Geochemistry of Proterozoic supracrustal rocks in Finland
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GEOLOGY AND GEOCHEMISTRY OF THE HÄMEENLINNA-SOMERO VOLCANIC BELT, SOUTHWESTERN FINLAND: A PALEOPROTEROZOIC ISLAND ARC

by
Gerhard Hakkarainen

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The Paleoproterozoic Hämeenlinna-Somero Volcanic Belt is situated south of the Bothnian basin in southern Finland, within the South Svecofennian Subprovince. Chemically and lithologically the belt resembles modern island arc environments. Three deformational events were recognized in the area. The dominant D_1 phase folded the supracrustal rocks isoclinally with E-W trending axial planes. The NE trending D_2 and SSE trending D_3 phases vary locally in intensity. Two large steeply dipping shear complexes of different ages are met within the area. The older, W-SW trending Hämeenlinna shear zone predates the intrusion of late-kinematic potassium granites but postdates the synkinematic granodiorite emplacement. The younger, NW trending Painio-Hirsjärvi fault zone shows a sinistral sense of shear and postdates the emplacement of potassium granites.

The belt is subdivided into two groups. (1) The (lower) Forssa group comprises calc-alkaline metavolcanics and metasediments. The metavolcanic rocks range from basaltic to rhyolitic in composition, with abundant andesites. The area was originally a complex of stratovolcanoes with high erosion rates, producing large amounts of reworked volcanic material. (2) The (upper) Häme group is characterized by an association of basaltic to andesitic lava flows with interlayered pyroclastics, erupted in an E-W trending fissure system. The volcanics are layered upon pelitic sediments and graywackes. The earliest extrusives in the Forssa group are rhyolites to dacites followed by andesites and basalts. Volcanism in the Häme group began with basalt eruptions and contemporaneous precipitation of Fe-sulfide formations at the base of the pile, and volcanism subsequently changed into andesitic.

Major and trace element geochemistry of the volcanic rocks resembles that in modern mature arcs. In general the volcanics are of medium-K type, with relatively high abundances of LILE. The Forssa group volcanics show a calc-alkaline fractionation trend. The Häme group rocks have more tholeiitic affinities, with Fe enrichment relative to Mg. The P_2O_5 content is slightly higher in the basalts of the Häme group than in those of the Forssa group. The Mg numbers in the basalts are moderate (40-52) and the Ni content low (20-50 ppm).

Key words (GeoRef Thesaurus, AGI): volcanic belts, metavolcanic rocks, basalts, andesites, deformation, geochemistry, stratigraphy, island arcs, Proterozoic, Paleoproterozoic, Hämeenlinna, Forssa, Somero, Finland

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INTRODUCTION

The Fennoscandian Shield is divided into three parts, the oldest being the Archean craton (3.1-2.7 Ga) in the east (Fig. 1). It is bordered to the west by the Paleoproterozoic Karelian and Svecofennian terrains (2.5-1.7 Ga). The youngest region of Proterozoic age is the Southwestern Gneiss Complex or the Southwest Scandinavian Domain (0.9-1.75 Ga) (Gaál & Gorbatschev, 1987). No Archean components have been found in the central part of the Svecofennides. The Svecofennian supracrustal rocks were syntectonically intruded by granodiorites, tonalites and quartz diorites, and minor ultramafic and gabbroic bodies. The cessation of the Svecofennian orogeny is postulated from the large scale anatexis of the supracrustals and the emplacement of the late-kinematic K-rich granites.

The Svecofennian volcanic rocks in Finland yield ages of 1.91 to 1.89 Ga (Patchett & Kouvo 1986, Gaál & Gorbatschev 1987, Kähkönen et. al. 1989) and plutonism was almost contemporaneous with volcanism (1.89-1.83 Ga; Patchett & Kouvo 1986). The estimated 30-40 Ma duration of volcanic activity in the Svecofennian resulted in volcanic belts of different chemical and lithological characteristics. They vary from bimodal suites in southern Finland (Ehlers & Lindroos 1990) to calc-alkaline and alkaline suites to the north (Kähkönen 1989), which indicates a complex development.

The Hämeenlinna-Somero Volcanic Belt (HSB) is part of the South Svecofennian Subprovince in southwestern Finland and forms a large arc-like structure striking E-W. It is one of the largest exposed coherent volcanic belts in the Finnish part of the Svecofennides. The lateral extent of the belt is 100 km in the E-W direction and 60 km in the N-S direction. This study focuses on the central parts of the belt.

Simonen (1953, 1980) divided the Svecofennian supracrustal rocks into three major categories. The

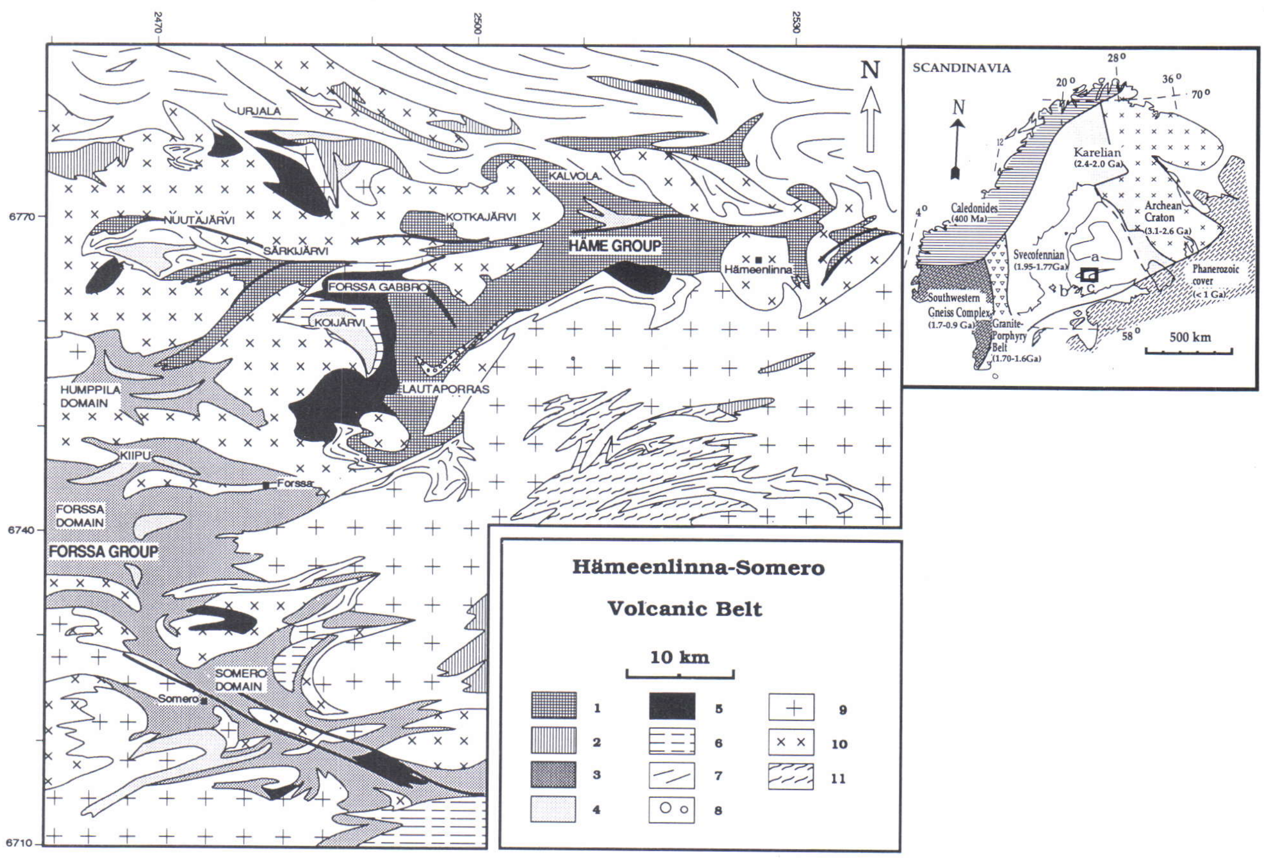


Fig. 1. Geological map of the central parts of the Hämeenlinna-Somero Volcanic Belt. The thick lines in the upper part represent the Hämeenlinna Shear Zone and those in the southern part the Painio Shear Zone. 1 = Häme group basalts and andesites, 2 = basalts and andesites (relationship to the Forssa and Häme groups unknown), 3 = Forssa group andesites and basalts, 4 = dacites and rhyolites, 5 = gabbros and ultramafic rocks, 6 = intercalations of quartz-feldspar gneisses and mica gneisses or schists, 7 = mica schists and gneisses (originally graywackes and pelites), 8 = volcanic conglomerates, 9 = late-kinematic K-granites, partly migmatitic, 10 = synkinematic granodiorites, tonalites and quartz diorites, 11 = migmatitic granodiorites and tonalites. The inset shows the major provinces (domains) of the Fennoscandian Shield. The dashed line represents the Ladoga - Bothnian Bay zone. The study area is shown by the square. a = Tampere, b = Enklinge, c = Orijärvi-Lohja.

Lower Svecofennian subgroup consists of immature graywacke-slates and quartz-feldspar rocks. The Middle Svecofennian subgroup consists of basic and intermediate volcanics and intercalated sedimentary rocks, while the Upper Svecofennian subgroup comprises argillaceous sediments. Roughly, the HSB corresponds to the Middle Svecofennian subgroup of Simonen (1980).

METAMORPHISM

The study area was metamorphosed to amphibolite facies but the original volcanic textures are still preserved. Common mineral assemblages in the mafic rocks are plagioclase and hornblende. Some of the hornblende phenocrysts are augite pseudomorphs and relict zonation in plagioclase is common. The sedimentary rocks contain assemblages of biotite, garnet and cordierite.

The metamorphic grade in the northern part of the study area is slightly lower than in the south. This is shown by locally persisting assemblages of cordierite-andalusite-chlorite-white mica in the northern pelitic schists. Retrograde reactions are manifested in the alteration of Ca-rich plagioclase to Na-rich plagioclase, zoisite and epidote and in alteration of hornblende to biotite. Mäkelä (1980) estimated the pressure and temperature to be 3-4 kbar and 600°C at Kiipu in the Forssa area. In the northern part of the study area the intrusive rocks comprise granodiorites and quartz diorites.

The higher metamorphic grade in the southern part is shown by a higher degree of melting of the supracrustal rocks and formation of migmatites. Still, the volcanic and sedimentary rocks in the southern part, situated in a depression adjoined by migmatite rocks, show lower-grade metamorphic features such as stable muscovite-cordierite assemblages. The boundary between the migmatite zone and the less metamorphosed northern zone with granodiorites and quartz diorites runs in a WSW-ENE direction near Forssa (Fig. 1). Further southwards, the amphibolite facies rocks in Orijärvi-Lohja yield temperatures and pressures of about 650° and 3 to 5 kbar (Schreurs & Westra 1986) and the grade of metamorphism was highest in the West-Uusimaa thermal dome.

SUBDIVISION OF THE STUDY AREA

The volcanic belts in southwestern Finland are characterized by various lithologies. The unique characteristic features of different belts are summarized below. The Orijärvi-Lohja area (Schreurs & Westra 1986, Colley & Westra 1987, Mäkelä 1989, Väisänen 1991) 50 km south of the study area (Fig. 1) consists of bimodal volcanic rocks, and abundant limestones and iron formations. The present study area is composed of tholeiitic to calc-alkaline rhyolitic to basaltic volcanic rocks, containing few Fe-oxide formations and limestones. The Tampere volcanics, 70 km north of Hämeenlinna, consist mainly of calc-alkaline high-K dacites and andesites and shoshonitic rocks associated with conglomerates (Kähkönen 1989). The Haveri tholeiitic basalt formation also occurs in this area (Mäkelä 1980, Kähkönen & Nironen, this volume).

Based on lithological differences (Table 1, Fig. 2), the belt is divided into two groups: (1) the Forssa group is dominated by andesites and (2) the Häme group by basalts. Furthermore, there are two domains whose relationship to these two groups is uncertain, the Nuutajärvi and Koijärvi domains.

Northwards the Häme group is in contact with migmatites and gneisses. The basalts rest on pelites, and in addition some of the extrusives in the upper part of the group occur as massive interlayers in the sedimentogenic migmatites and gneisses to the north. Within the Forssa group no basement below the volcanic rocks has been found (Table 1). Since both of the groups are embraced by large granitoid batholiths the only areas where they actually are in mutual contact are the Humppila and Nuutajärvi domains (Fig. 1).

Table 1. Lithological differences between the Häme and Forssa groups.

Forssa group	**Häme group**
No clearly discernible sedimentary basement.	Basement of pelitic schists and volcanogenic conglomerates.
The most abundant rock type is andesite.	The most abundant rock type is basalt.
Acid volcanic rocks are abundant.	Acid volcanic rocks are sparse.
Both uralite- and plagioclase-porphyritic rocks.	Mostly uralite-porphyritic rocks.
Intermediate and mafic lavas with pillow structures and autobrecciation.	The main part consists of massive lava flows, the offshoots (Kalvola) are autobrecciated and pillowed.
Sedimentary (pelitic) intercalations in thevolcanis formations.	No pelitic intercalations in the volcanic formations.

FORSSA GROUP

The Forssa group includes three synformal E-W trending structures, which in order from south to north are the Somero, Forssa and Humppila domains. The volcanic rocks range from uralite- and plagioclase-porphyritic basalts and andesites to various plagioclase-porphyritic dacitic and rhyolitic lavas and pyroclastic rocks, andesite being the most abundant rock type.

Humppila domain

Here the Forssa group consists of basaltic uralite-porphyritic agglomerates and lavas, and of thick andesitic to dacitic tuffs in the southern part. In the northern part there is a heterogenous association of laminated intermediate and acid tuffs, tuffites, agglomerates, lavas and minor pelitic interlayers. The Häme group basalts lie in a NE trending syncline, and the basalts are exposed on the present erosion surface in the eastern part of the domain only. At Humppila Fe-sulfide formations are as intercalations in the Häme group basalts close to the depositional contact with the Forssa group. The Fe-formations occur as 3-4 m thick disseminated layers between basalt units or as more dispersed in bodies of mica-rich altered basalt. Dacitic to rhyolitic pyroclastic interlayers or fragments are also found in the basalts. The relationship between the two groups is based on the fact that the Fe-formations elsewhere also occupy a stratigraphical position in the lowest part of the Häme group.

Forssa domain

In the Forssa domain several different lithological entities can be distinguished. Successions of thick andesitic lava flows and agglomerates are the most abundant ones. The lavas are partly pillowed and autobrecciated. Several acid eruptive centers with rhyolitic and dacitic lava domes, enclosed in agglomerates and laminated tuffs, occur within the andesites. The Kiipu area in the northern part of the Forssa domain contains a succession with reworked acid volcanic rocks, sulfide mineralizations and sparse limestone layers (Lindroos 1980, Mäkelä 1980).

In the area south of Forssa grading into distal facies volcanic and volcaniclastic rocks indicates increasing distance from the volcanic centers. The central vents were identified by successions of thick lavas, coarse agglomerates and poorly sorted tuffs. At the western margin of the Forssa domain, lavas are rare and laminated fine-grained tuffites are abundant. Accordingly, the volcanic centers were situated in the central part of the Forssa domain, where the largest sheets of basalt and andesite lavas occur and where the rhyolite domes are found. The narrow neck between the Somero and the Forssa domains comprises relatively mafic rocks with basaltic autobrecciated and partly pillowed lavas, lapilli tuffs and agglomerates interlayered with sparse andesitic tuff horizons.

Somero domain

The Somero domain was described by Mäkelä (1989) and Stel et. al. (1989). The geology is controlled by a synformal depressional structure oriented subparallel with the Painio shear zone, also called the Hirsjärvi fault by Mäkelä (1989). The WNW to ESE trending shear complex divides the area into two lithologically different parts (Fig. 1). South of the shear complex the rocks consist mostly of andesites

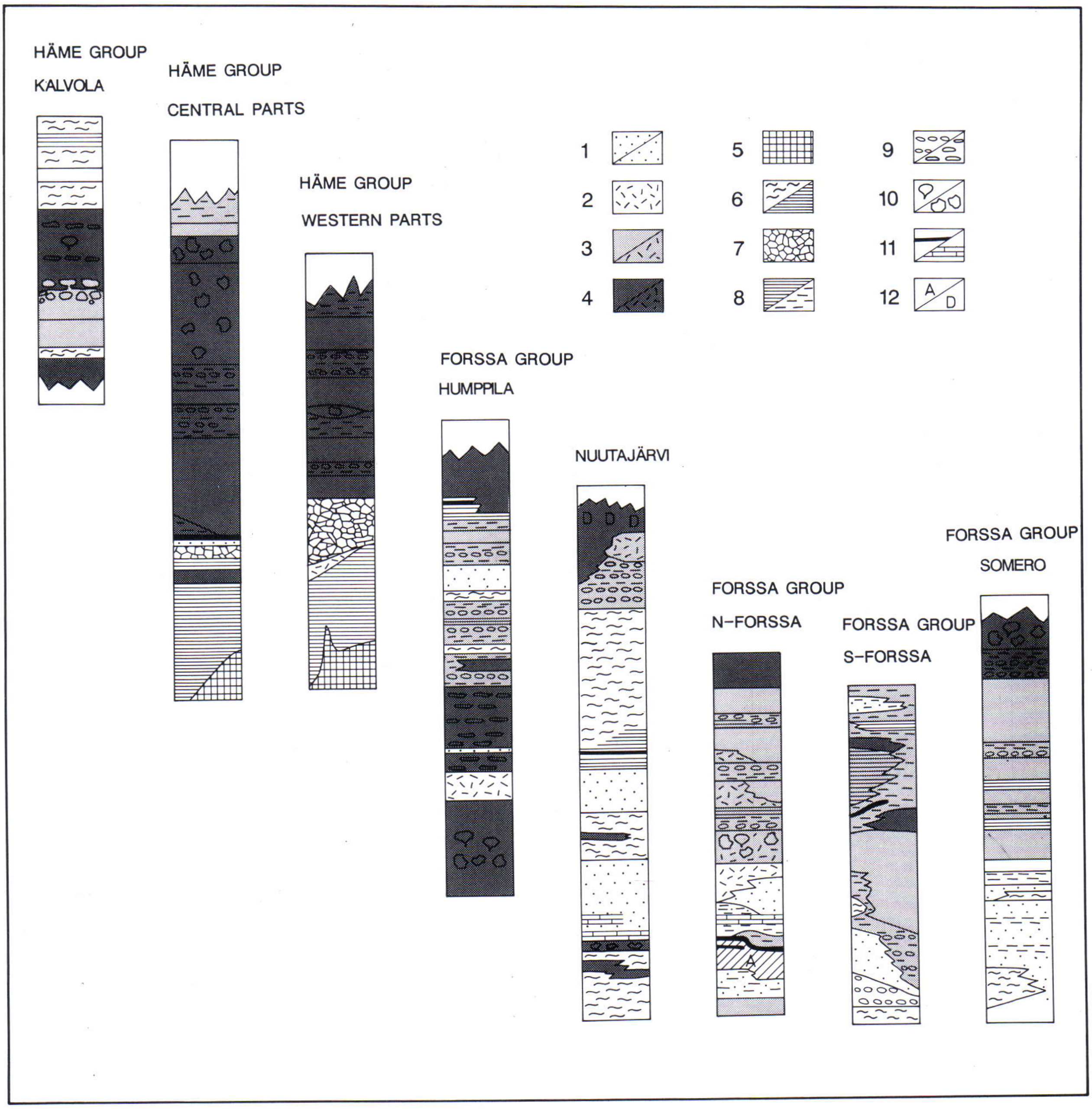


Fig. 2. Stratigraphic columns from the Forssa and the Häme groups. Kalvola represents an offshoot in the gneisses and schists to the north. The western parts of the Häme group constitute the Lautaporras area (Fig. 1). The central parts of the Häme group constitute the areas east of Lautaporras. The intermediate and mafic volcanic rocks in the uppermost part of the Nuutajärvi column belong to the Häme group. 1 = rhyolite, 2 = dacitic feldspar porphyry, 3 = andesitic uralite/plagioclase porphyry, 4 = basaltic uralite/plagioclase porphyry, 5 = gabbro, 6 = graywacke / pelite, 7 = conglomerate, 8 = tuffite / tuff, 9 = agglomerate, 10 = pillow lava / autobrecciated lava, 11 = Fe-sulfide formation / limestone, 12A = Mg-metasomatic rock, 12D = diopside-bearing rock.

and these belong to the Forssa group. This sequence contains a Zn-Ag sulfide mineralization described by Mäkelä (1989). In addition, a 300 m thick rhyolitic to dacitic plagioclase-quartz-porphyritic stratified tuff formation lies south of the Somero town. The successions north of the shear complex show a wider range of rocks including basalts, quartz-feldspar gneisses, and turbiditic pelitic schists and gneisses.

HÄME GROUP

The Häme group consists of tholeiitic plagioclase- and uralite-porphyritic basalts grading into even-grained or plagioclase-porphyritic andesites. In its present outline it is a 5 km wide irregular zone striking E-W for approximately 100 km. At Lautaporras the volcanic rocks are folded into a large northeastwardly plunging synform, which is partly intruded and split by the Forssa gabbro (Figs. 1 and 2). East of Lautaporras, in the central part, the belt bends from NE towards E. The group is built up of thick lava flows and interlayered basaltic pyroclastics. The most abundant rock type is a uralite porphyritic rock with 2-3 mm hornblende phenocrysts and smaller plagioclase phenocrysts which occasionally show oscillatory zoning. However, some of the andesitic end members contain only plagioclase phenocrysts. Augite is seldom found as phenocrysts due to the strong uralitization. The pyroclastic rocks are mostly poorly sorted, although some reworked tuffs in the upper part of the volcanic pile are graded.

Deformed basaltic feeder dikes occur throughout the Häme group. Most of them are fine-grained with small- or medium-sized hornblende phenocrysts, but coarse-grained porphyritic hornblenditic dikes and sills, containing more than 50% phenocrysts, also occur in the volcanic pile and in the underlying pelitic schists.

Several branches of the upper part of the Häme group extend into the gneissose sediments to north. At Kalvola they consist of several generations of autobrecciated and pillowed uralite-porphyritic basalts. Stratigraphically these rocks are succeeded by plagioclase-porphyritic andesites, which in turn are cut and brecciated by younger uralite-porphyritic basalt dikes.

On the southern margin of the group the basalts rest upon a 100-200 m thick sequence of volcanic conglomerates and interlayered tuffs. The conglomerates are poorly sorted and contain subrounded clasts of plagioclase- and uralite-porphyritic and even-grained basalts. They have a matrix-supported fabric and resemble debris flow deposits. Carbonate breccia pipes and a 1-2 m thick banded Fe-oxide-chert layer occur in the lowermost part of the conglomerates. Also in the lowermost part of the conglomerates at Lautaporras dacitic feldspar-porphyritic fragments are common, and their shapes vary from angular to well rounded. Similar rocks are found in the Forssa group. The conglomerates are located between two basalt formations but this arrangement is not depositional, rather it is caused by folding. (see page 92.)

Approximately 2-5 m thick laminated Fe-sulfide formations occur in connection with the basal conglomerates. Their occurrence is not restricted to the depositional level of the conglomerates, but they are partly interlayered with basalts higher in stratigraphy.

South of the volcanics and conglomerates there are pelitic and laminated schists containing corroded cordierite pseudomorphs and a metamorphic differential banding. Top of strata directions were determined from scour surfaces, graded bedding, slumping and load casts in several locations along the contact between the pelites and the basalts.

KOIJÄRVI AND NUUTAJÄRVI DOMAINS

The Koijärvi domain divides the Häme group into two parts. The NW corner of the domain consists of a syncline containing graded cordierite-mica schists, interlayered with rhyolitic lava flows and basaltic tuffs. The gradation between mica schists and volcaniclastics suggests a local origin for the sediments. The SE part consists of a thick sequence of rhyolitic lava flows, reworked pyroclastics and a banded chert-Fe-sulfide formation. The domain is bounded by the Koijärvi shear zone in the west and by the Forssa gabbro in the east. The observations of Neuvonen (1954) suggest that the Koijärvi domain was uplifted relative to the Häme group. It seems appropriate to infer that the Koijärvi domain represents a block that was juxtaposed vertically by faults to the same level as the Häme group.

The Nuutajärvi area forms an ellipsoid-shaped anticline. The internal stratigraphy is deduced from structural criteria and top of strata determinations. According to Neuvonen (1954), the supracrustal rocks can be divided into three major units. The author's observations are broadly compatible with those of Neuvonen, with slight modifications. (1) The oldest unit consists, from the lowermost member upwards, of basaltic pillow lavas, mudstones with interlayers of basaltic and rhyolitic to rhyodacitic tuffs, calcareous precipitates, and rhyodacitic lavas and reworked tuffs. (2) The middle unit consists of graywackes and pelites with minor basaltic to dacitic tuffs. Its lowermost part is dominated by pelites with local sulfide-rich intercalations. (3) The uppermost unit comprises basaltic to intermediate pyroclastics and lavas, which belong to the Häme group. It starts with andesitic agglomerates and lavas, which are succeeded by basaltic tuffs and lavas.

DEFORMATION

The structural styles of the Orijärvi-Lohja area and the Tampere Schist Belt have been investigated by several authors. The HSB is situated between these two areas.

Nironen (1989) proposed for the central parts of the Tampere Schist Belt an initial deformation D_1 with subvertical axial planes and horizontal fold axes. D_2 and D_3 are non-penetrative low-angle shears in relation to D_1 with dextral and sinistral asymmetric folding, respectively. Ploegsma and Westra (1990) described in the Orijärvi area a recumbent D_1 folding event with subhorizontal E-W trending axial planes that could be correlated with the D_1 event near Tampere. The NE-SW oriented D_2 dominates the tectonic style. The locally occuring D_3 consists of open folds with axial planes in NW-SE to NE-SW directions.

The deformational styles in the northern part of the HSB, which comprises all domains except Somero, are illustrated in Fig. 3 and listed in Table 2. The D_1

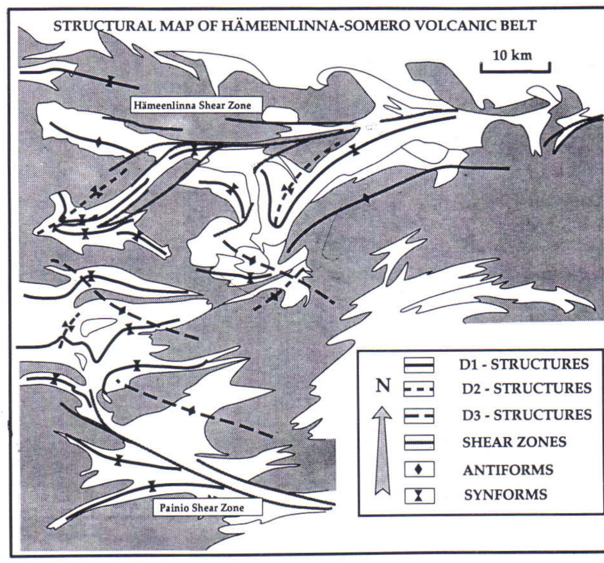


Fig. 3. Structural map of the Hämeenlinna-Somero Volcanic Belt. Only the major tectonic features are illustrated. Plutonic rocks are shown as shaded areas.

Table 2. Record of the deformational history in the Hämeenlinna-Somero Volcanic Belt.

pre-D_1	S_o	Slumpings, load casts, sedimentary dykes, ripple marks
D_1	F_1	Tight to open folding with subhorizontal fold axes.
	S_1	Dominant penetrative axial-plane schistosity, usually oriented E-W. Metamorphic differentiation.
D_2	F_2	Small-scale asymmetric drag folds to large-scale open folds with dominantly dextral sense of shear. Steeply plunging fold axes (> 60°).
	S_2	Axial-plane crenulation cleavage deforming S_0 and S_1, oriented 20-60° with subvertical axial planes.
D_3	F_3	Local large-scale undulatory uplifting associated with plutonic emplacement. Open folds with steep axial planes striking 115-130°.
	S_3	Weakly developed axial plane schistosity.
D_4	F_4	Non-penetrative brittle to plastic shear deformation.
S_4		NW-SE to NE-SW oriented shear zones locally bending the earlier S-planes.

event was an E-W oriented isoclinal to open folding, with initially subhorizontal fold axes. The D_2 event was regionally a non-penetrative asymmetrical shear folding, predominantly dextral with subvertical axial planes oriented 40° to 60°. D_2 developed locally a penetrative S_2 cleavage, which overprints the S_0 bedding and the S_1 axial plane schistosity. S_2 is markedly well-developed in the western part of the Häme group and in the northern part of the Humppila domain. At Lautaporras the basal conglomerates of the Häme group are structurally between thick basalt formations. They are exposed in the core of a D_1 anticline. During D_2 the S_1 and S_0 structures were folded into a large-scale open synform plunging towards the NE.

The D_3 event is observed locally and it is also recorded by Stel et al. (1989) in Somero. D_3 is defined by large subhorizontal open folds and the associated schistosity is developed only in narrow zones on the fold limbs. A prominent D_3 feature occurs in the migmatized gneisses east of Forssa, where S_2 and small-scale asymmetric folds of D_2 are folded by F_3. S_1 is here expressed as a metamorphic segregation in 0.5-1 mm thick mafic and felsic laminae or as a strong planar fabric in the aluminous mica gneiss layers. The regional consistency of S_2 implies that the D_3 event was not regionally prominent.

D_4 comprises narrow N-S oriented brittle shears with local folding of the earlier schistosities and the bedding around the fracture planes.

The southern migmatite zone and the northern part, dominated by granodiorites, show slightly different deformational patterns. The lineations are generally steep in the granodiorite zone. In contrast, the lineations in the migmatite zone tend to be subhorizontal plunging less than 45°. This may be explained by subparallelism of S_1 and S_2, resulting in type 0 fold patterns of Ramsay & Huber (1987). Transposition of S_1 towards S_2 causes the intersection lineations to be subhorizontal when corresponding axial planes have different dips. No observations of recumbent folding during D_1 were made in the northern parts, but in Somero the S_1 axial planes tend to be more horizontal, causing the differences in lineations mentioned above. Generally, the deformational styles of the HSB resemble those found in the Tampere Schist Belt, but the more flatlying S_1 planes in Somero may reflect the regional change from recumbent folding in Orijärvi to more upright folding northwards to the Forssa-Hämeenlinna area.

Several complexes of megashears transect the Svecofennian bedrock in southern Finland. Two large shear complexes are detected in the study area, the Painio shear zone in Somero (Mäkelä 1989, Stel et. al. 1989) and the Hämeenlinna shear zone (Fig. 3). The rocks in the shear zones vary from protomylonites and mylonites to pseudotachylytes. Usually a mylonitic foliation developed around the crushed clasts and changed them to resemble protomylonites.

The Hämeenlinna shear zone trends E-W and forms an incoherent lineament with irregular boundaries and consisting of several branches. At Humppila it branches out in a duplex which comprises the Nuutajärvi and Humppila domains. Observations on both dextral and sinistral sense of shear have been made. The Koijärvi sedimentary-acid volcanogenic basin was juxtaposed against the Häme group during this faulting. The diversity of movement directions indicates that the shear zone was affected by displacements both horizontally and vertically.

In the northern part of the Humppila domain the extremely well-developed S_2 is the dominant schistosity. The areas where S_2 dominates over S_1 and where the shears of the Hämeenlinna shear zone form duplex structures coincide fairly well with each other. In these areas both structures are oriented NE and hence these structures may have a genetic relationship.

The Hämeenlinna shear zone cross-cuts and deforms the intermediate synkinematic granitoids. However, within this zone there is a totally undeformed late kinematic K-granite. In contrast, the Painio shear zone regularly deforms the late kinematic pegmatitic and granitic veins. Hence the NW-SE trending lineaments tend to be younger and the E-W to NE-SW trending zones, like the Hämeenlinna shear zone, are slightly older. The movements in the Hämeenlinna and the Painio shear zones are of different ages and they are closely related to the emplacement of the plutonic rocks in respective areas.

GEOCHEMISTRY OF THE VOLCANIC ROCKS

In general, the rocks of the Forssa group range from basalts to rhyolites, but intermediate rocks are the most common ones. The Häme volcanics, in contrast, are dominated by basalts and basaltic andesites, while dacites and rhyolites are scarce. Representative analyses of the HSB volcanics are in Table 3. The classification based on alkalies is questionable to some degree since these elements are sensitive to alteration. However, the K_2O+Na_2O vs. SiO_2 diagram shows that the rocks of the Forssa and

Table 3. Representative analyses of the volcanic rocks from the Häme group (H) and the Forssa group (F).

Numb	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Label	459.2	109	215	65	144.2	323	48	459.1	338	121	37
Group	H	H	H	F	H	F	F	H	F	F	F
SiO_2	45.95	48.30	49.90	50.40	53.90	54.90	58.50	59.20	59.26	61.50	70.90
TiO_2	1.61	1.12	0.83	1.11	1.09	1.63	1.01	0.86	0.84	0.55	0.30
Al_2O_3	17.45	15.30	18.30	15.70	15.70	14.40	15.60	15.10	17.69	17.50	14.70
FeO*	11.60	11.36	9.81	11.23	10.44	11.27	8.69	6.33	8.71	6.14	3.25
MnO	0.18	0.20	0.17	0.20	0.17	0.18	0.17	0.13	0.07	0.12	0.06
MgO	6.67	6.74	5.62	4.67	3.97	3.18	2.96	2.87	2.17	2.67	0.64
CaO	8.43	10.20	8.59	8.79	7.36	7.37	6.30	9.48	4.39	5.66	1.77
Na_2O	2.17	2.91	2.84	2.31	2.74	3.25	2.81	3.30	3.79	3.77	4.02
K_2O	2.83	0.73	0.75	1.40	1.80	1.39	1.83	1.24	2.68	0.91	3.45
P_2O_5	0.17	0.30	0.30	0.24	0.37	0.27	0.25	0.20	0.19	0.18	0.09
Sum	97.06	97.16	97.11	96.05	97.54	97.84	98.12	98.71	99.79	99.00	99.18
Cr (ppm)	42	240	167	50	70	20	<10	-	-	-	-
Ni	70	90	32	30	30	10	14	20	26	24	16
Co	-	-	-	-	-	-	-	-	23	-	11
V	165	290	224	270	220	320	188	180	316	103	39
Cu	20	60	320	190	60	150	38	20	8	93	13
Zn	150	110	117	140	120	140	95	90	63	73	59
S	90	60	220	170	80	190	79	50	420	1330	90
Rb	-	-	<20	-	-	-	71	-	<20	27	90
Ba	353	192	225	242	373	393	234	343	272	297	729
Sr	270	530	576	316	470	290	214	440	163	217	194
Zr	90	60	91	90	130	150	144	150	149	113	244
Mg-value (%)	50.60	51.39	50.51	42.56	40.39	33.45	37.77	44.68	30.74	43.65	25.97
Sum of alkalies	5.00	3.64	3.59	3.71	4.54	4.64	4.64	4.54	6.47	4.68	7.47
CIPW Normative composition (wt%), Fe calculated as 0.85% FeO and 0.15% Fe_2O_3											
Q	0 .00	0.00	0.00	2.81	6.20	7.71	13.48	12.58	10.58	16.89	27.90
Or	16.73	4.31	4.44	8.27	10.64	8.22	10.84	7.33	15.84	5.39	20.43
Ab	14.76	24.62	24.03	19.54	23.18	27.5	23.78	27.92	30.53	31.9	33.84
An	26.13	26.56	35.01	28.36	25.26	20.63	24.56	22.76	20.66	27.07	8.49
Ne	1.95	00.0	00.0	00.0	00.0	00.0	00.0	00.0	00.0	00.0	00.0
Di	12.17	18.57	4.81	11.56	7.61	12.13	4.36	19.28	0 .00	0.00	0.00
Hy	0.00	5.72	24.01	20.35	19.44	15.45	16.18	5.39	16.42	14.39	5.77
Ol	18.29	12.24	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Il	2.91	2.13	1.58	2.11	2.07	3.1	1.42	1.63	1.60	1.04	0.58
Mt	2.80	2.75	2.37	2.71	2.52	2.72	2.10	1.53	2.11	1.48	0.79
Sum	96.19	97.51	97.44	96.35	97.87	98.06	98.36	98.96	99.99	99.34	99.45

1. Uralite-porphyritic basalt dyke, Häme group, Kalvola (x=6775.18,y=2505.08).
2. Uralite-porphyritic lava, Häme group, Lautaporras (x=6754.37, y=2494.20).
3. Even-grained metabasalt, Häme group, Särkijärvi (x=6764.45, y=2478.15).
4. Metabasalt, Forssa group, Forssa domain (x= 6735.80, y=2467.89).
5. Uralite-plagioclase-porphyritic lava, Häme group, Kotkajärvi (x=6767.53, y=2499.77).
6. Meta-andesite, Forssa group,Forssa-Somero domain (x= 6727.93, y=2470.60).
7. Even-grained andesitic metalava, Forssa group, Forssa domain (x=6738.20, y=2469.82).
8. Plagioclase-porphyritic andesite metalava, Häme group, Kalvola (x=6775.19, y=2505.08).
9. Uralite-plagioclase-porphyritic andesite, Forssa group, Forssa domain, Kiipu (x=6747.07, y=2467.06).
10. Andesitic metalava, Forssa group, Forssa domain (x=6737.82, y=2465.82).
11. Rhyolitic metalava, Forssa group, Humppila domain (x=6755.43, y=2469.24).

Analytical equipment: Philips PW 1400 XRF-spectrometer (powder briquettes).
Laboratories: Outokumpu Oy and Rautaruukki Oy

the Häme groups represent mostly subalkaline types. In the K_2O vs. SiO_2 diagram, they vary from low-K to high-K rocks but are dominated by medium-K types. The scatter in the total alkalis relative to silica is mainly due to variation in the potassium content and less dependent on the variation of sodium (Fig. 4b-c).

The rocks of the Forssa group show a general calc-alkaline fractionation trend in the AFM and SiO_2 vs. FeO^*/MgO diagrams (Figs. 4a and 5b), but the basalts and a few andesites show a diversified trend with tholeiitic affinities. With a few exceptions, the rocks of the Häme group have tholeiitic rather than calc-alkaline affinities. However, the tholeiitic affinities are not pronounced in either group and in the TiO_2 vs. FeO^*/MgO diagram (Fig. 5a) the basalts are transitional between tholeiitic and calc-alkaline rocks. The general trend is an enrichment in Fe relative to Mg in the early stages of crystallization in both the Häme and the Forssa groups. During progressive crystallization of dacites, rhyodacites and rhyolites in the Forssa group constant FeO^*/MgO ratios were maintained. According to Miyashiro (1974), TiO_2 decreases in calc-alkaline series and increases in tholeiitic series during fractionation. The TiO_2 contents in the HSB basalts show a decrease with increasing silica content, and in andesites (SiO_2 = 55-60%) titanium decreases less rapidly than for the other silica values (Fig. 6a). Also P_2O_5 values decrease with increasing silica in both groups. The P_2O_5 contents in the basalts of the Häme group (0.27-0.41%) are slightly higher than in those of the Forssa group (0.13-0.31%; Fig. 6b).

The trace elements Ni, Cr, Co, Zr, Sr and Ba distinguish to a lesser extent the two groups and the distribution fields overlap. The Ni content in the basalts and basaltic andesites are low, ranging between 20 and 60 ppm; nevertheless in the Häme group two samples contain 90 ppm Ni (Fig. 6d). The Häme basalts show slightly elevated Sr values compared to the Forssa basalts (Fig. 6c). The Häme basalts are mostly olivine-normative in contrast to

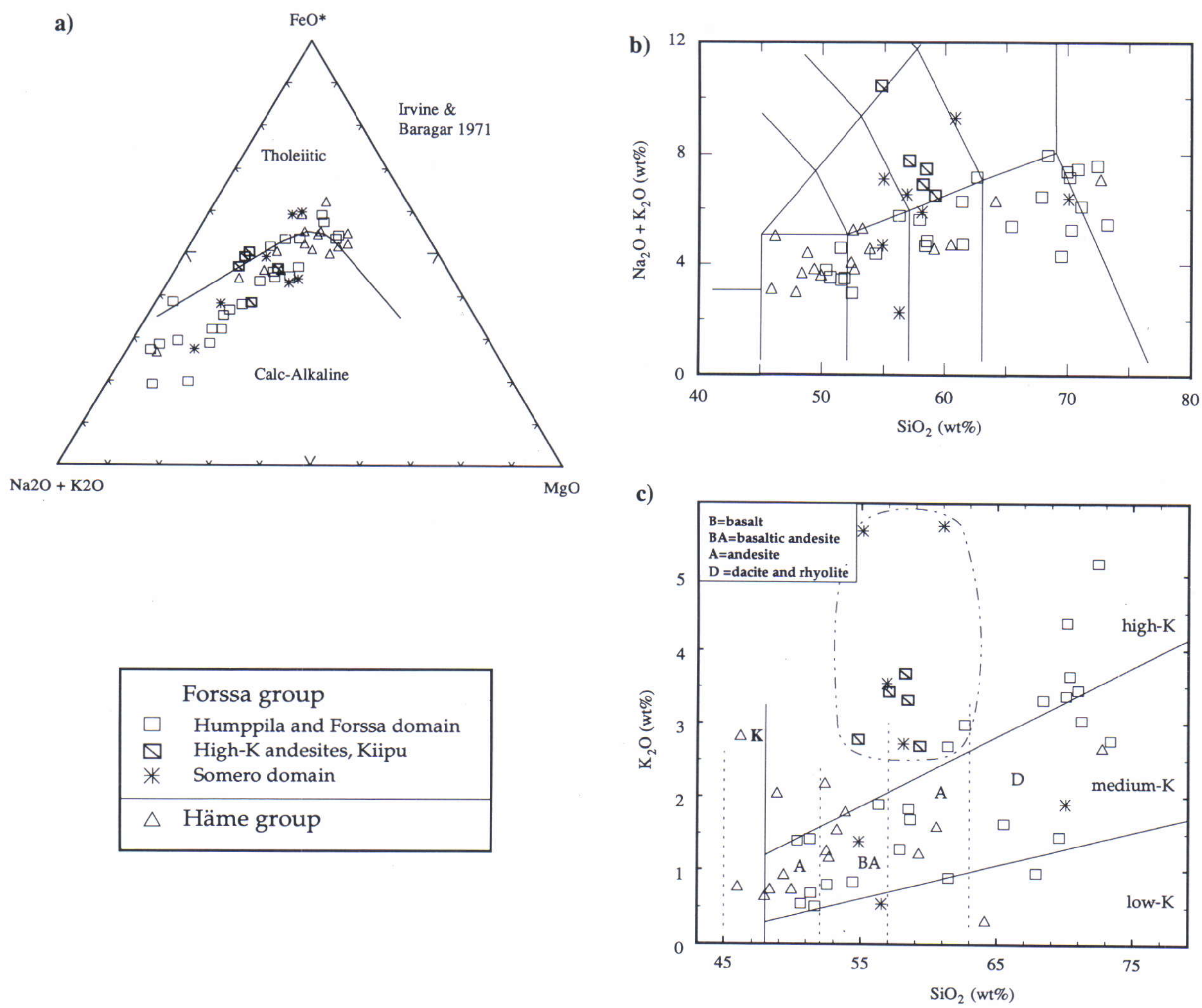


Fig. 4. Geochemical characteristics of the Hämeenlinna-Somero Volcanic Belt. AFM diagram after Irvine & Baragar (1971); K_2O vs. SiO_2 and total alkalis vs. SiO_2 diagrams after Le Maitre (1989). The point marked with "K" is a TiO_2- and K_2O-rich basalt from Kalvola. The dash-dotted line in Fig. 4c delineates the high-K andesites.

those of the Forssa group, which are quartz-normative. The normative An content ranges between 50 and 60% (see Table 3).

There are some exceptions to the summary given above. The andesites at Kiipu and partly those in Somero are high-K rocks (trachyandesites). Recent orogenic high-K andesites are relatively rich in P_2O_5, ranging from 0.32-0.54% (Baker 1982). Since the high-K andesites in Somero and Kiipu have low P_2O_5 contents of ca. 0.2%, their high K contents are probably due to alteration. At Kiipu also the FeO^*/MgO ratios and the V contents are high (Figs. 5b and 7b). In the V vs. MnO plot (Fig. 7b) the Kiipu trachyandesites deflect from the general differentiation trend. Both in Somero and Kiipu the high-K rocks are located close to sulfide mineralizations. Thus pre-metamorphic redistribution of alkalis and partly of ferromagnesian elements by ore-forming fluids is suggested to explain the deviations. The Ti-Zr relations in Fig. 7a show that these rocks do not differ from the main trend on behalf of these incompatible elements, which are stable during metasomatic alteration.

Some of the basalts in Kalvola, which form an offshoot from the Häme group, are fairly rich in TiO_2 and K_2O and poor in SiO_2 and P_2O_5 (Table 3, Number 1). The sample is taken from a 10 m thick dyke which is situated in an unaltered andesite. In most of the diagrams the sample deviates markedly from the general fractionation trend of the HSB. The high alkali content is due to K-enrichment, while the Na-content is similar to that of the other basalts of the area. The Kalvola basalts contain normative nepheline but the content of Ba and Sr is lower than in average high-K rocks with similar alkali contents from convergent plate boundaries (see Baker 1982). The high K and low P contents suggest that the elevated K-values are caused by metasomatic processes. The Kalvola basalts are interpreted, due to their stratigraphic position, as magmas that erupted during a late stage in the evolution of the Häme group, possibly from a different magmatic source.

The low Mg and Ni values indicate that the HSB volcanics underwent significant fractionation during ascent to the surface. The fast decrease in the Ni contents suggests an early olivine removal (Fig. 6d). The abundance of plagioclase phenocrysts indicates low-pressure fractionation conditions and the lower Sr content in the Forssa group basalts reflects a greater involvement of plagioclase precipitation. Also, the abundance of uralite shows that clinopyroxene was a major crystallizing phase.

The HSB volcanics are compared to Japanese volcanoes in Fig. 5. The Amagi volcano belongs to the Izu-Bonin arc and the Asama volcano belongs to the Northeast Japan arc. The chemistry of each of them represents a single trend calc-alkaline compositional variation. The single trend variation reflects a magmatic evolution from a single magmatic source, hence these volcanoes should be good for comparison purposes. The Forssa group displays two different trends; one follows the calc-alkaline Amagi trend and the other follows the more tholeiitic Hachijo-jima trend in the Miyashiros (1974) FeO^*/MgO vs. TiO_2 diagram. In the FeO^*/MgO vs. SiO_2 diagram the Forssa group also displays two different trends. Some of the samples defining the subhorizontal trend are altered, but this trend also embraces unaltered samples. Wilson (1991, p. 181) reports relatively high Fe_2O_3/FeO-ratios in recent island arcs. High oxygen fugacities in magmas imply that magnetite would be a near liquidus phase. Varying oxidation conditions during low-pressure fractionation play a fundamental role in determining whether the magmas fractionate along the tholeiitic or the calc-alkaline path. In Fig. 5b, the steep trend of the Forssa group is caused by magnetite/ilmenite precipitation during high oxygen

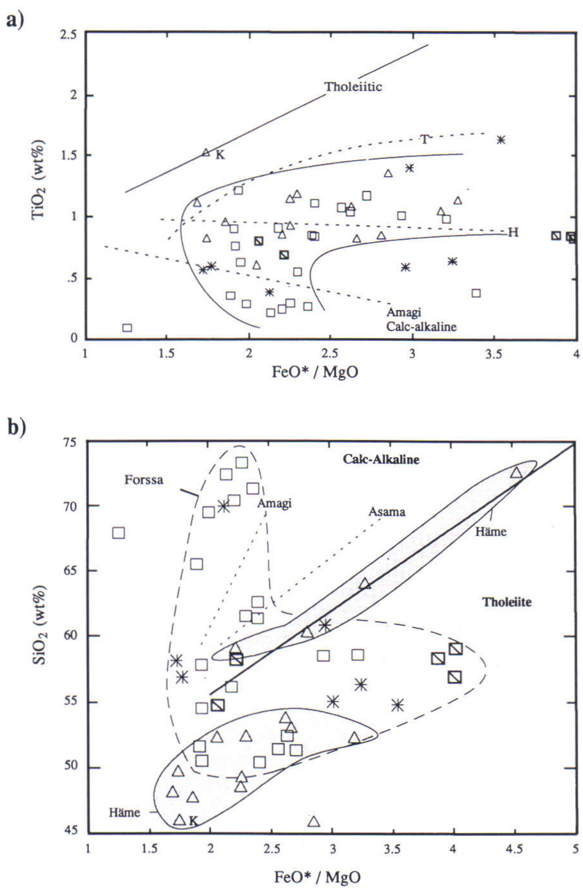


Fig.5. Geochemical variation diagrams for the rocks of the Hämeenlinna-Somero Volcanic Belt (after Miyashiro 1974). **a)** TiO_2 vs. FeO*/MgO. **b)** SiO_2 vs. FeO*/MgO. Symbols as in Fig. 4. The shaded fields outline the rocks of the Häme group and the dashed line outlines rocks of the Forssa group. Light dotted lines are fractionation trends. Lines in Fig. a: T= Hachijo-jima tholeiites; H= Hachijo-jima less typical tholeiites.

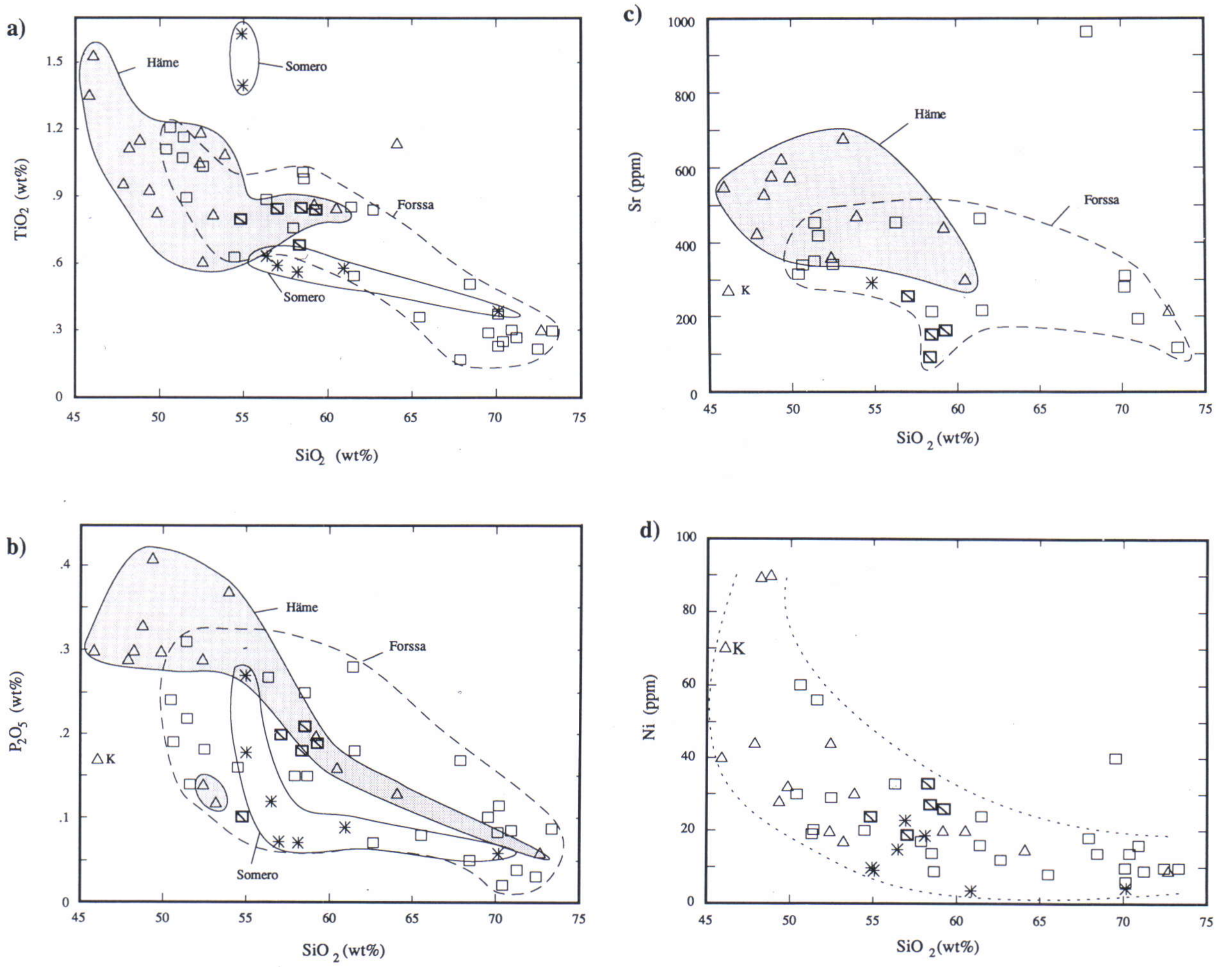
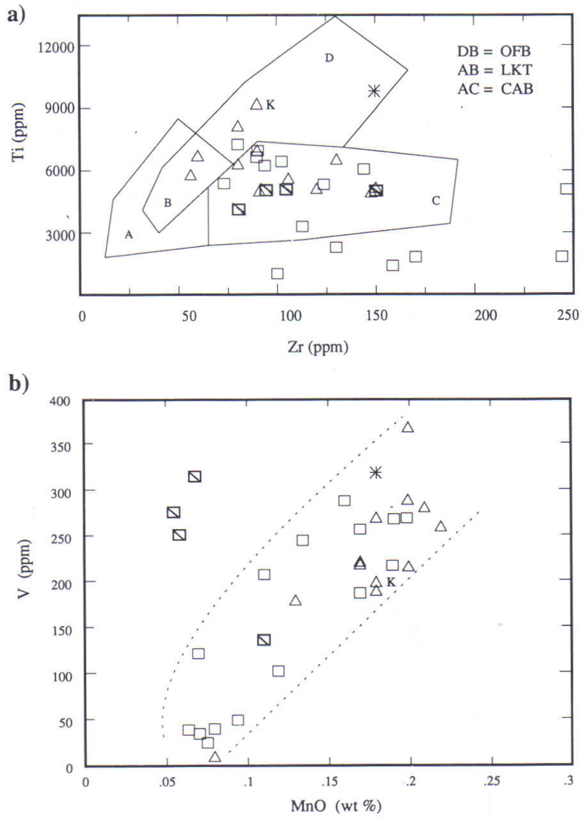


Fig. 6. Harker-type variation diagrams for the rocks of the Hämeenlinna-Somero Volcanic Belt. Symbols as in Fig. 4. The lines define the fields for the Häme and Forssa groups and the Somero domain.

fugacities. In Fig. 5a most of the intermediate rocks of the Forssa group follow a trend which is intermediate between the tholeiitic and calc-alkaline trend. This trend may be caused by less magnetite/ilmenite precipitation during lower oxygen fugacities. Amagi-type fractionation depletes the liquids from titanium more rapidly. The scatter of the samples and the deviating trends in the FeO^*/MgO-SiO_2-TiO_2 plots reflect interaction of replenishment, eruption and extensive differentiation, which resulted in variations of the oxygen fugacities in the magma chambers.

Variable conditions of low-pressure fractionation may occur in individual arc segments. For example, in the South Sandwich arc the volcanic rocks vary, in terms of their potassium content, from low-K to calc-alkaline types, but in terms of their FeO^*/MgO-ratios they can be classified as tholeiites (Wilson 1991, p. 173). The HSB volcanics are mostly calc-alkaline, but the FeO^*-MgO characteristics show that part of the basalts are tholeiitic. This diversity could be explained by similar variation in the fractionation conditions as in the South Sandwich arc.

In recent orogenic belts, occurence of andesites is mainly restricted to subduction settings. In mature arcs, like Japan, the andesite/basalt ratios tend to be greater than 2 (Gill 1981, p. 95, Aramaki & Ui 1982, Hall 1989, p. 391). The Forssa group has a high andesite/basalt ratio (estimated ratio = 2-4), while in the Häme group the andesite/basalt ratio is similar to that in primitive arcs (<1). Also, the TiO_2 content in the HSB is typical for recent volcanic arcs. The high Zr/Ti-ratios, low Ni and high LILE concentrations classify the HSB as a calc-alkaline island arc complex. Due to the monogenetic rock association in the Häme group the magmatic evolution may there be different from that in the Forssa group. Since basalts dominate in the Häme group, it could be regarded as a tholeiitic trench-side assemblage, but the relatively high Zr, LILE and P_2O_5 values discriminate the Häme group basalts from primitive arc tholeiites. Some of the basalts lack normative quartz. According to Miyashiro (1974), this is unusual even for



basalts of the inner volcanic zones in island arcs.

The chemical characteristics of arc volcanics vary in space and time. The alkalinity of arcs is regarded as an indicator of their maturity. Studies from the mature arcs in Japan suggest an increase in alkalinity away from the trench and several investigations show that a significant change in the geochemistry may also occur along the arcs (Gill 1981, p. 213). Based on the geochemical similarities between the volcanic rocks of the HSB and evolved, mature island arc rocks, such as those in the Honshu and Sunda arcs, it appears feasible to suggest that the formation of the HSB volcanics was preceded by crustal thickening.

Fig. 7. **a)** Ti vs. Zr diagram for the rocks of the Hämeenlinna-Somero Volcanic Belt (after Pearce & Cann 1973). Rhyolites and dacites are also plotted. CAB = calc-alkaline basalts, LKT = low-K tholeiites, OFB = ocean floor basalts, D = within plate basalts. **b)** V vs. MnO diagram. Symbols as in Fig. 4.

STRATIGRAPHY AND EVOLUTION

The complexity of the volcanic and sedimentary successions in the Forssa domain makes it difficult to establish a common stratigraphic record. The complexities may be explained by contemporaneous eruptions of different types of magmas from different volcanic centers or different magma batches from one center.

In the southern Forssa domain, andesites brecciated rhyolitic tuffs, and in the Somero domain andesitic fragments have been encountered in basalt lavas. In the Forssa domain basaltic to andesitic uralite-porphyry dikes cross-cut or are emplaced as sills in andesitic and dacitic plagioclase-porphyries. Furthermore, there are two thick coarsely plagioclase-porphyritic basalt dikes containing fragments of intermediate volcanic rocks. Evidently the volcanic activity started with acid eruptions, which were succeeded by intermediate and finally, by basaltic eruptions. The Häme group volcanics were deposited on sedimentary rocks, which may partly represent erosion products from the Forssa group. The wide distribution of basaltic feeder dikes suggests that the Häme group basalts were not erupted through a central vent; rather the eruptions took place along a fissure system. Volcanism started with explosive shallow-water eruptions that formed volcanic breccias and local pillow lavas. Contemporaneous erosion resulted in the development of debris flows, which formed volcanic conglomerates at the base of the Häme group. The lavas in the central parts of the Häme group do not exhibit pillow structures, and the poor stratification of the pyroclastics suggests that the central parts were formed partly in subaerial conditions. The Fe-sulfide formations at the base of the volcanic pile suggest that extension of the crust caused fissures which provided pathways for magmas. During the extensional period small anoxic basins were formed which favored the precipitation of strata rich in Fe-sulfides.

From the above data, a complex magmatic evolution can be deduced. The lowermost exposed sequences comprise the Forssa group rhyolitic to basaltic volcanics. They were followed by the extrusion of the Häme group basalts. The relatively K- and Ti-rich basalts of Kalvola cross-cut the intermediate end members of the Häme group and they commenced the latest extrusional event in the area.

DISCUSSION

The lithostratigraphic correlation and the tectonic setting of the volcanic-sedimentary sequences in southern Finland is principally unresolved. Interpretation of the Svecofennian stratigraphy has been done in some key areas; however the relationships between different belts is obscure and the tectonostratigraphic relationship between, for example, the supracrustals of the Hämeenlinna-Somero (this study), Tampere (Kähkönen 1987, 1989) and Orijärvi-Kemiö (Colley & Westra 1987, Mäkelä 1989) (Fig. 1) areas is yet to be solved. Most of the volcanics in the Svecofennides are calc-alkaline with arc affinities (Gaál & Gorbatschev 1987). In general, the volcanic belts in southwestern Finland show a northward transition from bimodal sequences in Enklinge-Orijärvi (Ehlers & Lindroos 1990, Lindroos 1990) through calc-alkaline associations (Hämeenlinna-Somero; Hakkarainen 1989, this study) to more alkaline volcanics in Tampere (Kähkönen 1987). The tholeiitic Haveri basalts in the Tampere region are considered to represent an initial-stage island arc environment (Mäkelä 1980). The concept that the southern Svecofennian volcanic belts were formed in an oceanic environment (Gaál 1990) was mainly based on the absence of evidence of an older continental basement. Huhma et. al. (1991) concluded that many of the zircons in the graywackes at Tampere are older (2.0-1.9 Ga) than the volcanic rocks (1.904-1.89 Ga) from the same area. This implies the existence of an earlier crust predating the formation of the arc volcanics.

If the abundances of LIL-elements in the HSB basalts are primary, an enrichment process in the mantle would be indicated. This could not likely take place in larger extents in a thin oceanic plate. For example, the Mariana-Izu arcs, with a 20-30 km thick crust, are primitive and dominated by tholeiitic low-K basalts. K-rich lavas occur in the Mariana arc (Lin et al. 1989), but volumetrically in smaller amounts, relative to the bulk volume, than the medium-K lavas in the HSB. Furthermore, in the HSB calc-alkaline rocks are more abundant than tholeiitic rocks. Miyashiro (1974) stressed that the ratio of calc-alkaline/tholeiitic rocks tends to increase with increasing thickness of the crust. Crustal thickening restrains primitive magmas from ascending to the surface. They are collected in shallow magma chambers where they evolve to calc-alkaline successions. Hence, the HSB volcanics were probably formed in a mature arc milieu.

Although the high andesite/basalt ratio is a general feature in the HSB, the Häme group volcanic rocks show a monotonous evolution with mainly basaltic derivatives. This kind of monogenetic volcanism can be ascribed to tensional stress fields (Nakamura & Uyeda 1980), which are found in the rear of subduction zones. The tholeiitic Häme group could have been produced at a short stage of tension (decoupling) during the generally compressional arc volcanism. Cyclic variation between plate decoupling and coupling in oceanic island arcs is described by Hawkins et. al. (1984).

The Japanese and Izu-Mariana arcs have high convergence rates of 7-9 cm/yr and together they form one of the fastest consuming plate margins active today. Japan represents an evolved stage of arc volcanism. The existence of several volcanic zones with geochemical island arc affinities in the Svecofennian Domain and their formation within a few tens of millions of years suggests fast movement rates in the pre-Svecofennian plate collage. Therefore, the magma generation in the HSB may show similarities to the magmatic evolution of the Japan-Mariana arcs. The volcanic rocks in the HSB show both tholeiitic and calc-alkaline affinities. Andesites, dacites and rhyolites are abundant and the basalts have higher potassium contents than the basalts in primitive island arcs. These characteristics suggest a subduction site like that of Group II in Gill (1981, p. 220), with relatively high convergence rates. The magmas in the HSB are chemically more diverse compared to the primitive, more depleted and iron-enriched magmas of Group I formed in arcs with thin crust. More than 80% of the erupted magmas in Group I are tholeiitic, which is not the case in the HSB.

More precise geochronological data are needed to establish a detailed and accurate model for the evolution of the Svecofennian crust, and the discussion presented below should be seen as tentative. The complex tectonostratigraphic relations of the volcanic belts at Orijärvi, Tampere and Hämeenlinna could be consistent with a model with several small tectonic entities. They vary in size from small microcontinents to accretionary prisms, and interact with each other through thrusting, subduction, docking etc. The amalgamation of primitive arcs, fore-arc basins, back-arc basins, and rifts upon each other provides material for crustal thickening and evolution to mature calc-alkaline volcanism. The formation of arc volcanics in southern Finland could have been predated by a rift-related bimodal magmatism, such as in Orijärvi (Colley & Westra 1987, Väisänen 1991) and Enklinge (Ehlers & Lindroos 1990, Lindroos 1990). A similar type of bimodal magmatism may have contributed to the crustal thickening that preceded the arc volcanism and the thickening resulted in a continental geochemical signature of the arc magmas.

Generation of oceanic subduction zones involves earlier imbrication and fracturing of the lithosphere. Early fractures and faults form zones of weakness in the lithosphere and these zones are apt to develop into new subduction zones when the plate margins are subjected to compressional stress (Hawkins et al. 1984). The bimodal magmatism in southern Finland could be a result of an early imbrication and extension of the oceanic crust. Some of the fractures could later have developed into arcs in southern Finland, when the stress field changed to compressional. The assumed subduction zone on the border to the Archean craton is earlier or of the same age with the earliest phases of the Svecofennides (Park 1985, Gaál & Gorbatschev 1987). A plausible explanation could be that a NE movement of the "proto-Svecofennian plate" caused a consuming subductional event on the border to the Archean craton. Continental margins tend to have slower closing rates than intra-oceanic margins (Sugisaki 1976). Therefore, fast movement of the "proto-Svecofennides" northeastwards could have exceeded the consumption of the oceanic plate at the Ladoga-Bothnian Bay zone. The compression caused by the onpushing plate would have been released in migration or formation of new subduction zones further away from the craton. If the motion of the Svecofennian collage was in a NE-ENE-direction (Gaál & Gorbatschev 1987), the angle between the movement direction and the orientation of the Bothnian-Ladoga arc (NNW-SSE) supports the interpretation of the conversion of the Bothnian-Ladoga arc into a dextral strike slip complex. This concept is favored by the locking event of the Bothnian-Ladoga arc described by Park (1985).

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