The volcano-tectonic setting and mineralization of the early Proterozoic Kemiö–Orijärvi–Lohja belt, SW Finland

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SUMMARY: The Kemiö–Orijärvi–Lohja region of SW Finland, which consists of metabasic rocks, metagreywackes, metavolcanic rocks of felsic composition (leptites) and syngenetic gabbro-tonalite bodies, is a westerly striking portion of the early Proterozoic (1900 Ma) Svecofennian Belt. This belt, which extends westward into Central Sweden is flanked by large post-kinematic granites. The grade of metamorphism decreases westward from amphibolite-granulite transitional conditions around Orijärvi to greenschist conditions in Central Sweden.

The volcanic sequence begins with submarine basic-intermediate lavas followed by turbiditic metasediments and ends with the deposition of felsic pyroclastic rocks. Sheets of gabbro related to larger synkinematic intrusive bodies occur within the felsic rocks. Disseminated Cu-Fe sulphides occur in the lower basic rocks and massive Cu-Pb-Zn ore bodies, of probable volcanogenic origin, are found in the upper felsic rocks. Mg-alteration and the formation of cordierite-anthophyllite rock characterizes the latter ore deposits.

The geochemistry of the metavolcanic rocks indicates a transition between alkaline and subalkaline compositions, and the geochemistry of intrusive bodies suggests they are comagmatic with the volcanic rocks they intrude. In more strongly deformed areas mobility of Fe, Si and K is indicated. The origin of some high Fe basic lavas is unclear. After consideration of the geology and geochemistry of the Svecofennian Belt it is suggested that it may represent an ancient analogue of present day New Zealand where 'back-arc' rifting is occurring in both oceanic areas and mature arc crust.

This paper reviews aspects of a research project in SW Finland carried out by the Department of Ore Geology, Petrology and Mineralogy at the Free University of Amsterdam under the leadership of L. Westra. The project started in 1974 with geological mapping on Kemiö island, subsequently mapping shifted eastwards to the Orijärvi–Lohja region. Since 1979 an important feature of the project has been the emphasis on thematic studies of the structure, petrology and mineralogy of the rocks. This paper summarizes the work of the authors and reviews geochemical data contained in unpublished reports by Jaspers (1978), Hofstee (1980), Wijte (1980), Kasteleyn (1982), Brouwer (1982), N. Schippers (1982) and M. Schippers (1983).

Earlier work on the Kemiö–Orijärvi–Lohja belt includes the classic studies of Eskola on the geology of Orijärvi (Eskola 1914) and particularly the development of the metamorphic facies concept (Eskola 1915). Other work includes that of Tuominen (1957, 1961) on the geology and structure of Orijärvi, of Parras (1958) on the granulite domain at Lohja (West Uusimaa), and of Simonen (1953, 1960, 1971, 1980) on the Svecofennian Belt in SW Finland in general; the Kemiö–Orijärvi–Lohja belt forms a portion of the Finnish Svecofennides. The only detailed studies of mineralization at Orijärvi are those of Eskola (1914) and Latvalahti (1970).

Regional geology

The Kemiö–Orijärvi–Lohja belt is composed of supracrustal and infracrustal rocks of early Proterozoic age (*c.* 1800 Ma, Simonen 1980). The belt strikes roughly E–W and is about 110 km long and between 5 and 20 km wide (Fig. 1). This belt is part of the Svecofennian Belt of SW Finland and Central Sweden and is contemporaneous with the early Proterozoic, NNW-trending Karelian Belt in Central and Eastern Finland. These two belts collectively make up the Svecokarelian orogenic domain.

Supracrustal rocks within the Svecofennian Belt are predominantly metavolcanic rocks such as mafic and felsic tuffs, volcanic breccias and agglomerates, and pillow lavas. These are intercalated with calcareous rocks, pelites and greywackes. Rarer rock types include volcanic ultramafites and cordierite-anthophyllite rock. In SW Finland rock suites are distinctly bimodal but in Central Sweden there is a strong predominance of felsic rocks.

In SW Finland the supracrustal rocks are intruded by a syngenetic suite of infracrustal rocks consisting mainly of gabbroic to tonalitic bodies with subordinate hornblendites and granodiorites. Both the supracrustal and infracrustal rocks are intruded by microcline-rich, anatectic

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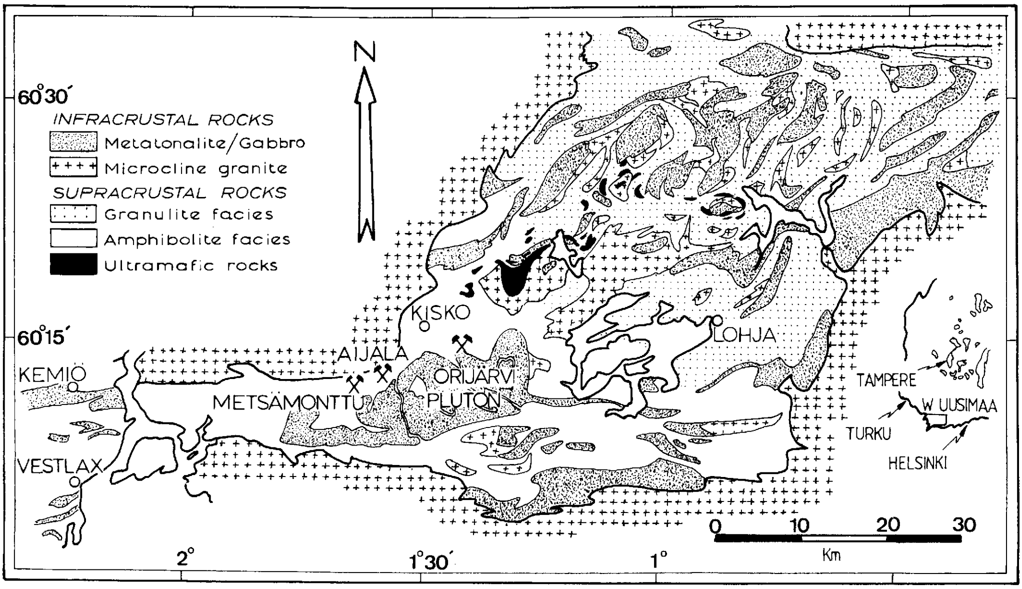

FIG. 1. Simplified geological map of the Svecofennian Belt of SW Finland.

granites and large masses of granite bound the Svecofennian Belt to the north and south (Fig. 1).

Three major phases of deformation have been recognized in the Svecofennian Belt (Verhoef & Dietvorst 1980; Schreurs & Westra 1986). The earliest phase was probably a recumbent folding followed by thrusting, possibly related to imbrication in a plate collision zone. This D1 phase is also responsible for the dominant foliation in the belt.

The major deformation, D2, is related to a N–S compression event, which began with homogenous deformation creating E–W striking upright folds (F2). Further crustal shortening resulted in the formation of two structural domains. A western domain with tight F2-folds and an eastern domain, NE of Orijärvi, in which shear zones and large scale boudinage are found. Differential movement between regional scale granite masses is probably responsible for the latter deformation style (Schreurs & Westra 1986). In certain zones, notably around Kisko and Orijärvi, the rocks have been affected by an open style F1-folding only and primary volcanic and sedimentary features are preserved.

The Kemiö–Orijärvi–Lohja belt is largely metamorphosed to amphibolite facies but to the east of Orijärvi there is a rapid transition towards granulite facies (Fig. 1). The boundary between the granulite and amphibolite domains is taken as the first appearance of hypersthene in metavolcanic rocks of intermediate composition. Transition from amphibolite to granulite facies is virtually isobaric and takes place in a zone only a few kilometres wide. Peak metamorphic conditions for the amphibolite facies on Kemiö island have been estimated at 550–679°C and 3–4 kbar (Dietvorst 1981), and 550–650°C and 3–5 kbar east of Orijärvi. Within the granulite domain, peak conditions are estimated at 750–825°C and 3–5 kbar (Schreurs & Westra 1986).

Volcanic stratigraphy and plutonic phases

Strong deformation, moderate to high grades of metamorphism, and patchy exposure resulting from glacial cover, prevent the accurate determination of the volcanic stratigraphy in large tracts of the Svecofennian Belt of SW Finland. Fortunately, zones with weak deformation in the Vestlax–Branten area of Kemiö and around Kisko and Orijärvi allow a reconstruction of the sequence of events.

1 Structurally the lowermost units are gabbroic bodies separated from the overlying volcanic sequences by prominent shear zones. Sulphide layers occur in the shear zones.

2 Structurally and stratigraphically the lowermost volcanic rocks occur above the gabbros, these volcanic rocks are frequently pillowed and are of mafic composition. Calcareous rocks are associated with these pillow lavas.

3 There is a gradual passage upward into polymict volcanic breccia (chiefly Vestlax) and turbiditic greywackes (chiefly Kisko).
4 Felsic volcanic rocks, mainly tuffs and flow breccias, form the top of the volcanic sequence.
5 The last event is the intrusion of syngenetic gabbro-tonalite intrusions and thin gabbroic sheets into all the previously mentioned units.

Way-up criteria for the sequence include pillow shapes and a host of sedimentary structures in the metagreywackes. Flame structures, load casts, slump folds, erosion channels, cross bedding, graded bedding, sole marks, and Bouma-type units have all been recognized.

Clasts within the polymict breccias include varieties of metamorphosed mafic and felsic volcanic rocks and blocks of gneiss. Given the early Proterozoic age for the volcanic sequence, the latter may represent fragments of Archaean basement. An interesting feature of some breccias at both Kemiö and Orijärvi is an abundance of felsic clasts ($>70\%$ SiO_2) in a dark mafic matrix (*c.* 53% SiO_2). In addition, at Orijärvi there are exposures of banded amphibolite consisting of dark mafic layers and pale felsic layers each up to 20 cm in thickness. Rare felsic blocks within some mafic layers have the appearance of breadcrust bombs and there is even a suggestion of sagging beneath the blocks. Although the compositional differences between these layers and between clasts and matrix may have been slightly accentuated by metamorphic differentiation, these mixed sequences are taken as an indication of contemporaneous acid and basic volcanism.

At both Kemiö and Orijärvi it is thought that the volcanic sequence is underlain by gabbroic bodies, however, contacts in the field are always sheared. Evidence to support an older generation of gabbro is the presence of rare clasts of gabbro in the volcanic breccias. Tonalite and granodiorite clasts have not been observed in the breccias.

The sequence of events in the syngenetic intrusions has been best established for the Orijärvi pluton (Fig. 1) where the following phases occur:

1 gabbro-diorite intrusions with rare minor bodies of hornblendite; these intrusions may represent a contaminated border phase of the main tonalitic body (phase 2);
2 tonalite-granodiorite intrusions brecciating phase 1 and showing varying degrees of foliation;
3 large gabbroic dykes;
4 veins of hornblende andesite-microdiorite;
5 veins of microcline granite.

The plutonic rocks carry a penetrative S1-foliation indicating that they are prekinematic. The major change from mafic to felsic rock reflects the variation seen in the volcanic sequences and this along with the close chemical similarities between the volcanic and plutonic rocks suggests the two are comagmatic.

Petrology of the rocks

General features of the meta-igneous rocks from the Kemiö–Orijärvi–Lohja belt are illustrated in the AFM diagrams (Fig. 2) and the SiO_2 v. K_2O plot (Fig. 3). These suggest a calcalkaline character, a feature supported by the calculation of the Peacock index for individual suites. Plutonic suites on Kemiö and at Orijärvi have indices of 62 and 63 respectively, volcanic suites from the same locations have indices around 60.

Ultramafic rocks

A variety of ultramafic rocks occurs in the Kemiö–Orijärvi–Lohja belt and includes hornblendites associated with the syntectonic gabbro-tonalite intrusions, rare peridotites (Eskola 1914; Mikkola 1955; Jaspers 1978) and ultramafic volcanic rocks showing pillow and breccia form (Schreurs *et al.* 1986) but without the development of spinifex textures. Olivine, generally very highly serpentinized, forms up to 40% of the mode in both peridotite (Table 1, No. 1) and volcanic ultramafites (Table 1, No. 2). Pyroxene is also present in the latter but has not been positively identified in the peridotites, however, amphibole in these rocks is almost certain to be replacing pyroxene. Plagioclase in the peridotites and volcanic ultramafites accounts for up to 20% of the mode and has an An content usually greater than 80. In the hornblendites, again, plagioclase can make up to 20% of the mode and is usually of labradoritic composition. Spinels, often Cr-rich, are the common accessory minerals in the ultramafic rocks.

Chemically, the peridotites (Table 2, No. 1) and the volcanic ultramafites (Table 2, No. 2) show low SiO_2, Al_2O_3, Na_2O and K_2O and high MgO, Cr, and Ni typical of ultramafic rocks. Schreurs *et al.* (1986) conclude on the basis of high TiO_2 and low CaO/TiO_2 and Al_2O_3/TiO_2 ratios, that the volcanic ultramafites of the Lohja (West Uusimaa) district have more affinities with picritic basalts than komatiites. An unusual feature shown by a few samples from the volcanic ultramafites not revealed by Table 2 is exceptionally high Rb in the range 500–2800 ppm (Schreurs *et al.* 1986). On an $Al/(Mg+Fe)$ v. $Mg/(Mg+Fe)$ plot (Fig. 4) the volcanic ultramafites show a

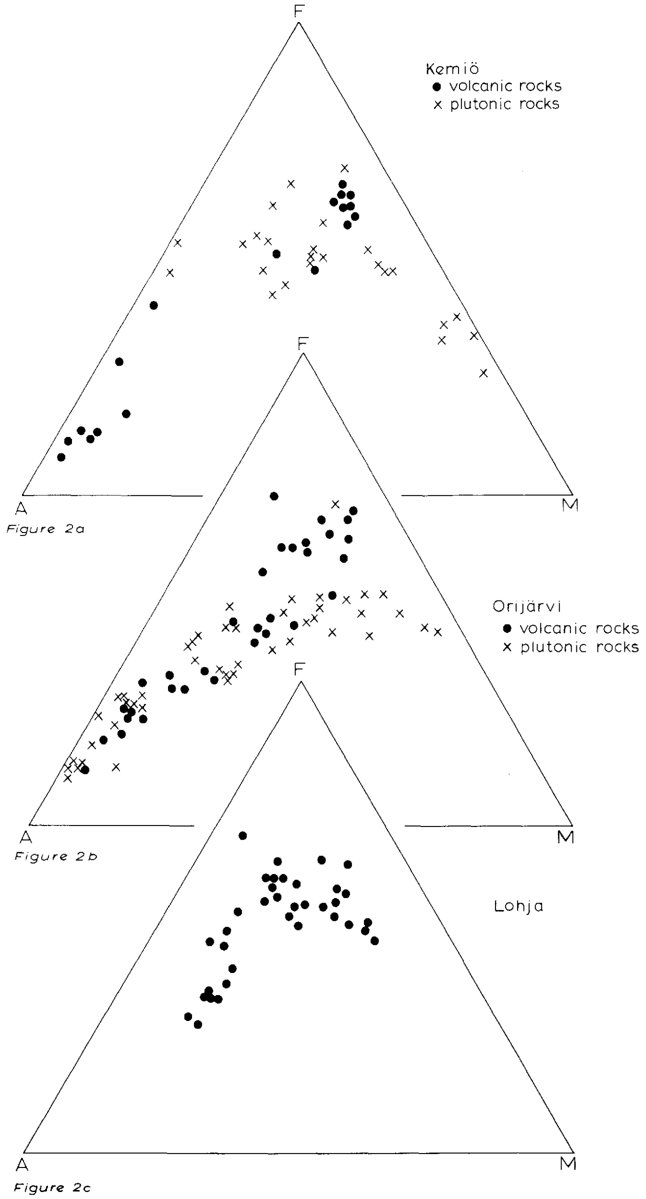

FIG. 2. AFM diagrams for the Kemiö–Orijärvi–Lohja belt: 2a—Kemiö, note the marked bimodality of the volcanic suite; the ultramafic rocks are mainly intrusive peridotitic bodies; 2b—Orijärvi, the Fe-rich volcanic rocks are mainly banded amphibolites and the mafic matrix of breccias containing felsic clasts; 2c—Lohja, the samples are mainly high-grade gneisses from the granulite-amphibolite transition zone.

trend similar to that for tholeiitic cumulate sequences from Skaergaard and Kilauea.

Mafic and intermediate rocks

The mafic and intermediate rocks (Table 1, Nos. 3 to 5) are now typically represented by a variety of gneisses:

1 a banded sequence of (two pyroxene)-biotite-hornblende gneisses, and basaltic amphibolites. Most of the rocks of this sequence can be interpreted as tuffaceous rocks and agglomerates;
2 (diopside)-amphibolites with calcsilicate lenses, interpretated as (pillowed) basalts and associated calcareous marine sediments;
3 massive (two pyroxene)-biotite-hornblende

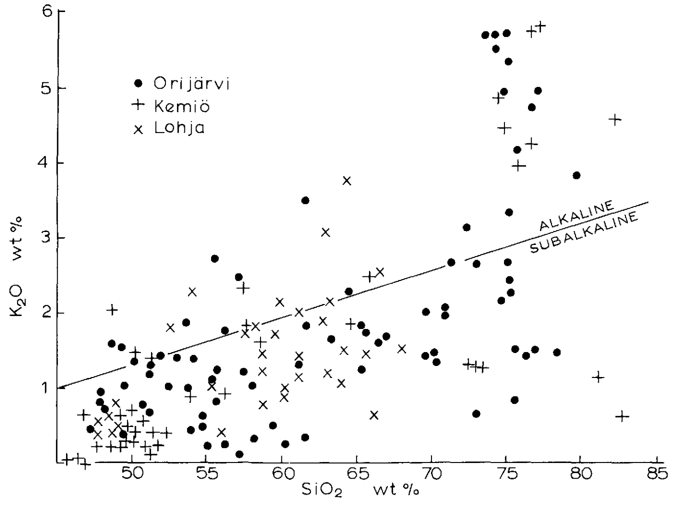

FIG. 3. SiO_2 v. K_2O plot for the Kemiö–Orijärvi–Lohja belt. The subalkaline/alkaline boundary is based on the distribution of analyses from Fiji (Colley, unpublished data) where the subalkaline rocks are arc tholeiites and calcalkaline andesites, and the alkaline rocks are of shoshonitic composition.

gneisses, recognizable as plutonic masses with a modal composition varying between gabbro and diorite.

Depending on the SiO_2 content, modal quartz varies from 0 to 35%. Plagioclase, of labradoritic to andesine composition and showing minor sericitization, is usually the most abundant mineral, forming up to 70% of the mode. Hornblende showing variable amounts of alteration to secondary amphibole is the principal, and sometimes the sole, mafic mineral. Biotite is generally a minor phase but can form up to 15% of the mode in some intermediate rocks. Sphene is the principal accessory mineral sometimes occurring in amounts (up to 12%) sufficient to

TABLE 1. *Summary of modal percentages for meta-igneous rocks from the Kemiö–Orijärvi–Lohja belt, SW Finland*

	1	2	3	4	5	6	7	8	9
Quartz	—	—	5–30	5–25	0–35	5–20	25–40	25–45	30–50
K-feldspar	—	—	tr	tr	tr	tr	10–30	tr	0–30
Plagioclase	20	<10	30–70	25–60	10–75	50–60	10–30	35–55	35–65
Plag (An%)	80	90–95	*c.* 60	40–55	30–70	40–60	20–50	30–40	20–40
Amphibole*	40	30–95	5–40	20–50	15–80	<10	tr	<10	0–10
Biotite	—	<10	0–10	5–15	0–15	5–20	5–10	3–15	10–20
Clinopyroxene	—	5–40	—	—	—	<10	—	—	—
Orthopyroxene	—	<10	—	—	—	5–15	—	—	—
Olivine	40	0–40	—	—	—	—	—	—	—
Sphene	tr	tr	tr	2–3	0–12	tr	tr	tr	tr

—, not observed; tr, trace amounts.
* Principally hornblende with variable amounts of alteration to secondary amphiboles.
1 Foliated peridotite (amphibolite facies), Kemiö
2 Ultramafic volcanic rocks (granulite facies), Lohja
3 Mafic-intermediate volcanic rocks (amphibolite facies), Orijärvi
4 Mafic-intermediate plutonic rocks (amphibolite facies), Orijärvi
5 Mafic-intermediate igneous rocks (amphibolite facies), Kemiö
6 Intermediate igneous rocks (granulite facies), Lohja
7 Felsic volcanic rocks (amphibolite facies), Orijärvi
8 Felsic plutonic rocks (amphibolite facies), Orijärvi
9 Felsic igneous rocks (amphibolite facies), Kemiö

TABLE 2. *Representative analyses for meta-igneous rocks from the Kemiö–Orijärvi–Lohja belt, SW Finland*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	44.24	46.76	47.8	49.16	49.52	51.43	58.97	61.50	63.55	69.73	75.34	75.83	76.76	76.93
TiO_2	0.24	0.96	1.04	0.94	1.62	1.82	0.68	0.66	0.66	0.32	0.21	0.23	0.36	0.19
Al_2O_3	8.16	8.61	21.79	16.38	13.48	16.00	15.09	20.39	17.07	14.68	13.14	11.75	12.72	12.43
$Fe_2O_3{}^T$	14.24	11.26	3.16	9.49	15.83	10.68	10.16	2.70	4.93	4.74	2.66	3.03	1.25	1.28
MnO	0.16	0.17	0.13	0.15	0.23	0.11	0.15	0.11	0.06	0.08	0.03	0.12	0.03	0.02
MgO	26.12	20.37	1.40	7.62	5.92	5.72	4.74	1.72	2.39	1.15	0.51	1.63	0.28	0.42
CaO	6.30	10.55	19.85	13.54	10.36	9.38	5.58	10.36	5.35	3.49	1.72	4.57	1.64	0.69
Na_2O	0.44	0.85	3.70	2.18	2.55	3.17	3.24	1.96	4.13	3.73	4.09	1.31	2.56	1.70
K_2O	0.05	0.39	0.94	0.41	0.27	1.34	1.24	0.37	1.67	2.01	2.25	1.49	4.23	6.31
P_2O_5	0.05	0.08	0.19	0.13	0.22	0.35	0.15	0.23	0.19	0.07	0.05	0.04	0.17	0.03
Sr	nd	191	nd	360	nd	1020	157	nd	791	145	99	nd	—	nd
Rb	—	15	nd	12	—	24	131	nd	9	7	1	nd	118	nd
Th	0.6	nd	0.7	—	1.1	2.3	—	0.9	3.7	8.1	11.3	8.0	19.0	13.9
Nb	—	nd	nd	8.2	—	13.5	13.0	nd	14.2	9.3	8.8	nd	—	nd
Zr	nd	66	nd	63	nd	84	100	nd	89	120	117	nd	252	nd
Hf	0.6	nd	—	—	2.6	2.1	nd	1.2	2.6	4.7	5.1	5.5	7.4	5.1
U	—	nd	—	—	0.6	1.2	—	—	2.6	3.5	4.1	—	1.4	—
Y	nd	12	nd	15	—	13	35	nd	12	23	26	nd	—	nd
Ta	—	nd	—	—	—	—	—	—	—	—	—	0.7	0.8	1.5
Sc	14	nd	nd	nd	52	nd	nd	nd	nd	nd	nd	nd	5	nd
Cr	2000	1570	nd	nd	135	nd	nd	nd	nd	nd	nd	nd	21	nd
Co	93	nd	nd	nd	37	nd	nd	nd	nd	nd	nd	nd	4	nd
Ni	510	1085	nd	57	nd	42	46	nd	11	5	4	nd	—	nd

—, below detection limits; nd, not determined

1 Foliated peridotite, Kemiö
2 Average for 21 volcanic ultramafites, Lohja (from Schreurs *et al.* 1986)
3 Pillowed metabasalt (core), Orijärvi
4 Metagabbro, Lohjä
5 Strongly foliated pillowed metabasalt, Kemiö
6 Foliated gabbro, Orijärvi
7 Gneiss, Lohjä
8 Clast of meta-andesite, Orijärvi
9 Foliated tonalite with dark inclusions, Orijärvi
10 Pink tonalite, Orijärvi
11 Coarse-grained foliated tonalite, Orijärvi
12 Meta-rhyolite flow (leptite), Orijärvi
13 Fine-grained leptite, Kemiö
14 Meta-rhyolite flow, Orijärvi

With the exception of no. 7 which occurs in the granulite facies, samples occur in the amphibolite facies.

raise the question of Ti mobility during metamorphism. Similarly zircon is often abundant enough (*c*. 1%) to suggest possible concentration during metamorphic and structural processes. Other minerals generally present in trace amounts include K-feldspar, muscovite and apatite. In amphibolites showing retrogression, principally those occurring in or close to major fault zones, epidote, chlorite, carbonate minerals, sericite and prehnite are developed. Primary igneous textures have not been seen in the mafic and intermediate metavolcanic rocks which typically have a strong foliation. In metagabbros, however, relict igneous textures, particularly ophitic ones, are sometimes preserved. To the east, in the granulite domain, all traces of original texture are lost and intermediate rocks have up to 20% modal ortho- and clinopyroxene (Table 1, No. 6).

The mafic and intermediate rocks typically have an igneous chemistry (Table 2, Nos. 3 to 9) with generally moderate to high values for TiO_2 and total alkalies suggesting a transitional position between alkaline and subalkaline chemistry. Support for this suggestion is provided by the spread of points on discrimination diagrams such as Ti v. Zr (Fig. 5) and Ti v. Cr (Fig. 6). Hf, Ta and Th have been analysed in a large number of samples, but because Ta is usually below detection limits all the samples fall on the Th-Hf edge of the Hf-Th-Ta plot and lie in the arc volcanic field of Wood (1980). Spidergram plots (Fig 7) for a selection of LIL and HFS elements show a hump in the LIL elements typical for volcanic arc basalts though Rb is notably higher than in most modern oceanic island arc suites (cf. Pearce 1982).

Throughout the belt, the mafic to intermediate rocks show two distinct patterns on chondrite-normalized REE plots (Fig. 8). The majority of rocks have a relatively flat REE pattern with a

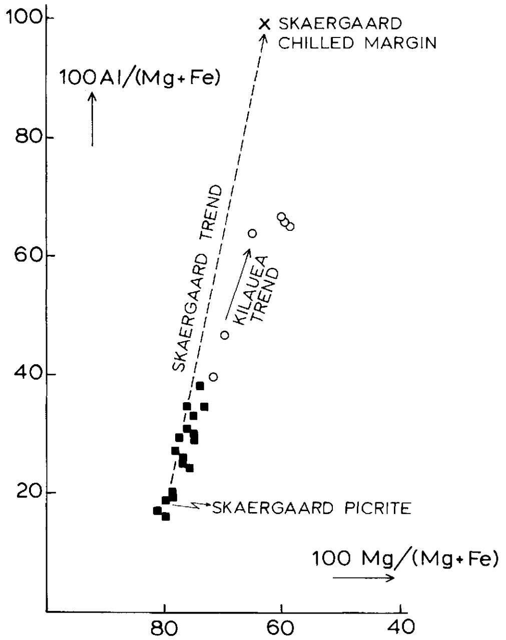

FIG. 4. Plot of 100 Al/(Mg + Fe) v. 100 Mg/(Mg + Fe) for ultramafic rocks from Lohja (West Uusimaa) from Schreurs *et al.* (1986). The trends of rocks from suites of Kilauea and Skaergaard rocks are taken from Irvine (1979). Solid squares are Lohja volcanic ultramafites and the open circles are diopsidic amphibolites from the same area.

slight positive Eu anomaly and comparatively high HREE resulting from the abundance of hornblende. The other pattern shown by a few rocks is strongly fractionated and indicates hornblende depletion leading to LREE enrichment.

A distinctive subgroup within the mafic-intermediate group is a high Fe basic rock containing usually greater than 15% total Fe expressed as Fe_2O_3 (Table 2, No. 5). These rocks form a distinct grouping on the AFM plot (Fig. 2). In the Orijärvi district the Fe-rich mafic rocks usually occur as banded amphibolites or as components of the matrix in breccias with felsic clasts and a mafic matrix. Given this setting there is a suspicion that the high Fe may in part be due to metamorphic differentiation rather than being a primary magmatic feature. However, on Kemiö, Van Lamoen (1979) has studied Fe-rich metagabbros and concludes that the high Fe results from magmatic differentiation.

There is no significant difference in chemistry between the amphibolite and granulite facies domains.

Felsic rocks

Mineralogically, the felsic volcanic rocks (Table 1, Nos.7 and 9) are dominated by quartz and plagioclase which can form up to 50% and 65%

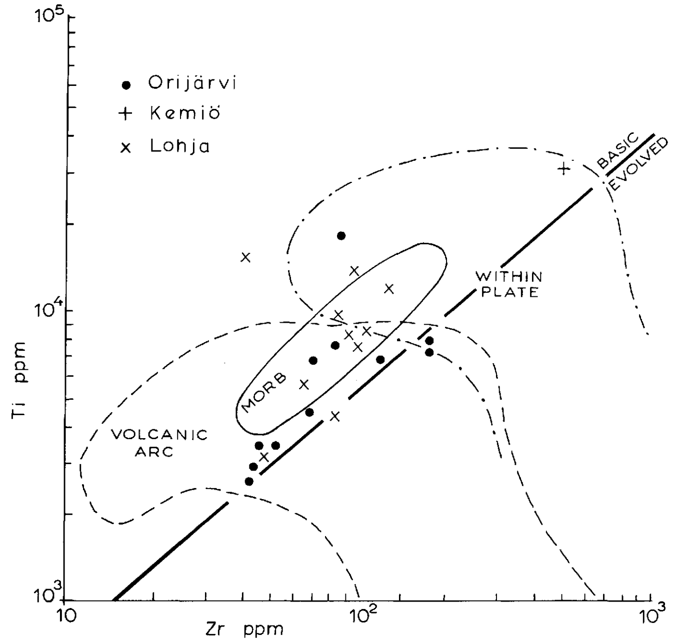

FIG. 5. Ti v. Zr plot for a selection of basic rocks from the Kemiö–Orijärvi–Lohja belt illustrating the transitional nature of the rock suites. Boundaries are taken from Pearce (1986).

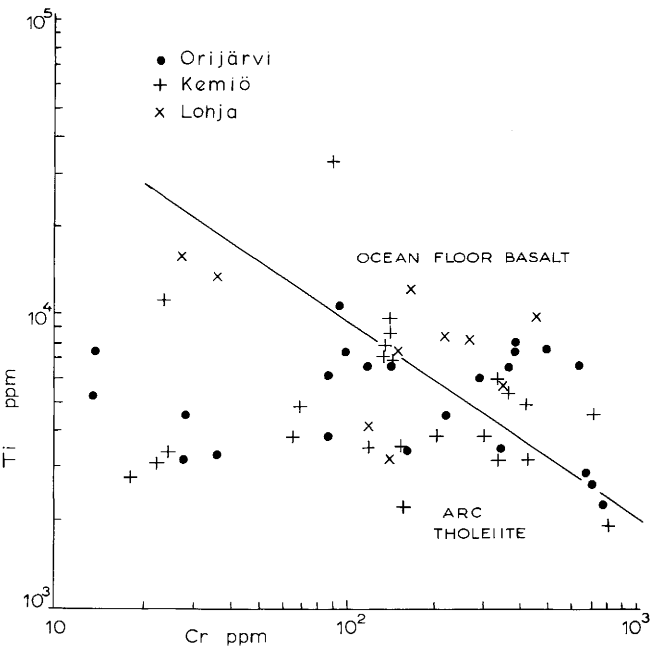

FIG. 6. Ti v. Cr plot for basic rocks in the Kemiö–Orijärvi–Lohja belt illustrating the transitional nature of the rock suites. Boundaries are taken from Pearce (1986).

of the mode respectively. In some rocks a significant proportion of the quartz appears to be secondary occurring in discrete clots and veins; this is often reflected by the very high SiO_2 content of these rocks which is usually greater than 80%. In the felsic plutonic rocks (Table 1, No. 8) quartz generally forms 25–30% of the mode. In both plutonic and volcanic rocks the plagioclase An contents are usually between 30 and 60. K-feldspar varies from a trace in tonalites to 30% of the mode in granodiorites and microcline granites. Hornblende in the felsic rocks generally accounts for less than 10% of the mode and 5 to 15% biotite is usually present. Accessory minerals include sphene, apatite and zircon. In contrast to the mafic-intermediate rocks, igneous textures are often preserved. Euhedral phenocrysts of quartz and plagioclase are seen in metavolcanic rocks and mymerkitic textures have been noted in tonalites and granodiorites.

Chemically, the felsic rocks (Table 2, Nos. 10 to 14) are characterized by very high SiO_2, low to moderate Na_2O, low to high K_2O and generally low Rb. On the SiO_2 v. K_2O plot (Fig. 3) there is a big spread of points at the acid end with a range from Na-rich rhyodacite to K-rich rhyolite. To some extent, the large spread of K_2O may indicate postmagmatic mobility of K. REE patterns are strongly fractionated with very pronounced negative Eu anomalies suggesting depletion of plagioclase. Plagioclase control on differentiation is further indicated by the rapid decrease in the Sr content of the felsic rocks. In areas where suites of mafic and felsic rocks have been studied (e.g. the Orijärvi pluton) the felsic rocks appear to be differentiation products of the mafic magmas, produced by fractionation of hornblende, plagioclase and minor biotite (Wijte 1980; Brouwer 1982).

Mobility of elements

Chemical and petrographic evidence indicates that certain elements may have been mobile during the post-magmatic period. Processes leading to element mobility could include seawater–rock interactions soon after consolidation of the rocks and later fluid interactions associated with prograde and retrograde metamorphism. Petrographic evidence to suggest mobility includes the widespread occurrence of secondary quartz and sphene in felsic and mafic rocks respectively. Unusually high amounts of zircon, principally as inclusions in biotite, could conceivably represent concentration of resistate minerals during metamorphic and structural processes. Chemical evidence indicating possible mobility includes the very variable K_2O and TiO_2 contents and remarkably high SiO_2 and Fe_2O_3 in some rocks.

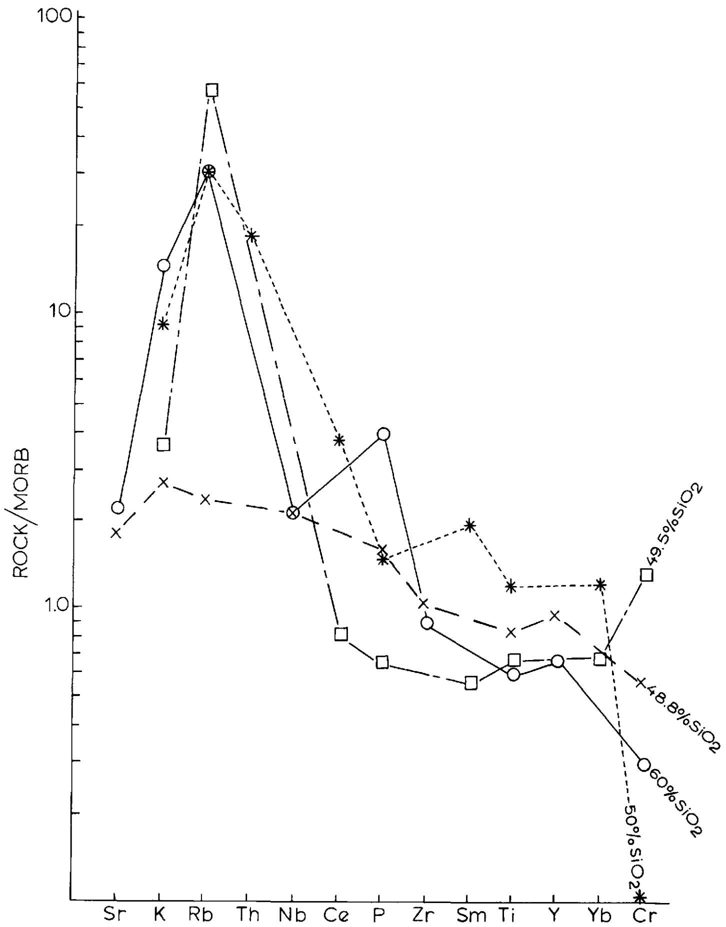

FIG. 7. Geochemical variations for three representative basic rocks and a representative intermediate rock from the Kemiö–Orijärvi–Lohja belt. Values have been normalized against tholeiitic MORB (MORB values from Pearce 1986). Ta is not plotted because values are below detection limits.

In spite of the uncertainty introduced by the above factors, it seems a reasonable assumption that a rock from the Svecofennian Belt showing a similar elemental composition and REE pattern to a modern igneous rock will have a chemistry largely determined by primary magmatic processes. It is less credible that the diverse fluid processes associated with seawater alteration and metamorphism could accidentally give a rock an elemental composition and REE pattern identical to a modern igneous rock.

Mineralization

Mineralization occurring within the Svecofennian Belt of SW Finland has been described by Eskola (1914) and Latvalahti (1979). Principally, the ores are of Cu, Pb and Zn and the major producing mines with their grades were at Aijala (1.58% Cu), Metsämonttu (0.27% Cu, 0.79% Pb, 3.51% Zn) and Orijärvi (0.74% Cu, 0.87% Pb, 3.01% Zn). Tonnages of ore raised at each mine were between 1 million and 1.5 million tonnes (Latvalahti 1979). The ores and their host-rocks are usually strongly deformed and metamorphosed.

Orijärvi mine is located in a zone that has been affected by D1 only, here characterized by an open style of folding and widely spaced axial plane schistosity. The rocks at Aijala and Metsämonttu mines have been deformed strongly by D1 and D2. D1 produced the penetrative schistosity and differentiated layering and D2 the dominant isoclinal F2-folding. The ore bodies at

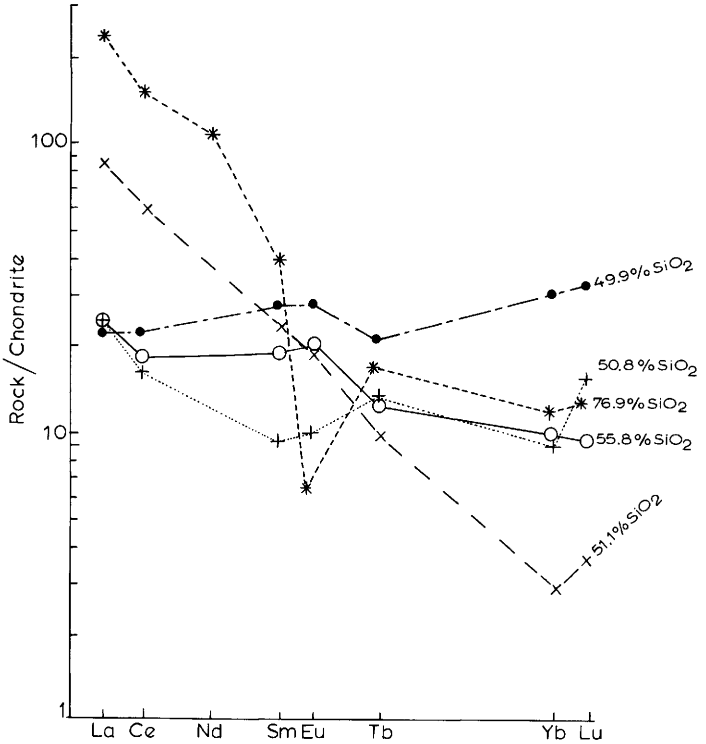

FIG. 8. Chrondrite-normalized REE patterns for five representative rocks covering the range of basic, intermediate, and acidic compositions from the Kemiö–Orijärvi–Lohja belt.

Aijala and Metsämonttu have been transposed and are parallel to the major S1-foliation.

At Orijärvi mine the mixed-sulphide ores are associated with felsic gneisses containing cordierite, sericite, and biotite; quartz-cordierite-anthophyllite rock; amphibolite occurring as a late sheet-like body; and skarn containing tremolite and anthophyllite. Ore in elongate, narrow bodies is chiefly found in the skarn with ore minerals such as pyrite, chalcopyrite, sphalerite and galena generally post-dating the skarn amphiboles. Disseminations, clots and stringers of sphalerite, pyrrhotite, chalcopyrite and galena occur in the very hard quartz cordierite-biotite rock. Within this rock, ore breccias are common with the sulphide minerals occurring in the matrix between the clasts. Eskola (1914) shows these harder ores predominating at deeper levels with the softer skarn ores occupying the upper levels. The other major ore type is quartz veining containing variable amounts of massive sulphide in which galena, pyrite and pyrrhotite are the principal minerals. The pyrite, which frequently shows annealing, contains emulsion-like exsolution trails of sphalerite. Although stratabound in the broad sense all the obvious textures apparent at Orijärvi are epigenetic.

At Aijala mine Cu-rich ores are associated with acidic gneisses (leptites), amphibolitic gneiss and gabbroic amphibolite. Locally, the first two are well banded suggesting a volcano-sedimentary sequence. Metamorphosed limestones have also been recorded (Eskola 1914). Generally, the ore occurs as streaks in chlorite-tremolite rock with the major minerals being pyrite, pyrrhotite, chalcopyrite, bornite, and covellite. Subordinate amounts of arsenopyrite, galena, and sphalerite are present. Other ore types include breccias with sulphides forming the matrix between felsic gneiss clasts, and more massive ores which sometimes exhibit a rudimentary banding. Latvalahti (1979) shows the ore occurring as narrow, deformed elongate bodies parallel to the major foliation in the host rocks.

At Metsämonttu mine the mixed-sulphide ore occurs in a very strongly deformed, isoclinally folded sequence of bedded felsic gneisses. Breccia horizons within the gneisses show strong flattening and elongation of clasts. Other host-rocks include biotite-bearing amphibolite, diopside amphibolite, dolomitic limestone, and skarns containing radiating 'suns' of tremolite or anthophyllite. The ore occurs principally as elongate bodies parallel to the major foliation in the host-rocks (Latvalahti 1979) and generally it is more massive than either the Aijala or Orijärvi ores. Finely brecciated zones occur within the massive ore. The mineralogy of the ores is dominated by pyrite, pyrrhotite, galena, sphalerite and chalcopyrite. Other subordinate minerals recorded by Latvalahti (1979) include boulangerite, tetrahedrite, arsenopyrite, molybdenite, cubanite and native gold.

Minor occurrences of mineralization in the Kemiö–Orijärvi–Lohja belt include small magnetite bodies associated with amphibole skarns and banded iron formation containing magnetite, apatite and quartz with accessory amounts of pyrite, pyrrhotite and arsenopyrite. A potentially more significant occurrence is the layer of sulphide minerals, principally pyrite and pyrrhotite, that is found at the contact of gabbro and pillow lava in both Kemiö and Orijärvi. Within both these districts the sulphide horizon, which is rarely more than a metre wide, can be traced for several kilometres. Thin brecciated layers containing epidote and jasper are associated with the sulphide horizon. Elsewhere in the sequence disseminated pyrite is frequently seen in felsic horizons that are interbedded with, or in contact with, mafic rocks.

Alteration

Ever since the recognition by Eskola (1914) of cordierite-anthophyllite rock in the Orijärvi district, there has been much debate on the significance of this rock type. Eskola (1914) regarded this unusually Mg-rich rock as a product of synmetamorphic metasomatism. Tuominen & Mikkola (1950) considered the rock represented the migration of Fe-Mg micas into fold hinges during deformation with subsequent metamorphism producing the cordierite-anthophyllite rock. Schermerhorn (1978) considered the rock to represent the metamorphic equivalent of strong hydrothermally altered host-rock. This view was endorsed and expanded by Latvalahti (1979) who described alteration 'pipes' of cordierite-anthophyllite rock and 'blankets' of cordierite-bearing, sericite and muscovite schists and gneisses. The former were regarded as parts of feeder channels for mineralization and the latter as an outer zone of more diffuse alteration.

Whilst cordierite-anthophyllite rock is generally closely associated with ore deposits in SW Finland and probably does represent intense hydrothermal alteration, there are other occurrences of cordierite-anthophyllite *bearing* gneiss which probably indicate less intense seawater alteration of the original volcanic pile, or metamorphism of diagenetic concretions within sedimentary units of the pile (Kasteleyn 1981). M. Schippers (1983) in a detailed study of cordierite-anthophyllite rock in and around Orijärvi concluded that the rock results from seawater alteration of felsic volcanic rocks and greywackes. Bulk chemical changes involved enrichment in Mg and Fe and depletion in Ca.

Chemically similar rocks, cordierite-hypersthene rocks, have been described by Schreurs & Westra (1985) from the Lohja district. They occur in the same volcanic sequence as the cordierite-anthophyllite rocks of Orijärvi and they are interpreted as the high-grade, granulite facies equivalents of the Orijärvi rocks.

Cordierite-anthophyllite rock is frequently cited as a good exploration target for locating mineralization in strongly metamorphosed sequences. It is clear from the Orijärvi district that whilst this is more or less true, caution is needed with those rocks not exceptionally rich in cordierite and anthophyllite. These rocks may represent 'background' seawater alteration in submarine volcanic piles with no close relationship to mineralization.

A geological model for the Svecofennian Belt

Previous work in the Svecofennian Belt of SW Finland and Central Sweden has tended to emphasize the calcalkaline nature of the rocks and infer from this a Precambrian island arc and subduction zone (e.g. Lofgren 1979; Hietanen 1975; Latvalahti 1979; Gaál 1982). An alternative model proposed for Central Sweden involves rifting of basement and tholeiitic and calcalkaline volcanism within the rift (Oen *et al.* 1982).

The meta-igneous rocks of the Kemiö–Orijärvi–Lohja belt show some calcalkaline characteristics such as little or no Fe enrichment (Fig. 2) and a Peacock index for individual suites of 60 to 63. An important feature of this belt when compared to the Svecofennides of Central Sweden is the greater abundance of mafic rocks. Plots of trace element data from these mafic rocks suggest that they are essentially volcanic arc basalts but with some characteristics (e.g. high TiO_2) indicating a transition towards ocean floor basalts (Fig. 5 & 6). Other factors to consider in developing a geological model are the high Rb content of rocks in the belt, particularly in the mafic rocks, and the abundance of microcline granite flanking and occurring within the Kemiö–Orijärvi–Lohja belt. With regard to the latter, large masses of K-rich igneous rocks are not typical of oceanic island arcs or for that matter continental volcanic arcs such as the Andes. The K and Rb rich nature of some rocks within the belt might imply some involvement of Archaean basement. However, at present, involvement of basement is not supported by the limited amount of isotopic data available. The few zircon dates (Simonen 1980) give an age of about 1.86 Ga for the K-rich granites of SW Finland. Recent Sm-Nd data presented by Huhma (1985) also indicate very limited participation of Archaean material in the formation of the K-rich granites.

The nearest modern analogue to the Svecofennian Belt is possibly the Taupo rift zone of New Zealand and its northerly offshore extension into the Havre Trough (marginal basin) and Kermadec Ridge (arc) pair. The Swedish portion of the Svecofennides would represent 'back-arc' rifting in a mature arc (c.f. Taupo volcanic rift zone) and would, to an extent, accord with the ideas of Oen *et al.* (1982). Lofgren (1979) has shown that there are close chemical similarities between the leptites of Central Sweden and acid rocks in New Zealand. The Finnish portion of the Svecofennides with its greater proportion of mafic rocks could represent rifting in a more oceanic situation (cf. Havre Trough–Kermadec Ridge) or merely a more advanced state of the rifting that is seen in Central Sweden. A number of rift basins show scissor-like opening (cf. sphenochasms of Carey 1976) and it is possible that this may have occurred in the Svecofennian Belt; Central Sweden being the point where the blades of the scissor join. This model does not deny or confirm the existence of a Proterozoic subduction zone but it does imply a more indirect relationship with possible subduction with the volcanism arising through rifting in a 'back-arc' situation in mature arc crust.

Mineralization within the SW Finland Svecofennian Belt is associated with pillow basalts and mixed mafic-felsic sequences. The former probably represents hydrothermal convection cells associated with rifting of ocean floor. Mineralization in the mixed sequences occurs mainly in the felsic units and in many respects is similar to that recorded in numerous Archaean Zn-Cu-pyrite deposits (Hutchinson 1973). Latvalahti (1979) has tentatively compared the Aijala, Metsämonttu, and Orijärvi deposits to the Kuroko-type deposits on the basis of similarities in chemistry, mineralogy, and alteration of ores and host-rocks. Other similarities include the bimodal mafic-felsic nature of the volcanism with felsic rocks predominating. In addition, recent work (Ohmoto & Skinner 1983; Cathles *et al.* 1983) has stressed the rift setting not only for Kuroko-type deposits but felsic-hosted massive sulphides in general (Sillitoe 1982).

In conclusion, the geochemical data on the igneous rocks and the nature of the mineralization favour a volcano-tectonic setting in which rifting has occurred in mature arc or continental crust. Present day analogues are possibly North Island, New Zealand, and Japan.

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