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TECTONIC EVOLUTION OF THE PALAEOPROTEROZOIC SVECOFENNIAN OROGEN IN SOUTHWESTERN FINLAND

by

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The tectonic evolution of the Svecofennian Orogen in southwestern Finland can be divided into pre-collisional, collisional and post-collisional stages. The pre-collisional stage includes the formation of the Southern Svecofennian Arc Complex, rifting of the arc complex and filling of the basin(s) with mafic and ultramafic lavas and erosional sediments. In the Orijärvi area, the oldest arc type volcanic rock was dated at 1895 Ma from the bimodal Orijärvi formation and the youngest at 1878 Ma from the mature Kisko formation. The Orijärvi granodiorite was dated at 1898 Ma which together with the similar geochemistry to the felsic volcanic rocks, implies that it is a synvolcanic intrusion. SIMS ages on detrital zircons in sedimentary rocks yield ages between 2.9-1.97 Ga suggesting that the erosional detritus was derived from outside the Southern Svecofennian Arc Complex.

The U-Pb ages of the synorogenic intrusions, now verified by the ion microprobe SIMS dating, indicate that collision of the Southern Svecofennian Arc Complex with the Central Svecofennian Arc Complex took place at 1.88-1.86 Ga. Zircon populations in synorogenic intrusions also included inherited older Palaeoproterozoic and Archaean zircons. Deformation related to the main collision is expressed by a D_1/D_2 deformation recorded as a bedding-parallel S_1 mica foliation deformed into tight to isoclinal D_2 folds with subhorizontal axial planes and a penetrative S_2 axial plane foliation. The syntectonic tonalites were emplaced during D_2 as sheet intrusions. In the Turku migmatite complex garnet and cordierite of the first generation are mostly breakdown products of biotite and sillimanite and their growth is mainly syntectonic with D_2 as they are elongated within the S_2 plane and deformed by D_3 folds.

The post-collisional convergence transposed previous structures into NE-SW or E-W trending upright or NW overturned D_3 folds. Granitic veins and dykes were intruded along S_3 axial planes. Large D_3 fold limbs are often strongly deformed, intensely migmatized and intruded by garnet- and cordierite-bearing granites. These observations suggest that the potassium-rich leucosomes, now dated at 1824 Ma, provide the age of D_3 deformation. Crustal anatexis continued until ca. 1810 Ma. Pressure and temperature estimates from garnet and cordierite indicate that the granulites reached temperatures in excess of 800 °C at approximately 6 kbar pressure while the adjacent amphibolite facies rocks crystallized at 100-150 °C and 1-2 kbar lower temperatures and pressures. Zircons in enderbites display synorogenic core ages of ca. 1.88-1.87 Ga and metamorphic overgrowths at ca. 1.83-1.80 Ga. It is suggested here that mafic mantle derived magmatism provided heat for granulite facies metamorphism. Mafic rocks are shoshonitic monzodiorites that triggered anatexis and formation of S-type anatectic granites, both dated at 1815 Ma. The geochemical characteristics of the mafic rocks suggest that they were derived from the subcontinental lithospheric mantle, that was previously enriched by fluids released during earlier subduction. It is suggested here that the hot upwelling asthenosphere convectively removed the subcontinental lithospheric mantle and raised the temperature. This triggered partial melting of the enriched parts of the mantle. Uprising mafic melts increased the already high temperatures at mid-crustal levels and caused granulite facies metamorphism, crustal anatexis and production of granitic melts.

The zircon ages of the volcanic and plutonic rocks indicate that pre-collisional and collisional stages of crustal evolution are ca. 10 Ma younger in the Southern Svecofennian Arc Complex than in the Central Svecofennian Arc Complex. Therefore, the evolution of the Svecofennian orogeny is diachronous with younging of successive orogenic events from the Archaean craton towards the southwest.

Keywords: tectonics, volcanic arcs, back-arc basin, synvolcanic magmatism, arc accretion, collision, diachronous evolution, geochronology, lithospheric thinning, mafic intraplating, high grade metamorphism, Finland

CONTENTS

PREFACE

This thesis consists of an introductory chapter (synopsis) and four articles referred to as their Roman numerals in the text.

Synopsis

Paper I
Väisänen Markku and Mänttäri Irmeli 2002. 1.90-1.88 Ga arc and back-arc basin in the Orijärvi area, SW Finland. *Bulletin of the Geological Society of Finland 74 (1-2), xxx-yyy* (in press)

Paper II
Väisänen Markku and Hölttä Pentti 1999. Structural and metamorphic evolution of the Turku migmatite complex, southwestern Finland. *Bulletin of the Geological Society of Finland 71 (1), 177-218.*

Paper III
Väisänen Markku, Mänttäri Irmeli and Hölttä Pentti 2002. Svecofennian magmatic and metamorphic evolution in southwestern Finland as revealed by U-Pb zircon SIMS geochronology. *Precambrian Research 116 (1-2), 111-127.*

Paper IV
Väisänen Markku, Mänttäri Irmeli, Kriegsman Leo M. and Hölttä Pentti 2000. Tectonic setting of post-collisional magmatism in the Palaeoproterozoic Svecofennian Orogen, SW Finland. *Lithos 54 (1-2), 63-81*.

SCOPE OF THE STUDY

The present thesis consists of four separate papers and an introductory chapter. Three of the papers are already published and one is in press. The main objective of the thesis is to study the tectonic evolution of the Palaeoproterozoic Svecofennian orogen in southwestern Finland. For the study area, see Fig. 1. The applied working methods have been a) geological mapping, b) structural geology, d) geochemistry of plutonic and volcanic rocks, e) ion microprobe (SIMS) dating and conventional U-Pb zircon and titanite dating of magmatic and volcanic rocks and f) metamorphic petrology.

Paper I describes the stratigraphy and the geochemical evolution of the volcanic and plutonic rocks in the Orijärvi area. The study is based on field mapping and basic structural geology of selected subareas in order to reveal different volcanic formations in the study area. Four formations were sampled for geochemistry and two formations were sampled for conventional U-Pb dating. The geochemistry and radiometric age determination were used to interpret the tectonic setting of the study area and the results were used to discuss the formation and tectonic setting of volcanic arc complexes in southern Finland. Irmeli Mänttäri performed the U-Pb dating.

Paper II investigates the structural, metamorphic and magmatic events in the Turku area. The work is based on extensive field work performed in co-operation with Pentti Hölttä. The purpose of this study was to establish the structural and metamorphic evolution of the high-grade Turku migmatite area, and define the mutual relationships and relative timing between structures, metamorphism and different magmatic events. This study is a contribution to the Finnish segment of the Global Geoscience Transects (GGT) Project, led by Kalevi Korsman and Toivo Korja from the Geological Survey of Finland (Korsman and Korja, 1999). Pentti Hölttä is responsible for metamorphic data.

Paper III documents the results of the U-Pb zircon ion microprobe (SIMS) dating performed at the NORDSIM laboratory in Stockholm. The aim of the study was to precisely define the age of peak metamorphism in the Turku granulite area, investigate and date the zircons in intrusive rocks in- and outside of the granulite area and compare the ages obtained with the conventional U-Pb zircon ages. The results are used to discuss the timing of deformation, magmatic and tectonic events and to discuss their regional significance. The work was performed in co-operation with Irmeli Mänttäri and Pentti Hölttä.

Paper IV describes the bimodal post-collisional magmatism in the Turku area discovered during the geological mapping. The purpose of this study was to date intrusions by the conventional U-Pb zircon method, define the intrusion depth by the pressure calculations on the contact metamorphic mineral parageneses and infer the petrogenesis of the intrusions by geochemistry. These results were used to interpret the tectonic setting of post-collisional magmatism in southern Finland. Irmeli Mänttäri performed the U-Pb dating, Leo Kriegsman did the P-T work on the contact metamorphism and Pentti Hölttä provided the microprobe mineral analyses.

INTRODUCTION TO THE FENNOSCANDIAN SHIELD IN FINLAND

The Fennoscandian Shield consists of the Archaean craton in the northeast, the Palaeoproterozoic Svecofennian orogen in the centre and the Southwestern Scandinavian Domain in the southwest (Nironen, 1997). The Archaean craton was rifted at several occasions and ocean floor was formed at ca. 1.95, now preserved as the obducted Jormua and Outokumpu ophiolites (Koistinen, 1981; Kontinen, 1987; Peltonen et al., 1996). The Palaeoproterozoic Svecofennian crust in Finland was formed by at least three pre-Svecofennian island arc complexes that collided with each other and with the Archaean craton creating during the Svecofennian Orogen (e.g. Lahtinen, 1994; Nironen, 1997; Korsman et al., 1999; Nironen et al., 2000; Rämö et al., 2001). These complexes have recently been described as different terranes (Nironen et al., 2000; Rämö et al., 2001). The names of these arc complexes or terranes vary considerably and the consensus of nomenclature is yet to come. Here the three terranes are called the Primitive Arc Complex (PAC) in the north close to the Archaean boundary, the Central Svecofennian Arc Complex (CSAC) in the centre and the Southern Svecofennian Arc Complex (SSAC) in the south (Fig. 1 inset). Terrane(s) further to the southwest in Sweden are outside the scope of this study. The PAC and the CSAC were accreted to the Archaean craton at ca. 1.91-1.89 Ga and the SSAC collided with the older arc complexes at ca. 1.89-1.88 Ga (Lahtinen, 1994; Korsman et al., 1999). After collisional tectonics, extensional collapse followed but large-scale crustal thinning and uplift was inhibited and isostatic balance was in density variations within the crust (Korsman and Korja, 1999). New data and interpretations of the timing of some of these processes are presented in this thesis (Papers I-IV).

The evolution of the CSAC greatly differs from that of the SSAC in that the crust in the CSAC was stabilized immediately after the main collisional stage at ca. 1880 Ma (Nironen et al., 2000) while the convergent process continued in the SSAC (Ehlers et al., 1993; Lahtinen, 1994; Paper II; Paper IV). This process roughly coincides with the peak metamorphism that locally reached granulite facies and caused wide-spread crustal anatexis and formation of migmatites and S-type potassium rich granites, typical for the geology in southernmost Finland (Korsman et al., 1984; Hölttä, 1986; Schreurs and Westra, 1986; Paper II). Therefore, Ehlers et al. (1993) designated the zone as the Late Svecofennian Granite-Migmatite Zone (LSGM) and they concluded that convergence was oblique to the trend of the orogen, i.e. transpressional. An alternative view of the tectonic evolution of the LSGM is provided by Korja and Heikkinen (1995) and Nironen (1997). They argue that the high heat flow and the intrusion of anatectic granites took place during the extensional collapse of an overthickened orogen.

Names of the volcanic and sedimentary belts in this thesis do not follow a strict and consequent nomenclature. This is because in Paper I and in this synopsis the latest recommendations (Nironen et al., 2002) are used that are slightly different to those in Papers II-IV.

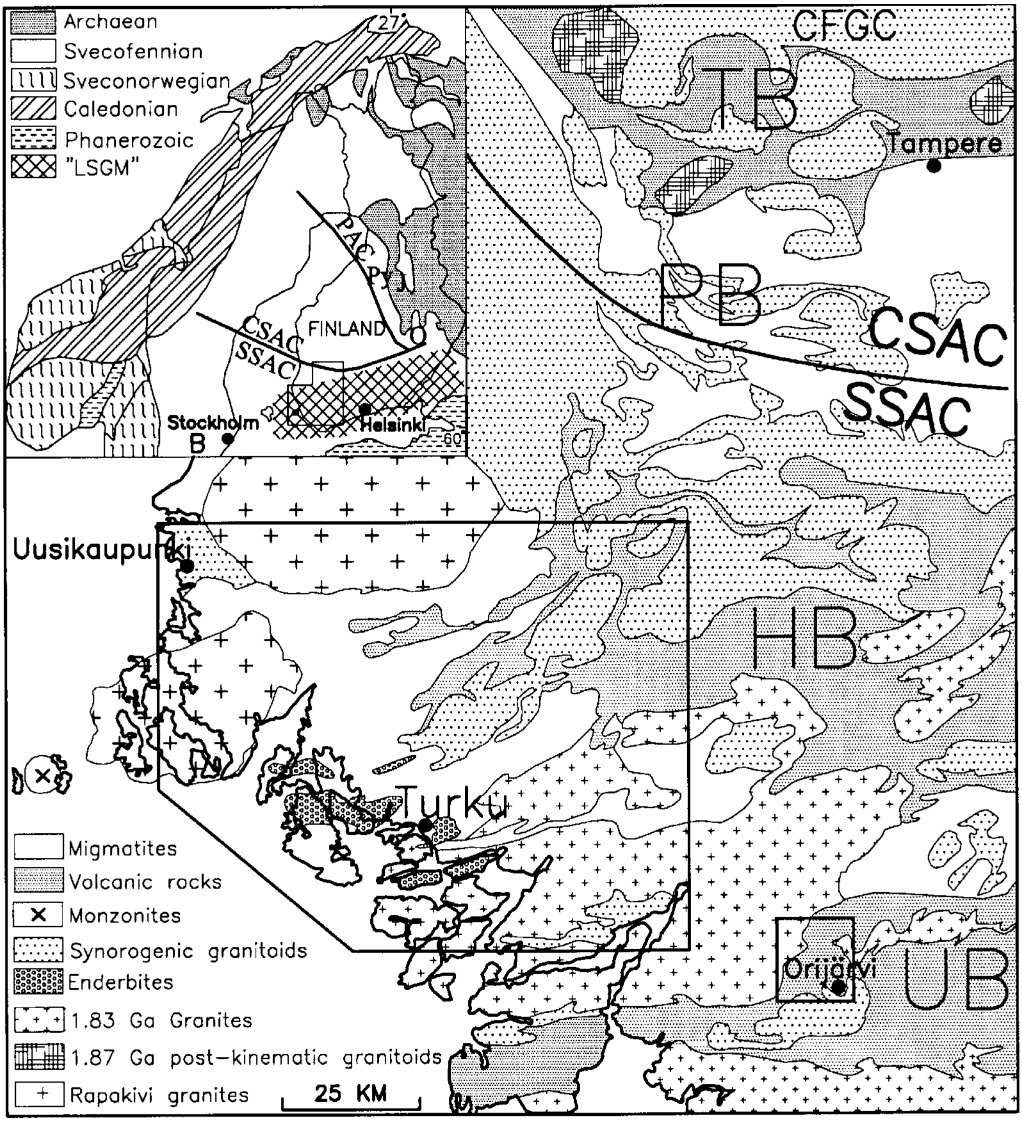

Fig. 1. Geological map of the southwestern Finland according to Korsman et al. (1997). Study areas displayed by a polygon (Turku) and a square (Orijärvi). B=Bergslagen; CFGC=Central Finland Granitoid Complex; CSAC=Central Svecofennian Arc Complex; HB=Häme Belt; J=Jormua; LSGM=Late Svecofennian Granite-Migmatite Zone; O=Outokumpu; PAC=Primitive Arc Complex; PB=Pirkanmaa Belt; Py=Pyhäsalmi; SSAC=Southern Svecofennian Arc Complex; TB=Tampere Belt; UB=Uusimaa Belt. Thick lines represent terrane boundaries after Sundblad (1991), Lahtinen (1996), Nironen et al. (2000) and Rämö et al. (2001).

TECTONIC EVOLUTION OF THE SVECOFENNIAN OROGEN IN FINLAND

The Svecofennian orogen has been classified as an arc-accretionary orogen (Gaál and Gorbatschev, 1987; Lahtinen, 1994; Windley, 1995; Nironen, 1997) after the pioneering work of Hietanen (1975), who was the first to point out the similarities between the Svecofennian volcanic and sedimentary formations and younger island arc complexes. After the formation of the arc complexes, they were accreted to (i.e. collided) with the Archaean craton and to each other. Coward (1994) discusses collisional tectonics and divided the different stages of deformation, relative to ocean closure, into pre-collisional, collisional and post-collisional tectonics. Although originally applied to continental collision, the terminology suits well even for collision of island arcs and is therefore used here. Although the term orogeny *sensu stricto* should be restricted to deformation processes, and lithologies involved should be designated separately, here the rocks are also called Svecofennian. Recent good reviews of the subject have been provided by Korja (1995), Nironen (1997) and Korsman et al. (1999).

Pre-collisional tectonics

Since Hietanen's hypothesis (1975) of island arc complexes, the tectonic setting for many of the Palaeoproterozoic geological formations in the Fennoscandian Shield has been widely accepted. Nironen (1997) and Korsman et al. (1999) provide the latest tectonic reviews on this issue and Lahtinen (1994, 1996) gives a detailed description on the geochemistry of selected samples from the CSAC and the SSAC. The main arguments provided in these and other descriptions (see more references in Lahtinen, 1994, 1996 and Korsman et al., 1999) are described below.

The oldest volcanic rocks dated at 1921±2 Ma are rhyolites from the bimodal island arc type rocks found in the Primitive Arc Complex along the Archaean boundary in Pyhäsalmi (Fig. 1 inset). They are closely associated with a younger set of more mature arc type volcanic rocks (Kousa et al., 1994). These are roughly coeval with gneissic tonalites found within the same zone and Lahtinen (1994) interprets them as subvolcanic intrusions. In spite of the present day proximity of the Archaean craton, the ϵ_{Nd} values are distinctly positive, on average +2.5, suggesting very little or no Archaean sources in the PAC magmatism (Lahtinen and Huhma, 1997). This suggests that at the time of formation, the PAC was separated from the Archaean craton, probably by an oceanic crust, now exposed in the Outokumpu and Jormua ophiolite complexes (Koistinen, 1981; Kontinen, 1987).

Towards the southwest, the supracrustal rocks of the Tampere Belt (Kähkönen, 1999) occur along the southern boundary of the large Central Finland Granitoid Complex. Evolved arc or continental margin type volcanic rocks dominate, dated at 1905-1890 Ma (Kähkönen et al., 1989). The Haveri formation makes an exception as it almost exclusively consists of E-MORB type basalts interpreted to have formed at the marginal basin (Kähkönen and Nironen, 1994). Isotopic compositions suggest a crustal history older than those of the other formations in the Tampere Belt and a correlation with the 1.95 Ga Jormua and Outokumpu ophiolites is possible, indicating rifting of a pre-existing older crust and eruptions tapping an underlying enriched mantle (Vaasjoki and Huhma, 1999). Detrital zircons dated by ion microprobe (SHRIMP, Claesson et al., 1993), whole rock geochemistry and initial ϵ_{Nd} values of igneous rocks suggest that ~ 2.0-2.1 Ga "protocrust", or "Fairyland" according to Kähkönen (1999), underlies the present erosion surface of the

CSAC (Lahtinen and Huhma, 1997).

There is growing evidence indicating that the SSAC and the CSAC were not originally part of the same arc complex. Park (1991) and Sundblad (1991) were the first to apply the concept of terranes in describing the domains of differing structural and lead isotopic characteristics to the Palaeoproterozoic Fennoscandian Shield and they proposed a terrane boundary south of the Tampere Belt. Recently, Rämö et al. (2001), using Pb and Sm-Nd isotopes, reached the same conclusion. The geochemistry of igneous rocks also points in the same direction. The Tampere Belt in the CSAC mainly comprises evolved arc or continental margin type volcanic rocks and related sediments (Kähkönen, 1989), whereas the Häme Belt within the SSAC shows a more primitive arc type geochemistry and thinner crust, suggesting separate mantle and crustal sources for these terranes (Lahtinen, 1996). MORB type volcanic rocks found within the Pirkanmaa Belt (Peltonen, 1995) are interpreted to represent fragments of former oceanic crust. Furthermore, detrital zircons in the Tampere and Orijärvi areas display different age populations (Claesson et al., 1993), supporting the idea of the existence of a former ocean between these areas. Based on data presented above and other geological arguments, Lahtinen (1994, 1996) proposed a suture zone between these arcs approximately along the Pirkanmaa Belt (Fig. 1 inset and Fig. 2).

Volcanic rocks of *the Orijärvi area* within the SSAC were investigated in this study (Fig. 1, Paper I). The area consists of four volcanic formations with different rock types and geochemistry. *The Orijärvi formation* is lowermost in the stratigraphy and shows a bimodal distribution of silica contents in volcanic rocks. The geochemistry of the mafic rocks displays a depletion in HFSE (high field strength elements) and an enrichment in LILE (large ion lithophile elements) interpreted to represent a subduction component. Basalts at low stratigraphic levels have the least differentiated chemical compositions and an oceanic subduction system is suggested. On the other hand, the bimodality in combination with the occurrence of marbles and iron formations point to a tensional (rift) tectonic setting similar to the Bergslagen area in central Sweden (Allen et al., 1996). A combination of these two processes is favoured here, i.e. tensional stresses during overall compressional subduction-related forces. A rhyolitic flow at a low stratigraphic level within the bimodal sequence was dated in this study with the conventional U-Pb zircon method, yielding an age of 1895.3±2.4 Ma.

Metasedimentary rocks overlying the Orijärvi formation contain detrital zircons. Only Archaean and older Palaeoproterozoic (dominantly 2.1 Ga and 2.7 Ga) zircons were found in the ion microprobe (SHRIMP) investigation (Claesson et al., 1993). This indicates that the volcanism preceding the sedimentation was subaqueous and not capable of producing erosional detritus. Therefore, sediments must have been transported from outside the present arc, probably from an older crystalline source. Recent investigations suggest, however, that less mature source material was also involved (Lahtinen et al., 2002).

Overlying the sedimentary formation is the volcanic *Kisko formation* where bimodality is not as pronounced as in the Orijärvi formation and where andesitic volcanic rocks are encountered. The overall geochemistry shows LILE enrichments suggesting an evolved arc type magmatism. In the upper part of the formation a dacite sample yielded a conventional U-Pb zircon age of 1878.2±3.4 Ma. The same sample also contains titanite that yielded a conventional U-Pb age of 1798±3 Ma. This age is interpreted to reflect cooling to below the blocking temperature of titanite (Paper I).

The Toija formation represents the initial stage of arc rifting where basalts show a geochemistry transitional between Island Arc and E-MORB. *The Salittu formation* is overlying the Toija formation and was deposited during extensive rifting of the crust as manifested by the ultramafic picritic E-MORB type volcanic rocks that do not show evidence of major crustal contamination. The two formations are inferred to reflect back-arc basin volcanism. The age of these formations is unknown but should be bracketed between ca. 1880-1870 Ma: the former age is the youngest dated arc type volcanic rock and the latter is the approximate age of synorogenic intrusions in the SSAC (Nironen, 1999; Paper III). The two new ages on volcanic rocks show that island arc type volcanism lasted ca. 15 m.y., maybe even longer (Paper I).

The number of age data of volcanism and sedimentation in the SSAC is scarce but constantly increasing. Four previously published U-Pb zircon ages exist. Vaasjoki and Sakko (1988) dated a metarhyolite from southeastern Finland that yielded an age of 1906±4 Ma, suggesting that volcanism was coeval with the oldest arc type volcanism in the Tampere Belt. This site is, however, not unequivocally within the SSAC. The other three age determinations, 1887±14 Ma from the Porvoo archipelago (Patchett and Kouvo, 1986), 1888±11 Ma from the Häme Belt (Vaasjoki, 1994) and 1888±11 Ma from Kemiö in the Uusimaa Belt (Reinikainen, 2001) have too large analytical errors to precisely date the age of volcanism. The new ages provided in this study (Paper I) are therefore the first ages accurate enough to be used for stratigraphic analysis. Paper III contains a new ion microprobe (SIMS) zircon age for the Orijärvi granodiorite of 1898±9 Ma. The tectonic setting of the granodiorite has been debated: both synorogenic (Latvalahti, 1979) and synvolcanic (Colley and Westra, 1987) origins have been suggested. The new age data on the granodiorite and the volcanic rocks, and the comparison of the geochemistry between them, now unequivocally point to a synvolcanic setting of the Orijärvi granodiorite. Synvolcanic intrusions should occur below the eruptive volcanic rocks that are described occasionally (e.g. Peltonen and Elo, 1999 in the CSAC) but are very rarely convincingly demonstrated. It is probable that more synvolcanic intrusions occur in the Uusimaa Belt as well as in other Svecofennian volcanic belts.

On the basis of the new data from the Orijärvi area and data from the litterature, a tectonic model for the Southern Svecofennian Arc Complex is presented in Fig. 2. In this model, the direction of subduction is inferred to be northwards, because the oldest and least differentiated volcanic rocks occur in the Uusimaa Belt and the volcanic rocks in the Häme Belt are more evolved (Lahtinen, 1996). This suggests that the Häme Belt is a rifted remnant arc. Lahtinen (1994, 1996), however, suggested that the subduction zone dipped southwards under the Häme Belt. This could be correct if only the uppermost evolved volcanic rocks are exposed and older, more primitive bimodal volcanics are hidden under the present erosional surface. That scenario would mean that the Häme Belt is the arc and the Uusimaa Belt is the remnant arc. Obviously, the question of subduction polarity still needs more data before a definite statement can be made.

The existence of older crustal components involved in the formation of the igneous rocks in the Uusimaa Belt is evident. Huhma (1986) and Patchett and Kouvo (1986) report some ϵ_{Nd} values that are lower than a pure juvenile crustal source, mostly between –1 to +3.5. They conclude that the most likely explanation to this is the mixing between a juvenile crust (ϵ_{Nd} = +4 to +5) with a small amount of Archaean detritus through subduction. Another explanation for the ϵ_{Nd} values is the contamination by older crust or older crustal pieces hidden below the present surface as pointed out by Nironen (1997) or a complete inheritance from a ca. 2.0 Ga crust Lahtinen and Huhma (1997).

Older Palaeoproterozoic and Archaean zircons were found in this study as detrital zircons in a metasediment and in inherited zircon cores sampled from the ca. 1.87 Ga Masku tonalite (Paper III). Archaean zircons were also documented from the Kalanti trondhjemite (Väisänen, 2001), previously interpreted to be >1.90 Ga in age (Patchett and Kouvo, 1986). Older Palaeoproterozoic and Archaean detrital zircons from southern Finland have been previously reported by Claesson et al. (1993). Therefore, it is evident that the sedimentary detritus contains older pre-Svecofennian eroded crustal material. Consequently, it is possible that some of these sediments were also subducted, were partially melted and thus explain the ϵ_{Nd} data of intrusive rocks. Since older zircons have also been detected as cores in younger zircons from the synorogenic Masku intrusion (Paper III), it raises the question whether the older crustal blocks are the source for the inherited zircons. It is, however, still possible that those zircons have been inherited from sediments. The only requirement is that such zircons were not completely melted but were partly preserved as cores rimmed by new zircon. So the question of the source of the pre-Svecofennian crustal component in southernmost Finland still needs more data to be answered.

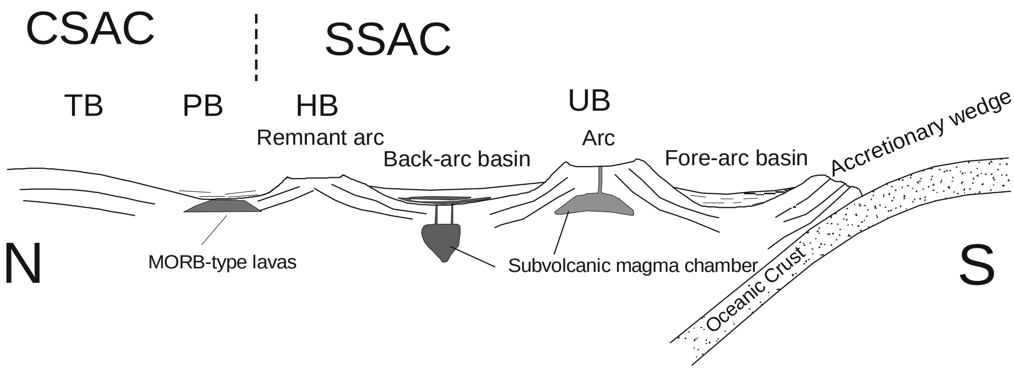

Fig. 2. Simplified schematic model of a modern island arc system, modified after Kähkönen and Lehtinen (1998), applied to the Svecofennian island arc complexes in southern Finland along a N-S profile during the pre-collisional stage (not to scale, deformation and erosion omitted). CSAC=Central Svecofennian Arc Complex; HB=Häme Belt; PB=Pirkanmaa Belt; SSAC=Southern Svecofennian Arc Complex; TB=Tampere Belt; UB=Uusimaa Belt.

Collisional tectonics

In models of accretionary orogens, crustal pieces of different origin, terranes, are successively amalgamated to form a craton (e.g. Windley, 1995). The Svecofennian orogen was formed when the newly formed, more or less juvenile arc complexes, also interpreted as terranes, successively accreted onto and against the Archaean craton to finally form the Fennoscandian shield. The accretion (collision) was sequential and three main collisional events have been proposed at 1.91-1.90 Ga, 1.89-1.88 Ga and 1.86-1.84 Ga (Lahtinen, 1994; see also Nironen, 1997). Gorbatschev and Bogdanova (1993) suggest that the Svecofennian Orogen was formed continuously without any major time gaps. The absolute age of collision is difficult to define unambiguously and may vary across the orogen. In this study the dated ages of synorogenic (collision-related) intrusions and associated metamorphism are regarded to reflect the time of collision. Of course, the collision may have started earlier than the collision-related magmatism. Slight modifications to the earlier models referred to above are suggested in the present study.

The age of collision of the northernmost PAC with the Archaean craton is poorly known. The proposed 1.91-1.90 Ga age (Lahtinen, 1994; Nironen, 1997) or 1.91-1.885 Ga age (Korsman et al., 1999) must be regarded as a maximum ages. As Rämö et al. (2001) pointed out, the PAC must have been separated from the Archaean by an oceanic crust during the time of its formation, 1.93-1.91 Ga (see above). The lack of undisputed collision-related intrusions during this period hampers the interpretation; gneissic tonalites are interpreted as synvolcanic intrusions (Lahtinen, 1994). The presence of younger volcanic and intrusive rocks in the same area (1890-1865 Ma in Kousa et al., 1994) allows an alternative model: the PAC may have remained intact until the accretion of the CSAC with the PAC and thereafter, the two terranes jointly collided with the Archaean.

The CSAC seems to have gone through a prolonged collisional history. Similar to the collision of the PAC, the evidence for early collision of the CSAC are scarce. Close to the Archaean boundary, synorogenic magmatism and metamorphism culminated 1885 Ma ago (Hölttä, 1988), whereas in the southern part of the CSAC magmatism is slightly younger, ca. 1880 Ma (Nironen, 1989). Metamorphism is coeval with synorogenic magmatism (Mouri et al., 1999). Therefore, it seems reasonable to conclude that the CSAC collided with the PAC at 1.89-1.88 Ga (Lahtinen, 1994; Nironen, 1997; Korsman et al., 1999).

The SSAC was separated from the CSAC by oceanic crust (Lahtinen, 1994), fragments of which are now preserved as MORB type picritic lavas in the Pirkanmaa Belt (Peltonen, 1995). That area was later transformed into a suture zone during the collision of the SSAC and the CSAC (Lahtinen, 1994, 1996). The northward tectonic translation of the SSAC has recently been supported by magnetotelluric data, where N-vergent structures are evident (Korsman et al., 1999). The early subhorizontal D1/D2 structures in the Turku area are obviously related to (the initial stage of?) collision. The associated metamorphism reached upper amphibolite facies conditions (garnet-cordierite stability) with onset of migmatization (Paper II). The age of this early metamorphism has not, however, been confirmed by ion microprobe dating on zircons recovered from anatectic leucosome (Paper III). The approximately coeval synorogenic granitoids have been dated at ca. 1.87 Ga (van Duin, 1992; Nironen, 1999), an age that is now confirmed by SIMS dating (1.88-1.86 Ga: Paper III). The collision must be younger than the youngest volcanic rocks, now dated at 1878 Ma from the Orijärvi area (Paper I). Therefore, it is concluded here that the collision of the SSAC with the CSAC took place at 1.88-1.86 Ga, i.e. 10-20 m.y. later than the collision of the CSAC with the PAC and the Archaean craton. Hopgood et al. (1983) concluded that U-Pb monazite ages in southernmost Finland, 1.88-1.87 Ga, yield the age of metamorphism, consistent with the collisional age suggested here. Ehlers et al. (2002) suggest that thrusting was completed by ca. 1865 Ma.

This study demonstrates that the Svecofennian arc accretion was a diachronous process in which volcanic arc magmatism as well as synorogenic magmatisms are getting slightly younger from the Archaean boundary towards the southwest. This also implies that deformation is getting simultaneously younger and means that care is needed in correlating structures across the belts and, particularly, across terrane boundaries. The structures observed may look the same in all areas but they may have been formed at different times. This is particularly true for structures formed during the early stage of the orogeny as demonstrated in Paper I: the Tampere Belt was deformed and intruded by synorogenic intrusions while at the same time on the other side of the terrane boundary in the Orijärvi area the arc and back-arc volcanism was active. Fig. 3 shows the tentative crustal evolution during 1.88-1.86 Ga collision in southern Finland. The 1.86-1.84 Ga collision proposed by Lahtinen (1994) is here regarded as belonging to the post-collisional convergence stage, described in Papers II and IV.

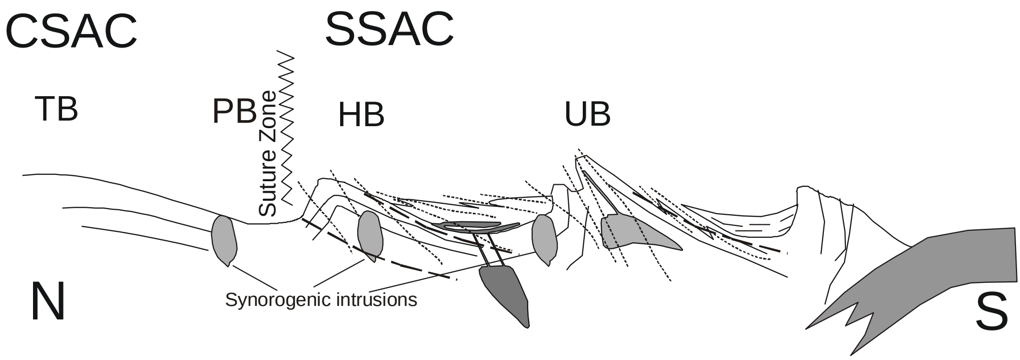

Fig. 3. Simplified schematic model of southern Finland during the collisional stage (ca.1.88-1.86 Ga) with N-vergent structures. Thin dashed lines indicate S2 foliations. Thick dashed lines are inferred thrusts. Structures N of the suture zone and erosion are omitted. Symbols as in Fig. 2.

Post-collisional tectonics

The post-collisional stage of the Svecofennian orogeny in the CSAC greatly differs from that in the SSAC. In the CSAC the ductile evolution ceased immediately after the main collision at 1.89-1.88 Ga and the subsequent magmatism at 1.88-1.87 Ga is post-kinematic (post-collisional) both in field appearance and geochemical characteristics. The intrusions are mostly very weakly deformed or undeformed and the C- and A-type geochemical characteristics imply a rather deep and hot magma source. Post-kinematic magmatism is diachronous as older ages occur in the east/northeast and younger ages occur in the west/southwest. It is concluded that no major crust forming processes took place in the CSAC after ca. 1.87 Ga (Nironen et al., 2000; Rämö et al., 2001).

At the same time the situation was totally different in the SSAC where the orogenic processes culminated when the SSAC moved northwards and collided with the CSAC. This collision caused N-vergent D1/D2 structures and synorogenic 1.88-1.87 (-1.86) Ga magmatism intruded (Papers II-III, see also above). After the collision with the CSAC, the SSAC shows continued convergence and northward motion. Subsequently, the post-collisional stage started in the SSAC. In the present study the structural, metamorphic and magmatic aspects of the post-collisional stage in the SSAC are discussed (Papers II-IV).

During the preceding collisional stage the rocks became strongly deformed and metamorphosed. During the post-collisional (intra-plate) convergence the crust was affected by additional deformation at still higher temperatures. Roughly N-S convergence produced the regional upright to locally N-NW overturned D3 folds and shear zones bounding the folded domains, i.e. the deformation became partitioned. Locally, even recumbent D3 folds are encountered suggesting at least local overthrusting and additional crustal thickening, provided that it was not compensated by thinning of the lower crust. The shearing was initially coeval with the late stage of D3 folding but evidently continued after folding had ceased. This is indicated by the presence of deformed S-type leucosomes and granites in these late shear zones. In a sense, such shear zones postdate D3 folding, but they are interpreted to belong to the same progressive deformation. Kinematically, the collision-related northward tectonic translation direction changed during the post-collisional stage to NW/W directed, i.e. to dextral transpression. Evidence for this are E to SE plunging lineations, dextral shear senses in E-W trending shear zones and E-side up movements in some of the N-S trending shear zones. E-side down movements on N-S trending shear zones can be interpreted either to differential movement during compression or to subsequent extensional collapse after compression (Ehlers et al., 1993; Selonen and Ehlers, 1998; Väisänen and Kriegsman, 1999; Paper II). Uplift from mid-crustal levels to approximately present level has most probably taken place soon after the convergent orogeny, i.e. between ca. 1.815-1.80 Ga. At 1815 Ma the rocks were in a pressure regime of ca. 4-5 kbars (Paper IV), at 1.80 Ga in a pressure regime of ca. 2 kbars (Hubbard and Branigan, 1987; Eklund et al., 1998). Mineral parageneses in the contact metamorphic aureole around the 1570 Ma Kolinummi anorthosite also record pressures at around 2 kbars (Väisänen et al., 1994). Therefore, the exhumation was most rapid immediately before or around ca. 1.80 Ga and subsequently very little uplift took place.

In the Turku high-grade area, peak metamorphism and crustal anatexis were coeval with post-collisional crustal shortening during the D3 deformation. This is suggested to have taken place during crustal thickening simultaneously with thinning of the mantle lithosphere (Paper II). The peak metamorphism is dated at 1824±5 Ma from zircons recovered from granitic, garnet-cordierite bearing, leucosome in metapelite. This also date the (final stage) of F3 folding, as the sampled leucosomes intruded and filled the fold hinges. Leucosome in the synorogenic Masku tonalite was dated at 1804±14 Ma suggesting that crustal melting continued until ca. 1.81 (1.80?) Ga in the Turku area (Paper III).

Shoshonitic magmas enriched in incompatible trace elements, Fe, P, Ti, F and LREE may represent the heat source for high grade metamorphism. It is suggested here that hot upwelling asthenosphere convectively removed the subcontinental lithospheric mantle and raised the temperature. This triggered partial melting of the enriched parts of the mantle. Uprising mafic melts increased the already high temperatures at mid-crustal levels and caused granulite facies metamorphism, crustal anatexis and production of anatectic granitic melts (Paper IV). Deeper in the crust still hotter temperatures were reached at least locally as even high-temperature A-type anatectic melts with an age of ca. 1830 Ma have now been discovered in southern Finland (Jurvanen et al., 2002). Fig. 4. shows the crustal evolution during ca 1.87-1.80 Ga stage.

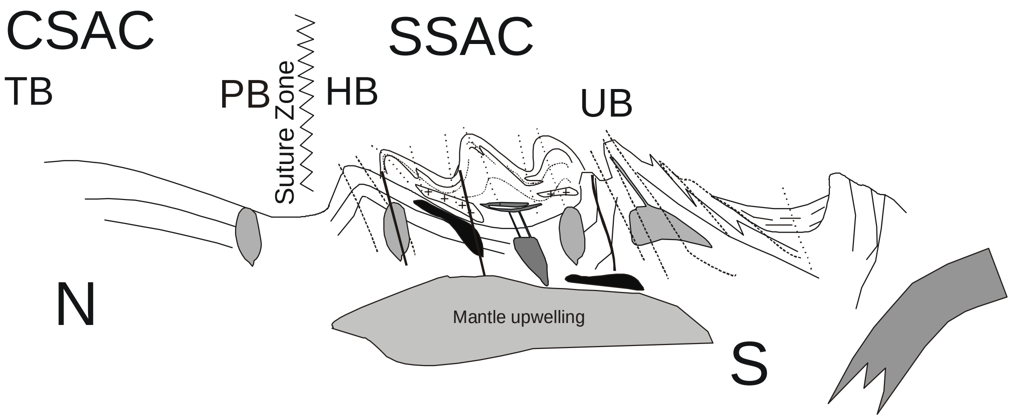

Fig. 4. Simplified schematic model of southern Finland during the post-collisional stage ca.1.87 (1.86) -1.80 Ga. Dotted lines represent S3 foliations, Thick solid lines denote late orogenic shear zones. Black areas are shoshonitic intraplate magmas, crossed hatches are anatectic granites. Structures N of the suture zone are omitted. Symbols as in Fig. 2.

CONCLUSIONS

From the four papers and the synopsis included in this thesis the following conclusions can be reached:

(1) The oldest indications of crustal evolution in southwestern Finland can be found in older Palaeoproterozoic and Archaean detrital zircons from metasediments and in inherited zircons from intrusive rocks. Sedimentary detritus in metapelites was mostly derived from outside the local volcanic formations as all dated detrital ages so far are older than the ages of the volcanic rocks. Inherited zircons in plutonic rocks are derived either from recycled sediments or from older crustal blocks.

(2) The oldest crust-forming processes in the Orijärvi area within the Uusimaa Belt are related to the formation of a bimodal volcanic arc in the Orijärvi formation where a rhyolite was dated at 1895 Ma. The Orijärvi granodiorite, dated at 1898 Ma, is a synvolcanic plutonic rock that geochemically resembles the felsic volcanic rocks in the same area. The volcanism developed more evolved compositions upwards in the stratigraphy and in the upper part of the mature arc in the Kisko formation, where a dacite was dated at 1878 Ma.

(3) During the subsequent tensional stage the volcanic arc was rifted apart. Rifting lead to bimodal volcanism and deposition of sedimentary rocks of the Toija formation. Geochemically, the mafic lavas of the Toija formation are transitional between the arc-type and MORB-type lavas. During continued rifting, the E-MORB- type mafic and ultramafic lavas with minimal crustal contamination were erupted in the Salittu formation. The Toija formation and the Salittu formation are interpreted as parts of a back-arc basin.

(4) The Häme Belt and the Uusimaa Belt once belonged to the same arc system but the Häme Belt was rifted away and became a remnant arc. The Uusimaa Belt, the Häme Belt and the basin between the two build up the Southern Svecofennian Arc Complex.

(5) The Southern Svecofennian Arc Complex collided with the Central Svecofennian Arc Complex at ca. 1.87-1.86 Ga and synorogenic magmas intruded in the southern arc complex at that time. This age defines the collision-related, N-vergent D1/D2 deformation. Metamorphism reached upper amphibolite facies conditions during D_2 and migmatization of metapelites started.

(6) After the main collision the Southern Svecofennian Arc Complex continued to move northwards during post-collisional convergence. This produced upright to N/NW-overturned regional F3 folds in a dextral transpressional setting simultaneously with peak metamorphism that in the Turku area reached granulite facies conditions. This produced large amounts of anatectic granites. Leucosome formation and the F3 folding is dated at 1824 Ma and a mantle derived shoshonitic intrusion coeval with the anatectic granite is dated at 1815 Ma.

(7) In the Turku area, granulite facies metamorphism caused new metamorphic zircon growth even in synorogenic intrusions.

(8) Mantle derived magmatic intraplating caused the high heat flow in southern Finland to produce the anatectic granites. Locally, A-type granites from deeper sources were formed.

(9) Crustal uplift was most intense around 1.80 Ga. This coincides with the timing of mafic underplating.

(10) The Svecofennian Orogen is associated with diachronous volcanism and magmatism that become gradually younger towards the southwest. Consequently, the associated structural and metamorphic events also get younger towards the southwest.

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