
1980; Gorbatschev *et al.* 1984). The Late Pro-
terozoic Sveconorwegian cycle was a period of
reworking of the Mid-Proterozoic crust, with
minor crustal accretion by synkinematic mag-
matism (Falkum and Pedersen 1980).

*Mid-Proterozoic high-grade belt:
The Southwest Orogen*

The lithology of the Southwest Orogen is made
up of medium- to high-grade orthogneisses and
paragneisses. Supracrustal sequences are divided
into the Åmål facies with felsic metavolcanics,
arkosic to quartzitic arenites, and meta-argillites
and into the Stora Le-Marstrand facies consisting
of graywackes, schists, and metabasalts (Gor-
batschev 1980). The orthogneisses are tonalitic
to granodioritic in composition. The oldest
known geochronological age is 1780 Ma, and the
youngest, obtained from diabase dikes, 1550 Ma
(Welin and Kähr 1980; Welin *et al.* 1980c). The
low $I_{Sr}$ values of granites testify to mantle-derived
material. The older gneisses are unconformably
overlain by supracrustals deposited between 1600
and 1000 Ma, known in Sweden as Dal and Kap-
pebo groups, and in Norway as the Telemark
suite. Field and Råheim (1981) have produced
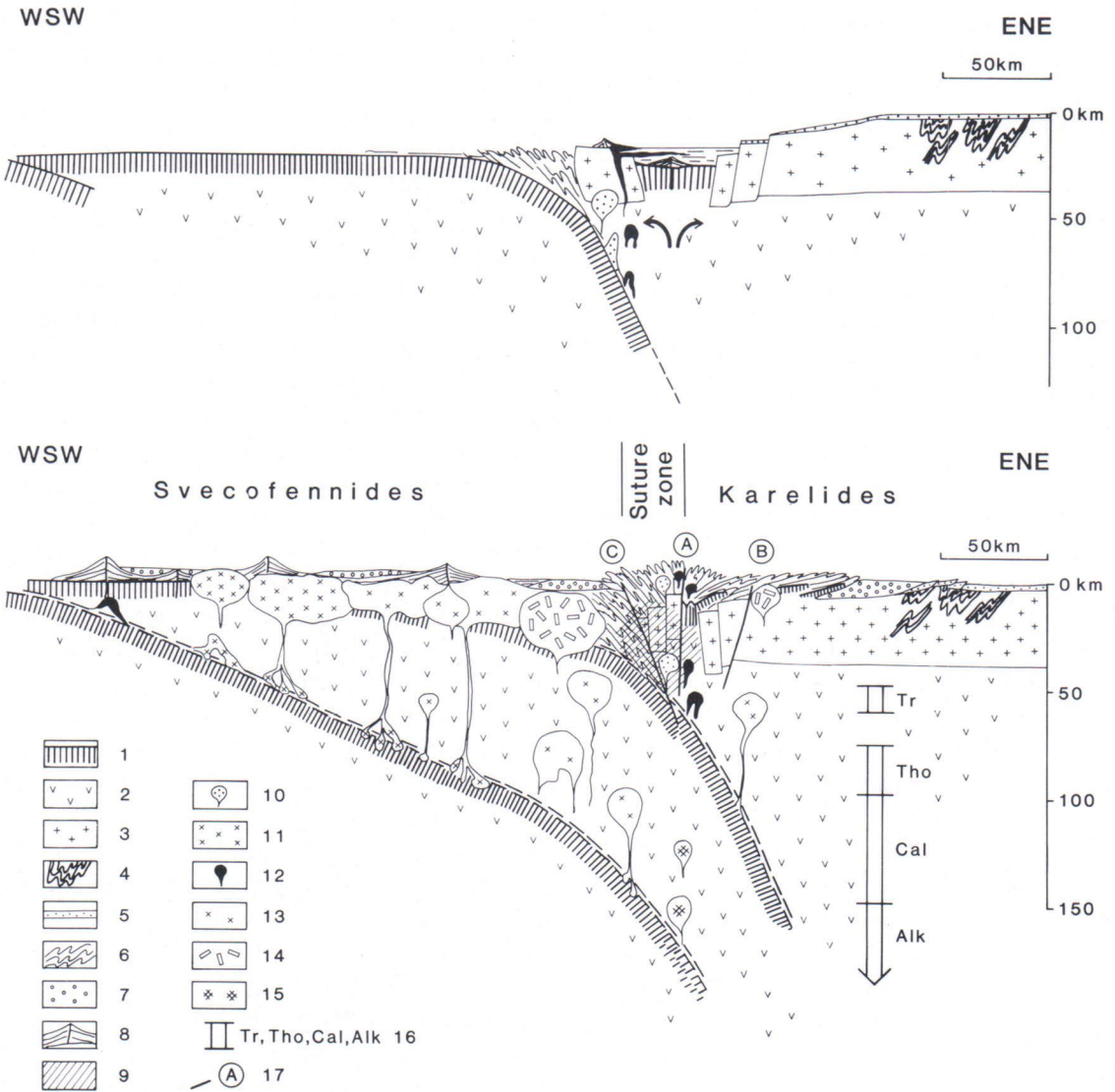geochronological evidence for a high-grade evo-

Fig. 4. Plate tectonic model for the Svecokarelian cycle of the Baltic shield c. 1920 Ma ago (above) and c. 1880 Ma ago (below), approximately to scale. Explanations: 1. Oceanic crust, 2. Upper mantle, 3. Archean granitoids, 4. Archean greenstone belts, 5. Early Proterozoic platform cover, 6. Eugeosynclinal sediments, 7. Younger proximal turbidites, 8. Volcanic rocks, 9. High-grade metamorphism, 10. Trondhjemite-tonalite magma, 11. Tholeiite magma, 12. Ni-bearing gabbro-peridotite, 13. Calc-alkaline magma, 14. Porphyritic granite-granodiorite, 15. Alkaline magma, 16. Generation depth of trondhjemite-tonalite (Tr), tholeiitic (Tho), calc-alkaline (Cal) and alkaline (Alk) magma, 17. Faults: A. Haukivesi fault, B. Suvasvesi fault, C. Pihlajavesi/Kolkonjärvi fault.

lutionary event in southern Norway in the period between 1600 and 1500 Ma.

*Grenvillian segment: The Sveconorwegian cycle*

The newly formed Mid-Proterozoic crust re-mained undisturbed during the anorogenic stage, the Gothian period between 1600 and 1300 Ma (Falkum and Peterson 1980). East-west compression affected the crust during the orogenic stage, the Sveconorwegian period between 1200 and

1000 Ma, forming a mobile belt trending N-S with vergence to E. This pattern has been explained by Falkum and Pedersen (1980) as a Cordilleran-type collision belt with a subduction zone dipping to E, the hypothetical trench being situated parallel to the western coast-line of Norway. No regional high-grade reworking has been found in connection with the Sveconorwegian cycle (Field and Råheim 1981). In the western zone the lithology is dominated by synkinematic intrusions, but in the east the pre-Sveconorwegian crust has been reworked in east-vergent low-angle thrusts. This has been correlated with the Grenville front (Zwart and Dornsiepen 1978; Falkum and Pedersen 1980; Berthelsen 1980; and Baer 1981). K-Ar ages of about 1000 Ma within the zone led to the interpretation of a continent-continent collision suture, the »Sveconorwegian Front» (Burke *et al.* 1977; Berthelsen 1980).

Looked at in detail, the easternmost part of the orogeny consists of two subparallel cataclastic belts trending N-S, each of which has resolved into a wide subvertical cataclastic belt and a narrow subvertical thrust zones. The eastern belt, the »Sveconorwegian Front», has been named the »Protogine zone» and the western belt the Mylonite zone (Gorbatschev 1980). Owing to the occurrence of 1500-Ma-old granites and the lack of ultramafic rocks in the Protogine zone it has been interpreted as an ensialic structure instead of a suture (Gorbatschev *et al.* 1984).

## Extensions of the Baltic shield

The Precambrian of the Baltic shield submerges under the Phanerozoic cover of the East European platform in the south. Precambrian rocks reappear in the Ukraine, in the Voronezh shield, and in the Ukrainan shield. Analogies between the Ukrainian shield and the Baltic shield have been pointed out by Semenenko (1972) and confirmed by the recent geologic map of the Ukrainian shield (Shcherbak 1984). Other geologic

maps based on drill core data and geophysics are available of the Precambrian surface under the platform cover (Znosko 1972; Bogdanova and Gafarov 1978; Aksamentova *et al.* 1982; Garetskiy 1982). Based on these data a schematic map has been compiled in Fig. 5.

We could attempt to interpret the available data using the Baltic shield as a model. Correlations are made difficult by the lack of reliable isotopic data (available only on the Ukrainan shield) and some misconceptions, for instance, high-grade terrains are interpreted automatically as Early Archean, a common belief in the literature (see as example Salop 1977). Granulite-facies rocks in the Baltic shield were formed in four periods: 2900—2700 Ma (Belomorian and Kolan gneisses), 2000—1900 Ma (Granulite complex of Lapland), 1900—1800 Ma (Svecofennian), and 1600—1500 Ma (Southwest Orogen). It is almost certain that at least some of the Proterozoic granulite belts have analogies under the East European platform, for instance, the granulites in the SW part of the Ukrainian shield can easily be interpreted as equivalents of the Svecofennian high-grade belts.

Kulikov *et al.* (1984) have pointed out similarities between the Archean bedrocks of the Baltic shield and the Ukrainian shield and postulated the existence of a 3000 km long N-S trending East European greenstone superbelt comparable in style and dimension to some Phanerozoic fold belts.

Some general statements can be made concerning the Svecokarelian orogenic belt in northern and eastern Europe. Both Karelian and Svecofennian belts continue southward in the Baltic region, northern Poland and in the western part of the Ukrainian shield; how much is underlain by Archean crust and how much is juvenile Proterozoic crust cannot be estimated from the data available. The structural trends within the assumed Early Proterozoic belt are very different, partly perhaps because of primary arc patterns and partly because of superposed deformations. The overall N-S trend along the western margin
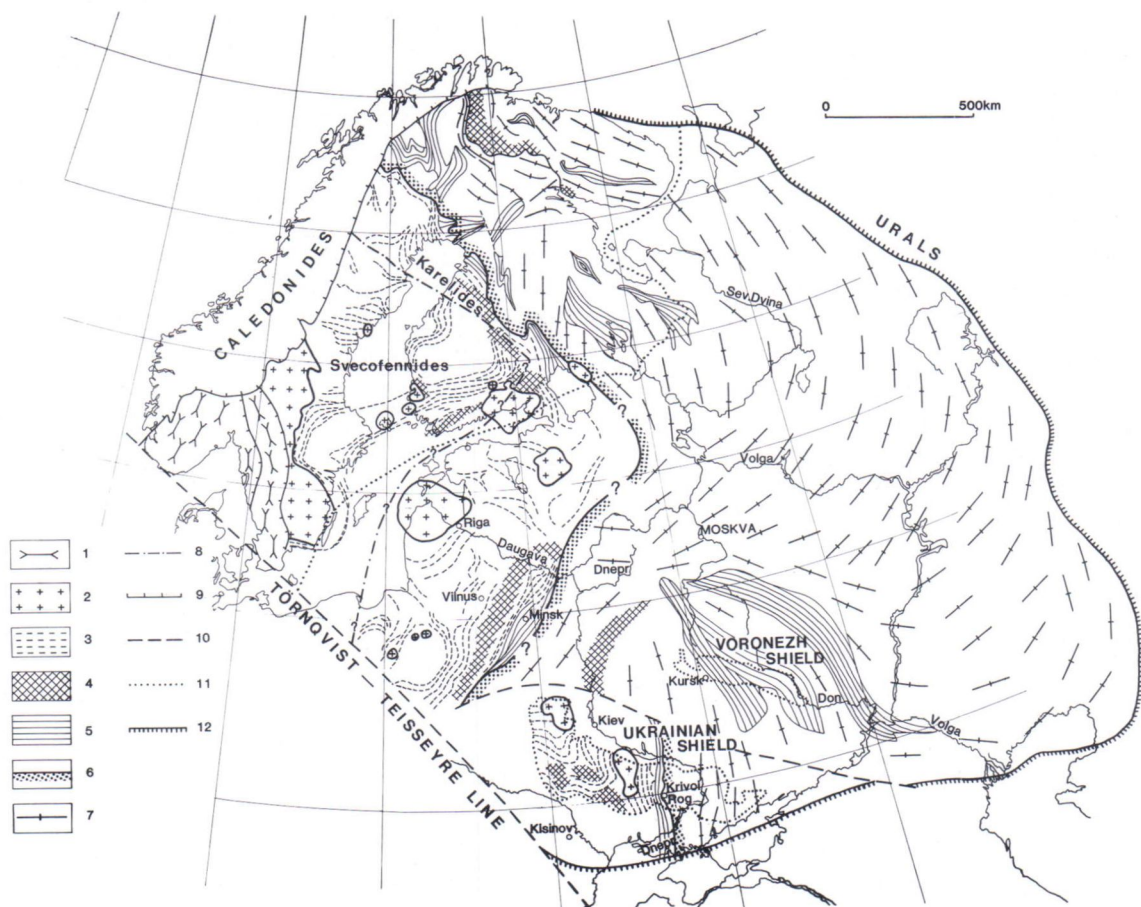
Fig. 5. The Precambrian of northern and eastern Europe. Explanation: 1. Late to Mid-Proterozoic gneisses, 2. Rapakivi granites and associated rocks, 3. Early Proterozoic geosynclinal rocks. 4. High-grade gneisses (granulite facies), 5. Early Proterozoic sediments and volcanics deposited on platforms or continental margins, 6. The eastern boundary of the Early Proterozoic geosynclinal system. 7. Archean, 8. Western limit of Archean crust, 9. Thrust, 10. Fault, 11. Shield boundary, 12. Platform boundary.

of an Archean craton is, however, indisputable and it is also marked by the occurrence of rapakivi granites and associated rocks. The Early Proterozoic belt is bordered in the SW by the Törnqvist—Teisseyre line, and in the south it is truncated by the Alpine system (Strupka 1980).

## Conclusions

Plate tectonic processes generated continental crust since at least the beginning of, the Late Archean cycle 2900 Ma ago. Ensialic crust older than 2900 Ma existed in the basement of the greenstone belts, forming the nucleus of the eastern-central part of the Baltic shield and probably accreting eastward during the Late Archean. The nature and extent of the Early Archean crust are both unknown and should be studied in suspected areas in Finland and Soviet Karelia, where ages older than hitherto known might be obtained. Supracrustal rocks 3650 Ma old in an analogous position, close to the Archean-Early Proterozoic boundary have been discovered

in the Ukrainian shield (Shcherbak 1984). Also some of the supracrustal fragments in the Archean granitoid terrain of eastern and central Finland may be part of an older greenstone belt association.

With the generation of a passive continental margin 2100 Ma ago a tectonic set-up was created that prevailed into Late Proterozoic times. Substantial juvenile crust was formed by accretion above Circum Pacific-type subduction zones with eastward dips shifting stepwise westward.

The continental crust of Europe continued to grow in Phanerozoic times, basically through similar processes. After the Caledonian mountain chains were created by the continent-conti-

nent collision of the Fennosarmatian platform with the Laurentian—Greenland landmass, the tectonic realm in Devonian and Early Carboniferous times was again dominated by continued subduction of the Proto-Tethys plate at an arc-trench system parallel to the southern margin of Laurasia (Ziegler 1984). The Alpine system has closed this history of plate tectonic processes by the continent-continent collision of the Eurasian plate with the African plate. The 2200-million-year geologic evolution of Baltic shield fits into a continuous tectonic process forming and shaping the continental crust during at least half of the Earths history.

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