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GEOCHEMISTRY AND PETROLOGY OF THE METAVOLCANIC ROCKS OF THE EARLY PROTEROZOIC TAMPERE SCHIST BELT, SOUTHERN FINLAND

by

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The Tampere Schist Belt is an early Proterozoic volcanic-sedimentary belt composed mainly of greywacke-mudstone metasedimentary rocks and mafic-intermediate-felsic metavolcanic rocks. The latter are mostly pyroclastic but there are also lavas and sills. The metavolcanic rocks studied here have U-Pb zircon ages of 1.904—1.889 Ga. They vary widely in chemical composition. This is in part caused by compositional changes during alteration and metamorphism but these processes are mostly of minor importance.

In spite of the compositional changes, the metavolcanic rocks may be divided into chemo-stratigraphic units each of which has certain properties of its own. Differences between the units are shown also by immobile trace elements. Some units straddle the low-K/medium-K boundary and have tholeiitic affinities, some are shoshonitic, some are trachytic, but those dominated by calc-alkaline medium-K or high-K intermediate rocks are the most frequent. The oldest unit is the 1.904 Ga old Intermediate Unit at Orivesi, characterized by calc-alkaline high-K dacites, trachydacites and andesites. The youngest unit is the 1.889 Ga old Upper Volcanic Unit at Ylöjärvi, characterized by medium-K basalts, basaltic andesites and andesites with tholeiitic affinities. Low-pressure fractional crystallization caused a part of the compositional variation within the units. However, in several units the typical properties and variation trends are such that the effects of partial melting, magma mixing and other igneous processes must be considered.

The Tampere Schist Belt resembles Archaean greenstone belts in many respects but its metavolcanic rocks are more silicic and higher in K than those in typical Archaean successions. In addition, the mafic rocks at Tampere tend to be lower in Ni than Archaean metabasalts with equal Mg' value.

In general, the volcanic rocks of the Tampere Schist Belt resemble those of Recent volcanic arcs. However, considering the whole Svecofennian terrain, the 1.9 Ga crustal evolution was more rapid than that at modern convergent plate margins.

Key words: metavolcanic rocks, chemical composition, stratigraphic units, petrology, alteration, igneous processes, tectonic controls, Svecofennian, Proterozoic, Tampere, Orivesi, Ylöjärvi, Finland

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INTRODUCTION

In Finland, the early Proterozoic Svecofennian terrain is dominated by I-type 1.89—1.87 Ga old granitoids, but supracrustal schists, gneisses and migmatites are also abundant (Fig. 1; Simonen, 1980a; Nurmi & Haapala, 1986; Front & Nurmi, 1987). The supracrustal rocks are characterized among the metasedimentary rocks by turbiditic greywackes, siltstones and pelites, and among the metavolcanic rocks by mafic, intermediate and felsic rocks (thereafter without the prefix meta-). The volcanic rocks have U-Pb zircon ages of about 1.91—1.88 Ga (Patchett & Kouvo, 1986; Kähkönen *et al.*, in press). The 2.2—2.1 Ga old Jatulian volcanic rocks and diabases (Sakko, 1971) and the 1.96—1.97 Ga old ophiolite-like complexes (Koistinen, 1981; Kontinen, 1987) indicate that the Svecofennian events were preceded by rifting of the Archaean craton and formation of oceanic crust. In spite of the absence of blueschists and other signs of high-pressure metamorphism, the Svecofennian terrain is thought to resemble convergent plate margins (Hietanen, 1975; Gaál & Gorbatschev, 1987).

Since the time of Sederholm (1897), the well-preserved and well-exposed volcanic-sedimentary Tampere Schist Belt (Fig. 2) is considered a key area of the Svecofennian supracrustal successions. The present paper studies the typical geochemical features of the volcanic rocks of the Tampere belt in selected areas. It is shown that

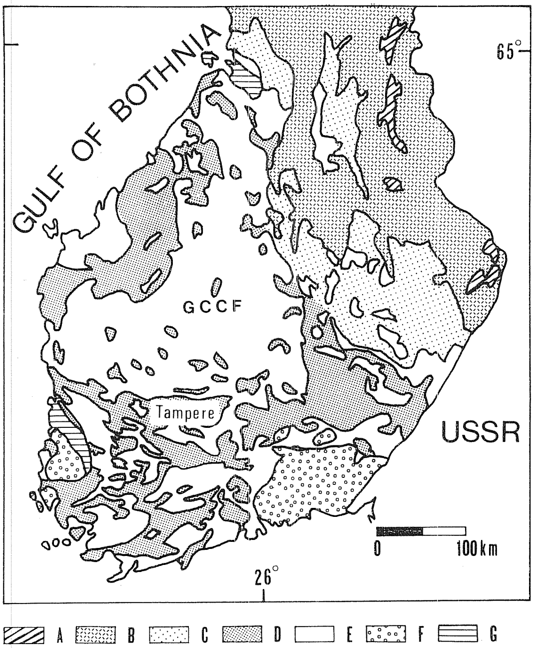


Fig. 1. Simplified geological map of central and southern Finland, after Simonen (1980a). A. Archaean greenstone belts; B. Archaean granitoids; C. Karelian schists; D. Svecofennian schists, gneisses and migmatites; E. Svecofennian plutonic rocks; F. rapakivi granites; G. Jotnian sedimentary rocks. GCCF = granitoid complex of central Finland.

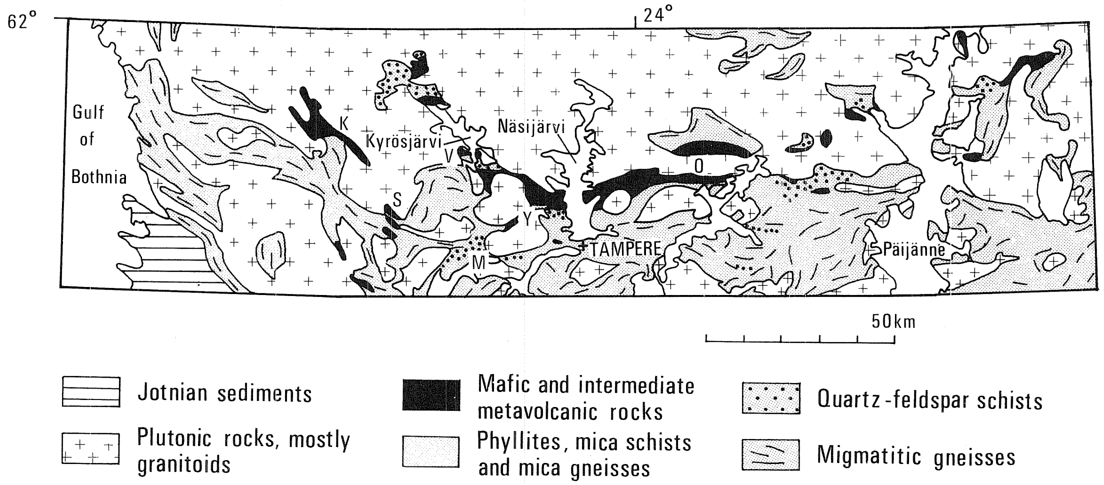


Fig. 2. Simplified geological map of the Tampere Schist Belt, slightly modified after Simonen (1980b). K = Kankaanpää; O = Orivesi; M = Mauri; S = Suodenniemi; V = Viljakkala; Y = Ylöjärvi.

the belt may be divided into units which have their characteristic lithological and geochemical properties. The roles of various igneous processes and alteration are discussed as the reasons for compositional variations within the units. Attention is also paid to the tectonomagmatic affinities of the volcanic rocks.

REVIEW OF THE GEOCHEMISTRY OF VOLCANIC ROCKS

General comments

The chemical composition of volcanic rocks and the variations therein are controlled by factors such as the tectonic environment of volcanism, chemical and mineral composition of the sources, variations in the degree of partial melting and in the proportions of phases fused, composition of fluid phase during fusion, assimilation of pre-existing crust or volcanic-sedimentary pile, mixing of magmas, fractional crystallization, accumulation of phenocrysts, liquid-state differentiation, age, alteration and metamorphism. In volcaniclastic rocks the effects of redeposition must also be taken into account.

Alteration and metamorphism

The relative sensitivity to alteration and metamorphism varies from element to element. Elements such as Ti, P, Zr, Zn, Cr, Y, Nb and rare-earth elements (REE) are relatively immobile during alteration and metamorphism, while K, Cs, Rb, Ba, Al, Fe, Ca and Si are less resistant (Condie, 1976, 1981, 1982a; Garcia, 1978). According to Garcia, Sr and Ni show minor to major changes but Condie assigns them to the category which mostly displays little or no change.

Altered rocks may have alkali metal contents and ratios which deviate from those in unaltered rocks. They can, therefore, be identified through the igneous spectrum (Hughes, 1973). Consideration of mobile and immobile elements together may also be fruitful. For instance, the content of P and Zr in fresh basalts and basaltic andesites tends to increase with increasing alkali metal content (Ewart, 1982; Pearce, 1982). High K in basalts low in P and Zr may thus indicate compositional changes.

Fractional crystallization, partial melting and other igneous processes

The trends due to fractional crystallization are best shown by trace element variations, but some features can be seen in major element behaviour. For instance, fractionation of olivine ± pyroxenes without magnetite causes an increase in the Ti content, K content and FeO*:MgO ratio with the increasing Si content. If plagioclase is abundant in the assemblage fractionated, a decrease in Al is observed.

Major element variations associated with partial melting may be evaluated by means of high-pressure melting/crystallization experiments. The experimental trends do not necessarily agree with natural variations (e.g., Stern & Wyllie, 1978; Huang & Wyllie, 1986) and differences in procedures may yield conflicting results (see Mysen, 1982, for a review). In spite of these conflicts, some conclusions can be made.

Melting of volatile-free mantle peridotite produces basalts, picrites and komatiites, and in the presence of water andesitic liquids may also be obtained (Basaltic Volcanism Study Project, 1981, p. 553). The melts have low FeO*:MgO ratios (Basaltic Volcanism Study Project, 1981, p. 547; Gill, 1981, p. 231; Mysen, 1982), therefore 10—20% fractionation of olivine ± orthopyroxene is thought to modify the compositions to approach those of typical basalts and andesites.

Partial melting of hydrous mafic rocks produces intermediate and rhyolitic liquids when the degree of fusion is below 40—50% (Helz, 1976; Stern & Wyllie, 1978; Green, 1982). In general, the lower the degree of fusion the more silicic are the melts. Dry melting of mafic rocks produces trachytic liquids when the degree of fusion is low (Green, 1982).

The behaviour of trace elements depends on the mineral/liquid distribution coefficients (D values), on the modal proportions in the solid residue, and on the particular process.

Fractional crystallization is mostly modelled using the Rayleigh equation (Neumann *et al.*, 1954; Arth, 1976):

$$C_l:C_0 = F^{(\bar{D}-1)} \qquad (1)$$

where C_l is the concentration of the element in the melt remaining, C_0 is the concentration of the element in the original melt, and F is the proportion of melt remaining. $\bar{D}$ is the bulk solid-melt distribution coefficient:

$$\bar{D} = X^aD^a + X^bD^b + \ldots \qquad (2)$$

where X^a, X^b,... are the weight proportions of minerals a, b,... in the crystallizing assemblage, and D^a, D^b,... are the mineral-melt distribution coefficients for minerals a, b...

Partial melting is modelled with the equation of equilibrium "batch" melting (Shaw, 1970; Arth, 1976):

$$C_l:C_0 = 1:(\bar{D} + F(1-\bar{D})) \qquad (3)$$

where C_l is the concentration of the element in the melt, C_0 is the concentration of the element in the solid source, and F is the proportion of melt. $\bar{D}$ is the bulk distribution coefficient of the solid residue (see eq. 2).

Equation (1) assumes equilibrium between the surface of crystallizing phases and the melt. The process was called surface-equilibrium fractional crystallization by Arth (1976) and fractional crystallization by Hanson (1980). Equation (3) assumes equilibrium between the total solid and the melt. It can be applied also to crystallization. The crystallization process modelled by equation (3) is total equilibrium fractional crystallization according to Arth (1976) and equilibrium crystallization according to Hanson (1980). Equation (1) is more realistic when modelling rapidly crystallizing volcanic systems, while crystallization in slowly cooling plutonic conditions is better modelled using equation (3). Natural processes may often be intermediate between the two extremes.

D values depend on the temperature and the composition of the melt. For instance, clinopyroxene-melt distribution coefficient for Cr, D_{Cr}^{cpx}, is higher at lower T and in intermediate or silicic melts than at higher T and in basaltic liquids. Reviews and compilations of D values are given by Arth (1976), Irving (1978), Gill (1981) and Hanski (1983).

Depending on the solid phases, trace elements are compatible (bulk $\bar{D} > 1$), incompatible (bulk $\bar{D} < 1$) or have bulk $\bar{D}$ near unity. Elements such as K, Ba and Zr are incompatible with most igneous mineral assemblages while Ni and Cr are compatible. Sr is compatible if plagioclase composes a significant proportion in the solid assemblage. Zr also becomes compatible when zircon begins to crystallize, in arc magmas at approximately dacitic composition (Pearce, 1982; Tarney *et al.*, 1982). Nevertheless, Zr can be used as an index of the degree of crystallization or partial melting in basaltic and andesitic systems.

The behaviour of trace elements in total equilibrium processes differs from that in surface-equilibrium processes. For instance, surface-equilibrium fractional crystallization yields compatible versus incompatible element trends which slope more steeply than those caused by batch melting (Pearce, 1982).

Crystallization may be an open-system process in which the magma is not only continuously crystallized but the magma chamber is periodically fed with new pulses of magmas and periodically tapped. Such a process may lead to wide variations in incompatible elements with minor variations in compatible and major elements (O'Hara, 1977).

Silicic pyroclastic flows show wide variations in incompatible elements although the variations in major elements are minor (Hildreth, 1979, 1981). The variations are attributed to compositionally zoned magma chambers, but the reasons are under discussion. Hildreth (1979, 1981) attributed the variations to processes such as thermo-gravitational diffusion, vapour-phase transfer and liquid complexing. Instead, Baker and McBirney (1985) emphasized the role of fractional crystallization of accessory phases in the formation of compositional zoning.

Volcanic rocks in various tectonic environments

The major plate tectonic environments of young volcanic rocks are (1) divergent plate margins exemplified by mid-ocean ridges, (2) convergent plate margins like island arcs and active continental margins, and (3) intraplate (also called within-plate) settings such as oceanic islands and intracontinental rifts (e.g., Pearce & Cann, 1973; Basaltic Volcanism Study Project, 1981; Wyllie, 1981). The volcanic rocks of these environments can often be distinguished from one another by chemical features (Chayes, 1964; Pearce & Cann, 1973; Beccaluva *et al.*, 1979; Wood *et al.*, 1979a; Pearce, 1982, 1983; Shervais, 1982; Mullen, 1983; Holm, 1985). Typical characteristics considered are the SiO_2 frequency distribution, and the contents and ratios of Ti, Zr, Hf, P, K, Sr, Y, Cr, Ni, Th, Ta, Nb and REE in basalts. Although overlapping occurs and the discrimination diagrams are not always successful (Floyd & Winchester, 1975; Cox, 1983; Holm, 1985; Weaver & Johnson, 1987) certain generalizations are warranted. Average and typical compositions of volcanic rocks of the various environments are given in Ewart (1979, 1982), Bailey (1981), Condie (1982b), Pearce (1982) and Holm (1985).

The volcanic rocks of mid-ocean ridges are characterized by subalkaline basalts (normal mid-ocean ridge basalts or N-type MORB) low in K, Cs, Rb, Ba, Th, U and light REE (named LIL elements by Schilling, 1973). Based on higher contents of incompatible elements, T-type (transitional) and E-type (enriched) MORB are distinguished from N-type MORB.

The volcanic rocks of oceanic islands are dominated by alkaline and subalkaline basalts (oceanic island basalts or OIB) relatively rich in Ti, Zr, Nb, Ta and LIL elements. Subalkaline OIB resemble T-type and E-type MORB to some degree but there are also differences (Pearce, 1982). Subalkaline and alkaline basalts dominate among the volcanic rocks of continental intraplate settings. Some of these successions are bimodal in being rich in rhyolites and poor in intermediate rocks. Since they are often rich in Ti, Zr and LIL elements, the basalts resemble OIB, but some continental flood basalts have low Ti, Nb and Ta contents not typical of intraplate basalts (Floyd & Winchester, 1975; Morrison, 1978; Holm, 1982, 1985; Zeck & Morthorst, 1982; Cox, 1983).

The volcanic rocks of convergent plate margins are characterized by the basalt-andesite-dacite-rhyolite association of volcanic arcs. They are mostly dominated by andesites and dacites (Ewart & Le Maitre, 1980; Gill, 1981; Thorpe, 1982; Leeman, 1983). Basalts and basaltic andesites are, in general, more frequent in intra-oceanic arcs underlain by a thin crust than in mature island arcs or in arcs near active continental margins. According to their K contents, the arc volcanic rocks vary from low-K island arc tholeiites to shoshonites very high in K (see, Baker, 1982). A characteristic feature of arc basalts, known since the study of Chayes (1964), is the relatively low Ti content. The low-Ti character is observed in arc volcanic rocks in general and is associated with the relatively low Ta and Nb content (Gill, 1981; Pearce, 1982). The volcanic rocks of the earliest continent-continent collisional stages are calc-alkaline while those of later stages are bimodal and partly alkaline (Condie, 1982b). Basalts are less common than more silicic rocks among collisional volcanic rocks (Basaltic Volcanism Study Project, 1981, p. 825; Gill, 1981; Leeman, 1983).

Convergent plate margins comprise also extensional marginal basins which may be ensimatic (intra-oceanic) or ensialic (Saunders & Tarney, 1984). The volcanic rocks of these basins display wide variations in composition and present difficulties in tectonomagmatic classifications. The basalts may be indistinguishable from N-type MORB but often they are, like arc basalts, depleted in Ta and Nb (Pearce, 1982; Saunders & Tarney, 1984). Back-arc basin volcanic rocks also contain calc-alkaline rocks, peralkaline rhyolites and alkaline basalts (Smith *et al.*, 1977; Arculus & Johnson, 1978; Lordkinapidze *et al.*, 1979; Weaver *et al.*, 1979; Marcelot *et al.*, 1983).

Compositional variations with time

The composition of volcanic rocks varies with time on many scales. A single eruption from a compositionally zoned magma chamber may change to less silicic with time (Hildreth, 1981). The products of eruptions in a stratovolcano may become more felsic or more mafic with time (Gill, 1981). Volcanic arcs may show a trend such that the low-K rocks dominating the early stages of arc evolution change later to rocks higher in K (Gill, 1970; Jakeš & White, 1972).

The volcanic rocks of Archaean greenstone belts differ from young volcanic rocks in some respects. Komatiites are more frequent and alkaline rocks less frequent in Archaean greenstone belts than in younger volcanic sequences. Archaean basalts and andesites tend to be higher in Cr and Ni than their younger counterparts (Condie, 1982a, 1985).

SAMPLES AND ANALYTICAL METHODS

Most samples of this study are from road and railway cuttings. The samples, totalling 345, were collected in 1976, 1979 and 1982. Sample locations are shown in Appendix I. Sample numbers 1—294 in the text refer to the samples from 1976, numbers 319—417/79 to those from 1979, and numbers 1—60/82 to those from 1982.

In general, samples with pronounced weathering or schistosity, with abundant sulphides and with veins of quartz and carbonate were omitted. Some specimens with these properties were treated for comparison with better-preserved samples. Sites poor in phenocrysts were preferred over those rich in phenocrysts.

The proportions of phenocrysts were approximated from hand specimens. Thin sections were studied from 170 samples. The amounts of phenocrysts and carbonate were point-counted or approximated under the microscope. Determination of composition of plagioclase relied largely on refractive indices. Chlorites were determined as Fe- or Mg-rich types according to their anomalous interference colours and length slow/length fast characteristics.

Samples were extracted with a hammer. For analysis they were jaw-crushed and swing-milled in a carbon-steel pan absent in Cr. Some samples analyzed by Rautaruukki Oy were milled in an agate pan. Contamination during sampling and grinding was minimal.

The contents of SiO_2, TiO_2, Al_2O_3, FeO* (total Fe as FeO), MnO, MgO, CaO, Na_2O, K_2O and P_2O_5 were determined from pressed rock powder briquettes with an automatic Philips PW 1400 XRF spectrometer at the Geological Laboratory of Outokumpu Oy in 1983. The procedure for the correction calculations was based on the Philips alpha coefficients (de Jongh, 1973). The results of these analyses are available from the author on request. They are displayed in Harker-type diagrams in this study.

Seventy-five samples of the total of 345 were analyzed anew from pressed rock powder briquettes for major elements and for Zr, Cr, Ni,

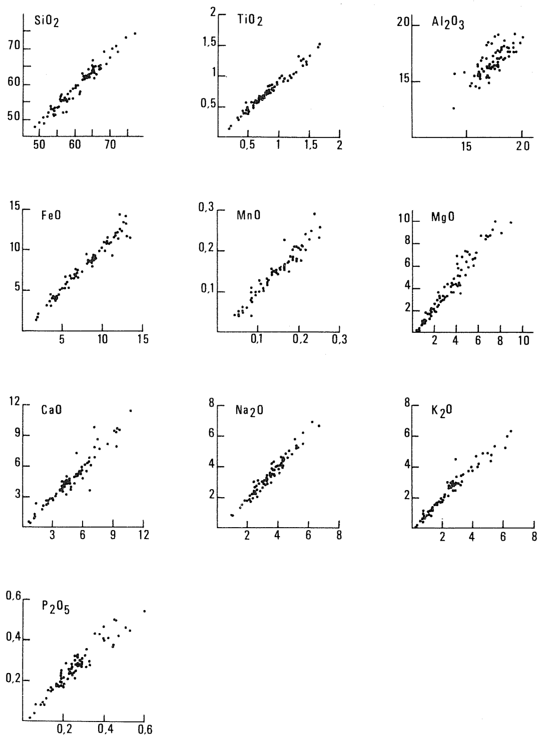


Fig. 3. A comparison of the major element XRF analyses made with the fundamental parameter method (horizontal axes, Rautaruukki Oy) and alpha coefficient method (vertical axes, Outokumpu Oy). Oxides in weight %. FeO indicates total Fe.

Sr, Ba, V, Zn and Cu with a Philips PW 1400/AHP XRF instrument at the laboratory of Rautaruukki Oy (Ala-Vainio, 1986; Table I). The correction procedure was the fundamental parameter method. The results of the major element analyses made with the two methods are compared in Fig. 3. In general, the correlations are good, but the dispersion in Al is wide. For Mg there seem to be systematic differences when the MgO content exceeds 4—5%.

GENERAL GEOLOGY OF THE TAMPERE SCHIST BELT

General comments

On the basis of supracrustal lithological properties, the Svecofennian terrain was divided into three parts by Gaál & Gorbatschev (1987). The northern and southern Svecofennian provinces are rich in volcanic rocks while the central Svecofennian province is dominated by sedimentary rocks deposited in the so-called Bothnian Basin (Hietanen, 1975).

The Tampere Schist Belt lies about 50 km north of the suggested boundary between the southern and central Svecofennian provinces. It is about 200 km long and about 20 km across at its widest (Figs. 2 and 4). It is composed of sedimentary and volcanic rocks characterized by greywackes-siltstones-pelites and basalts-andesites-dacites-rhyolites, respectively. The volcanic rocks at Orivesi and Ylöjärvi have U-Pb zircon ages of 1.904—1.889 Ga (Kähkönen *et al.*, in press). The Hämeenkyrö batholith (Fig. 4) intruding the belt has a U-Pb zircon age of 1.882 Ga (Patchett & Kouvo, 1986). To the north, the Tampere belt is bordered by the granitoid complex of central Finland, which is about 1.88—1.89 Ga old (Huhma, 1986). To the south the schists change abruptly to gneisses and migmatites.

J.J. Sederholm published his classical study on the supracrustal rocks of the Tampere Schist Belt in 1897. Since then the area has been investigated by, among others, Stigzelius (1944), Seitsaari (1951), Simonen & Kouvo (1951), Simonen (1952, 1953a), Matisto (1968, 1977), Pihlaja (1974), Campbell (1978, 1980), Söderholm (1978), Mäkelä (1980), Gaál *et al.* (1981), Kähkönen (1981, 1987), Perttula (1982), Aro (1983), Ojakangas (1986), Rautio (1987), Kähkönen *et al.* (in press) and Nironen (in press).

Lithological properties

The sedimentary rocks of the Tampere Schist Belt are characterized by greywackes-mudstones. Near Lake Näsijärvi they are mostly mid-fan turbidites deposited from westerly palaeocurrents (Ojakangas, 1986). In places, conglomerates with predominantly volcanic provenances occur in substantial amounts. Arkoses are known at Mauri and Suodenniemi 25—50 km W of Tampere. Those at Mauri were deposited in fluvial-deltaic environments with palaeocurrents towards the east or NE (Matisto, 1968). In the southern parts of the belt, among the greywackes-mudstones, black schists occur. The Haveri Formation at Viljakkala (Fig. 2) contains black schists, limestones and cherts (Mäkelä, 1980). Calcareous rocks have been observed elsewhere in drill cores at two places (Marmo, 1957; Mäkelä, 1979).

The volcanic rocks of the belt are mostly

Table I. XRF-analyses of the metavolcanic rocks of the Tampere Schist Belt. XRF analyses by Rautaruukki. Oxides in weight %, elements in ppm. FeO*: total Fe as FeO. Mg' value = Mg/(Fe^{2+} + Mg), Fe_2O_3: FeO was set at 0.15.

	Intermediate Unit at Orivesi												dyke
	2	10	11	23	24	30	31	37	42	46	54	53	27
SiO_2	63.57	61.56	64.14	64.61	66.15	62.16	63.30	68.70	63.80	62.21	60.36	72.01	50.86
TiO_2	0.42	0.59	0.44	0.45	0.39	0.54	0.39	0.30	0.60	0.61	0.67	0.19	0.96
Al_2O_3	17.05	15.95	16.64	16.69	17.72	16.93	16.67	15.72	16.26	16.03	16.35	14.25	17.98
FeO*	4.02	6.40	5.16	4.25	3.71	5.95	5.64	3.87	5.08	4.67	6.19	1.75	10.24
MnO	0.08	0.12	0.10	0.08	0.08	0.14	0.13	0.08	0.11	0.10	0.12	0.04	0.24
MgO	1.43	2.81	2.24	1.03	0.83	2.16	2.61	1.65	1.86	2.20	2.61	0.96	4.02
CaO	2.30	5.24	4.63	3.49	3.76	3.78	1.05	1.92	4.18	3.59	4.44	0.58	6.27
Na_2O	3.55	2.56	3.35	3.41	3.64	4.25	5.94	4.21	3.12	4.07	3.31	1.48	2.78
K_2O	4.94	2.70	2.23	3.15	2.77	2.81	0.72	2.53	3.83	2.20	3.56	6.00	2.69
P_2O_5	0.18	0.19	0.12	0.21	0.16	0.23	0.19	0.14	0.18	0.24	0.30	0.05	0.50
SUM	97.54	98.12	99.05	97.37	99.21	98.95	96.64	99.12	99.02	95.92	97.91	97.31	96.54
Zr	190	160	140	230	200	150	190	170	220	210	170	180	100
Cr	80	110	30	60	20	30	40	20	60	60	70	30	40
Ni	0	10	20	0	20	20	0	10	20	0	0	0	0
Sr	380	320	240	650	570	450	170	260	490	510	550	150	570
Ba	1790	850	1240	2010	1530	1520	620	1820	1800	1450	1270	1880	1230
V	50	140	110	60	50	120	50	40	100	100	140	20	180
Zn	30	70	60	50	40	70	30	30	70	60	90	20	120
Cu	30	20	20	10	10	20	0	0	40	10	30	0	10
K_2O:Na_2O	1.39	1.05	0.67	0.92	0.76	0.66	0.12	0.60	1.23	0.54	1.08	4.05	0.97
K_2O + Na_2O	8.49	5.26	5.58	6.56	6.41	7.06	6.66	6.74	6.95	6.27	6.87	7.48	5.47
FeO*:MgO	2.81	2.28	2.30	4.13	4.47	2.75	2.16	2.35	2.73	2.12	2.37	1.82	2.55
Mg' value	41.86	47.06	46.77	32.91	31.17	42.36	48.37	46.33	42.57	48.81	46.05	52.62	44.28

Table I. cont.

	Subalkaline Basaltic to Rhyolitic Unit at Orivesi									
	67	72	76	78	79	80	70	058/82	73	65
SiO_2	51.24	49.09	50.03	48.44	54.90	60.24	60.38	64.14	68.94	75.82
TiO_2	0.89	0.85	0.83	0.93	0.75	0.47	0.66	0.65	0.36	0.17
Al_2O_3	16.49	17.39	17.23	19.25	17.96	17.12	16.22	17.71	15.62	13.69
FeO*	11.83	12.34	11.09	11.09	10.81	6.99	6.37	4.81	2.87	1.60
MnO	0.22	0.20	0.22	0.20	0.17	0.14	0.17	0.13	0.06	0.06
MgO	5.32	4.56	5.30	4.04	4.19	1.97	2.52	1.48	0.81	0.52
CaO	8.84	9.00	8.80	10.33	4.17	5.35	4.15	3.12	1.07	0.52
Na_2O	1.95	2.17	0.81	2.03	4.76	3.67	3.88	4.54	4.11	2.34
K_2O	1.26	1.07	1.99	1.08	0.59	0.65	1.70	2.34	4.15	4.54
P_2O_5	0.34	0.43	0.38	0.38	0.18	0.40	0.31	0.22	0.06	0.03
SUM	98.38	97.10	96.68	97.77	98.48	97.00	96.36	99.14	98.05	99.29
Zr	90	80	80	70	100	110	110	160	220	190
Cr	120	70	70	110	100	30	30	20	30	40
Ni	40	20	20	40	20	0	0	10	0	10
Sr	680	560	880	560	420	600	690	500	290	230
Ba	410	410	830	450	430	550	950	910	1800	2570
V	300	240	280	330	270	60	80	70	20	20
Zn	120	150	110	130	120	70	120	80	60	50
Cu	90	90	80	80	110	0	20	10	10	0
$K_2O:Na_2O$	0.65	0.49	2.46	0.53	0.12	0.18	0.44	0.52	1.01	1.94
K_2O+Na_2O	3.21	3.24	2.80	3.11	5.35	4.32	5.58	6.88	8.26	6.88
FeO*:MgO	2.22	2.71	2.09	2.75	2.58	3.55	2.53	3.25	3.54	3.08
Mg' value	47.65	42.79	49.17	42.45	43.97	36.33	44.47	38.38	36.36	39.68

Table I. cont.

	Shoshonitic Unit at Orivesi									Trachytic Unit at Orivesi			Conglom-erate	South. limb
	81	87	88	90	104	107	108	109	86	94	95	103	98	113
SiO_2	56.16	52.13	55.95	55.39	56.71	52.43	46.50	55.56	61.12	63.80	62.83	64.18	64.12	57.39
TiO_2	0.68	0.78	0.69	0.77	0.71	0.93	1.00	0.81	0.71	0.70	0.74	0.71	0.55	0.59
Al_2O_3	14.97	15.49	16.03	17.94	16.80	18.04	18.62	17.19	18.98	17.81	18.41	17.55	15.81	13.97
FeO*	8.57	8.83	8.34	7.93	7.13	8.01	10.05	7.81	4.17	4.03	3.40	4.00	5.62	6.64
MnO	0.15	0.18	0.18	0.15	0.16	0.15	0.18	0.15	0.09	0.08	0.11	0.07	0.12	0.13
MgO	7.06	7.77	6.60	4.24	4.91	5.52	6.73	4.03	0.81	0.50	0.97	0.32	2.38	5.60
CaO	5.15	8.21	6.65	4.91	5.23	6.05	5.35	6.89	2.33	1.18	3.64	1.78	2.25	6.29
Na_2O	2.68	3.37	2.40	3.60	4.11	3.63	3.38	3.17	5.48	4.82	3.54	3.97	2.99	3.32
K_2O	2.74	1.50	2.60	3.20	2.72	3.21	4.13	2.65	5.12	6.03	5.33	6.30	4.86	2.86
P_2O_5	0.28	0.43	0.30	0.38	0.43	0.58	0.48	0.44	0.46	0.32	0.28	0.28	0.25	0.33
SUM	98.44	98.69	99.74	98.51	98.91	98.55	96.42	98.70	99.27	99.27	99.25	99.16	98.95	97.12
Zr	140	120	130	160	130	180	210	170	180	220	230	230	180	190
Cr	340	460	340	150	130	160	160	140	40	90	60	60	120	350
Ni	80	90	100	30	20	40	30	50	10	0	10	10	30	100
Sr	760	830	540	800	420	770	640	900	450	440	560	860	520	730
Ba	720	860	640	1240	1300	870	1110	1020	1520	1510	1970	1680	1340	930
V	190	210	150	170	180	200	170	200	140	70	50	80	130	160
Zn	90	100	100	100	100	110	130	90	70	80	80	60	90	70
Cu	70	60	120	60	60	110	20	30	20	30	40	20	60	70
$K_2O:Na_2O$	1.02	0.45	1.08	0.89	0.66	0.88	1.22	0.84	0.93	1.25	1.51	1.59	1.63	0.86
$K_2O + Na_2O$	5.42	4.87	5.00	6.80	6.83	6.84	7.51	5.82	10.60	10.85	8.87	10.27	7.85	6.18
FeO*:MgO	1.21	1.14	1.26	1.87	1.45	1.45	1.49	1.94	5.15	8.06	3.51	12.50	2.36	1.19
Mg' value	62.51	64.05	61.57	51.98	58.23	58.25	57.55	51.09	28.22	20.07	36.61	13.94	46.16	63.06

Table I. cont.

	Vaavujärvi sill		Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline					Supracrustal rocks between the Lower and the Upper Volcanic Unit at Ylöjärvi in the southern limb of the major syncline						post-D_1 dyke
	3/82	7/82	124	127	130	356/79	357/79	134	060/82	141	142	144	145	285
SiO_2	57.67	62.79	70.74	62.29	63.00	58.93	59.03	52.67	59.93	71.29	66.37	65.61	56.33	54.85
TiO_2	0.82	0.65	0.32	0.59	0.56	0.88	0.86	0.80	0.66	0.44	0.48	0.62	1.14	1.17
Al_2O_3	18.45	15.92	15.13	17.46	17.63	16.94	17.06	13.42	15.29	17.34	17.87	17.51	15.66	17.50
FeO*	7.92	6.27	3.60	6.71	6.49	8.71	8.53	10.15	8.57	1.84	3.37	3.24	10.17	8.43
MnO	0.13	0.15	0.06	0.14	0.12	0.16	0.20	0.17	0.07	0.05	0.05	0.05	0.14	0.17
MgO	2.11	2.31	1.03	1.52	1.32	3.34	3.00	8.62	4.99	0.84	1.53	1.85	5.26	4.08
CaO	2.60	4.49	0.96	4.16	4.16	4.43	5.94	9.31	2.79	1.07	2.22	4.19	5.38	5.01
Na_2O	6.56	3.80	4.41	4.99	4.58	4.09	3.14	1.71	1.84	3.44	5.53	5.10	2.82	3.47
K_2O	2.30	2.44	2.94	0.95	0.96	1.08	0.81	1.35	4.05	3.16	1.83	0.68	1.44	3.83
P_2O_5	0.26	0.16	0.08	0.19	0.18	0.16	0.17	0.28	0.23	0.10	0.11	0.26	0.18	0.26
SUM	98.82	98.98	99.27	99.00	99.00	98.72	98.74	98.48	98.42	99.57	99.36	99.11	98.52	98.77
Zr	150	160	200	170	150	140	150	120	160	210	160	220	140	160
Cr	40	70	60	40	30	120	110	590	660	30	30	50	260	60
Ni	20	20	20	10	10	20	20	160	160	20	10	10	30	30
Sr	200	330	120	270	270	270	230	580	350	170	270	330	200	600
Ba	780	1200	1280	430	480	520	400	510	1090	590	450	240	400	380
V	120	140	20	70	60	170	160	210	150	20	50	70	240	180
Zn	100	90	140	90	70	110	70	100	70	20	30	30	70	100
Cu	10	50	10	10	80	60	50	10	250	0	0	0	40	30
$K_2O:Na_2O$	0.35	0.64	0.67	0.19	0.21	0.26	0.26	0.79	2.20	0.92	0.33	0.13	0.51	1.10
K_2O+Na_2O	8.86	6.24	7.35	5.94	5.54	5.17	3.95	3.06	5.89	6.60	7.36	5.78	4.26	7.30
FeO*:MgO	3.75	2.71	3.50	4.41	4.92	2.61	2.84	1.18	1.72	2.19	2.20	1.75	1.93	2.07
Mg' value	35.04	42.72	36.68	31.44	29.17	43.70	41.59	63.23	54.10	48.03	47.89	53.62	51.15	49.49

Table I. cont.

	Lower Volcanic Unit at Ylöjärvi in the northern limb of the major syncline									
	234	235	236	250	251	257	259	261	266	267	217*
SiO_2	54.60	63.26	67.20	58.74	53.52	55.89	54.50	63.80	64.39	59.97	67.85
TiO_2	1.35	0.94	0.49	0.56	0.72	0.75	0.80	0.80	0.47	0.78	0.47
Al_2O_3	16.99	15.97	16.57	19.48	16.56	16.59	17.57	18.43	15.80	15.86	16.56
FeO*	10.55	8.25	4.48	5.12	9.81	9.55	9.20	4.02	5.34	7.66	3.82
MnO	0.19	0.19	0.08	0.09	0.21	0.18	0.18	0.06	0.13	0.14	0.05
MgO	3.54	2.48	1.42	2.69	6.41	3.96	3.77	1.58	3.07	3.90	1.13
CaO	7.32	4.58	3.80	5.70	6.93	7.14	5.65	3.99	3.98	4.89	2.78
Na_2O	2.39	2.40	3.07	2.28	2.51	3.41	5.13	5.10	2.64	4.22	3.95
K_2O	1.23	0.63	1.88	2.60	1.17	1.00	1.69	1.19	3.11	1.23	2.49
P_2O_5	0.27	0.13	0.16	0.36	0.30	0.23	0.22	0.18	0.13	0.18	0.09
SUM	98.43	98.83	99.15	97.62	98.14	98.70	98.71	99.15	99.06	98.83	99.19
Zr	150	170	230	140	90	70	110	160	140	160	190
Cr	60	140	40	170	180	80	30	80	130	100	50
Ni	20	30	20	50	50	20	20	30	60	20	20
Sr	290	290	330	940	790	340	430	410	230	190	230
Ba	330	230	970	1190	730	430	530	800	840	550	140
V	270	160	70	120	220	280	270	190	110	160	70
Zn	140	110	90	70	150	100	100	50	100	90	70
Cu	80	10	10	80	20	80	10	20	10	30	10
$K_2O:Na_2O$	0.51	0.26	0.61	1.14	0.47	0.29	0.33	0.23	1.18	0.29	0.63
K_2O+Na_2O	3.62	3.03	4.95	4.88	3.68	4.41	6.82	6.29	5.75	5.45	6.44
FeO*:MgO	2.98	3.33	3.15	1.90	1.53	2.41	2.44	2.54	1.74	1.96	3.38
Mg' value	40.45	37.83	39.09	51.54	56.95	45.64	45.34	44.31	53.79	50.76	37.45

* sample 217 represents the intermediate rocks between the Lower Volcanic Unit and the Upper Volcanic Unit in the northern limb of the syncline.

Table I. cont.

	Upper Volcanic Unit at Ylöjärvi in the southern limb of the major syncline					Upper Volcanic Unit at Ylöjärvi in northern limb of the major syncline				Upper Volcanic Unit at Ylöjärvi in the central parts of the major syncline				
	159	160	166	171	172	204	213	215	216	179	182	183	184	185
SiO_2	52.69	52.64	48.77	52.51	56.04	61.28	55.99	54.01	52.46	57.87	62.74	57.93	54.39	57.03
TiO_2	1.61	1.31	1.43	1.28	1.35	1.07	1.40	1.41	1.59	1.04	0.83	1.20	1.21	1.12
Al_2O_3	18.70	16.51	18.41	18.37	16.46	18.07	17.76	17.38	16.36	15.83	16.49	17.47	15.75	18.93
FeO*	11.99	12.54	11.54	12.91	12.41	8.44	9.94	11.09	11.57	8.31	6.72	11.51	12.03	8.73
MnO	0.16	0.23	0.24	0.16	0.20	0.10	0.16	0.19	0.21	0.16	0.08	0.18	0.19	0.12
MgO	3.59	4.60	4.49	3.86	4.75	1.06	3.32	4.36	5.95	3.46	1.92	3.43	7.11	3.99
CaO	6.20	6.79	8.88	5.14	4.11	3.69	3.89	5.71	6.29	6.27	4.15	3.14	3.95	4.22
Na_2O	2.46	2.19	2.06	3.17	2.45	3.13	4.19	3.53	2.24	3.01	3.08	0.90	1.35	3.13
K_2O	0.46	0.44	0.09	0.63	0.20	1.77	1.78	0.59	1.12	2.02	2.66	2.39	0.47	1.21
P_2O_5	0.26	0.22	0.24	0.26	0.23	0.24	0.23	0.25	0.20	0.25	0.27	0.22	0.26	0.26
SUM	98.12	97.47	96.15	98.29	98.20	98.85	98.66	98.52	97.99	98.22	98.94	98.37	96.71	98.74
Zr	150	130	130	160	130	210	160	160	150	220	310	150	120	170
Cr	40	40	30	40	60	50	60	50	250	110	70	110	320	70
Ni	20	20	20	30	40	20	20	20	70	20	30	20	50	20
Sr	320	180	240	340	180	210	120	280	320	340	210	140	250	290
Ba	140	210	80	320	70	550	320	200	420	520	820	560	110	440
V	300	310	210	220	290	140	230	240	380	170	80	160	330	110
Zn	130	150	190	120	140	70	110	230	220	190	90	150	170	130
Cu	10	80	60	20	360	0	0	10	50	30	20	20	30	50
K_2O:Na_2O	0.19	0.20	0.04	0.20	0.08	0.57	0.42	0.17	0.50	0.67	0.86	2.66	0.35	0.39
K_2O+Na_2O	2.92	2.63	2.15	3.80	2.65	4.90	5.97	4.12	3.36	5.03	5.74	3.29	1.82	4.34
FeO*:MgO	3.34	2.73	2.57	3.34	2.61	7.96	2.99	2.54	1.94	2.40	3.50	3.36	1.69	2.19
Mg' value	37.74	42.61	44.06	37.71	43.66	20.27	40.34	44.32	51.01	45.74	36.64	37.63	54.47	48.06

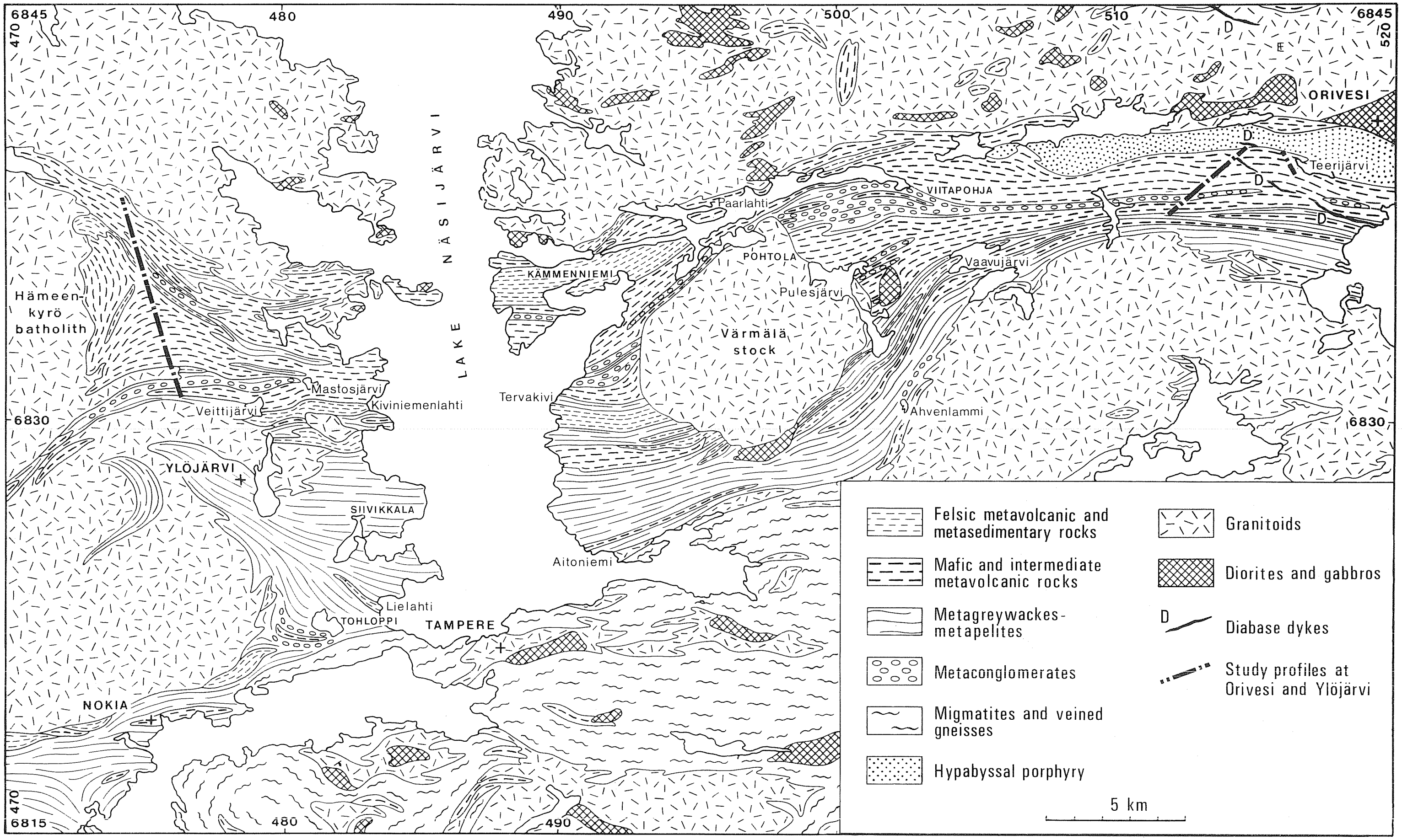


Fig. 4. Lithological map of the Tampere Schist Belt between Ylöjärvi and Orivesi, after Seitsaari (1951), Simonen (1953b), Matisto (1961, 1964), Geological Survey of Finland (1978, 1979, 1982), Gaál *et al.* (1981), Laitakari (1987), Rautio (1987), Nironen (in press), and observations by J. Leveinen and the author.

pyroclastic in origin but lavas, sills and subvolcanic rocks are also known. Pillow lavas have been observed only at Haveri (Stigzelius, 1944; Ollila, 1977; Mäkelä, 1980). The volcanic rocks range from basaltic to rhyolitic in composition and intermediate types with calc-alkaline affinities are the most common (Kähkönen, 1987).

Metamorphism

The supracrustal rocks of the Tampere Schist Belt were generally metamorphosed under conditions of low-pressure amphibolite facies. The staurolite-andalusite assemblages in the schists at Ylöjärvi indicate metamorphic PT conditions of between 1.5 kb, 500°C and 3 kb, 600°C (Campbell, 1978, 1980). The climactic metamorphism was followed, after a retrograde stage, by contact metamorphism caused by igneous emplacement. The samples now studied generally indicate amphibolite facies metamorphism. At Ylöjärvi a late growth of biotite is observed. At Orivesi, the small poikiloblasts of muscovite and the non-oriented needles of amphibole may indicate a late metamorphic event.

In places at Ylöjärvi, the mafic volcanic rocks often have assemblage albite + chlorite + epidote + carbonate ± biotite typical of greenschist facies. According to Simonen and Neuvonen (1947) and Simonen (1952), the metamorphism of amphibolite facies was post-dated by recrystallization at lower T in strongly deformed zones. The differences between the amphibolite and greenschist facies-type assemblages may have been caused by variations in the composition of fluid phases during the climactic metamorphic event (Campbell, 1978). This view is supported by the fact that several of the mafic rocks with greenschist facies-type assemblage of this study do not show signs of strong deformation.

Structural features

The essential structural features of the Tampere Schist Belt between Ylöjärvi and Orivesi are as follows. The belt as a whole, its lithological properties (Fig. 4), stratifications, magnetic anomalies and pronounced schistosities all have a predominantly E-W strike. Schistosities and bedding planes are mostly subvertical although stratification in places dips gently. The younging direction of the strata is regularly about north or south in extensive areas (Fig. 5). Lineations, such as elongations of pebbles and fragments, small-scale fold axes and mineral lineations, are predominantly steeply oriented, but subhorizontal fold axes have also been observed (Fig. 6). Polyphase folding is already apparent from the studies of Seitsaari (1951) and Simonen & Kouvo (1951); Campbell (1978) recognized five generations of folds at Ylöjärvi (see also Nironen, in press).

Between Ylöjärvi and Orivesi the Tampere Schist Belt is a large syncline with approximately E-W striking subhorizontal fold axes and steep to vertical axial planes (see also Simonen, 1953a and Nironen, in press). In the limbs of the major syncline there exist minor anticlines and synclines. The folding was predominantly isoclinal but notably open at Kämmenniemi and Pohtola—Viitapohja (Figs. 4—6). The subvertical lineations are in part caused by subsequent deformations but may largely be attributed to the major folding with subhorizontal fold axes (Fig. 6.b). The subsequent deformation phases explain much of the deviations from the E-W strikes but, in general, they do not markedly complicate the

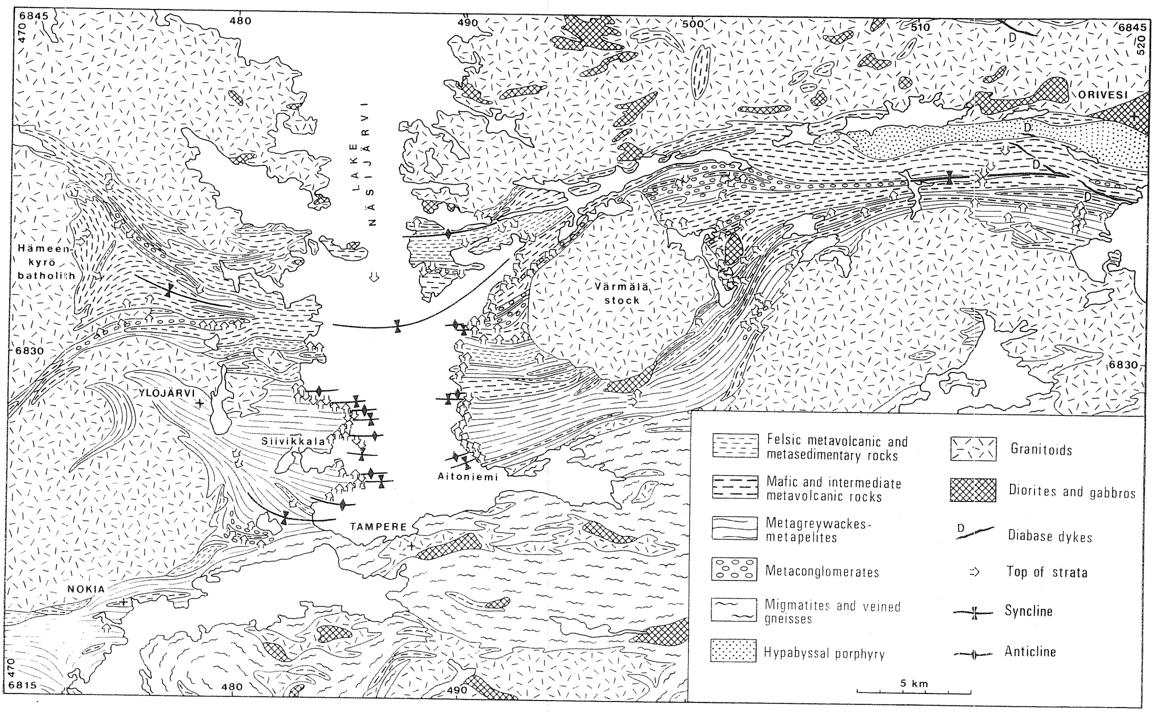


Fig. 5. A compilation of the top of strata observations and a simplified structural interpretation of the Tampere Schist Belt between Ylöjärvi and Orivesi. Bedding is mostly subvertical but at Kämmenniemi and Pohtola—Viitapohja bedding dips gently and is in places subhorizontal. Data from Simonen and Kouvo (1951), Simonen (1953a), Rautio (1987), Nironen (in press), and observations by J. Leveinen and the author. The data contain also observations from the field notebooks of Seitsaari and unpublished maps of Outokumpu Oy.

a

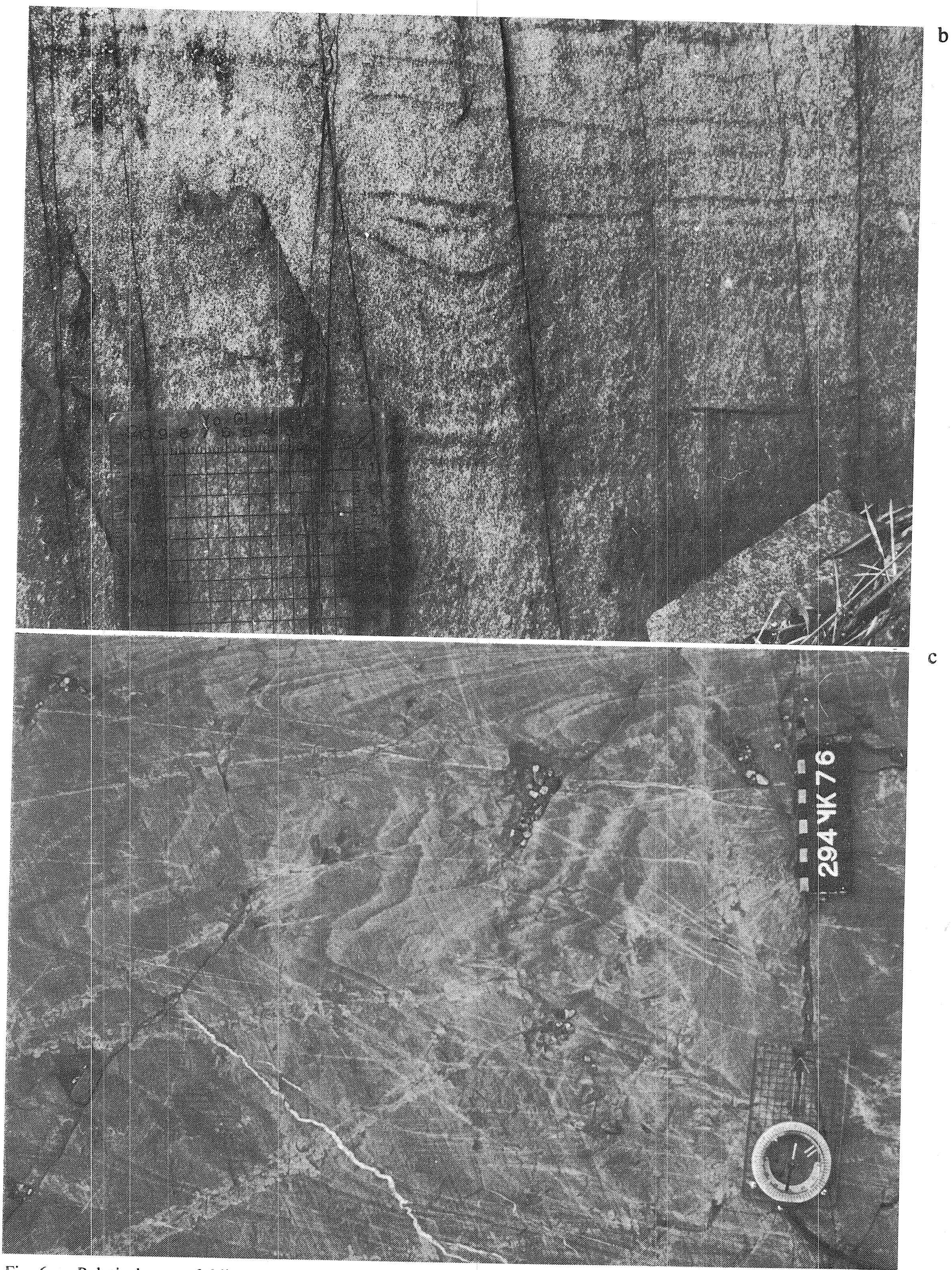


Fig. 6. a. Relatively open folding with vertical axial plane at Kämmenniemi. Road cutting approximately perpendicular to the general strike, looking east. The notebook is 20 cm high. Map sheet 2124, X = 6835.9, Y = 491.8; b. Subhorizontal east-plunging bedding/schistosity intersection lineation at Kämmenniemi. The subvertical stretching lineation is also discernible. Grid coordinates as in Fig. 6.a; c. Symmetrical folding in the hinge zone of the major syncline at Orivesi.

stratigraphic interpretation. There is no convincing evidence for tectonic deformation preceding the major folding which is thus called the D_1 deformation.

Stratigraphy

Since the study by Simonen (1953a), the traditional concept on the stratigraphy of the Tampere Schist Belt has been that greywackes-mudstones, deposited on an unknown basement, compose the lowermost unit (Fig. 7). Quartz-feldspar schists of both volcanic and sedimentary origin overlie the greywackes-mudstones and are followed by mafic and intermediate volcanic rocks. The Veittijärvi conglomerate with associated sedimentary rocks is the next unit in the sequence and it is overlain by mafic volcanic rocks. Seitsaari (1951) concluded that at Orivesi the volcanic rocks are underlain by sedimentary rocks.

The generalized stratigraphy described by Simonen (1953a, 1980a) is valid insofar as greywackes-mudstones comprise the lowermost part of many sequences and at Ylöjärvi underlie the volcanic rocks now studied (Figs. 5 and 7). At Ylöjärvi, recent observations of the younging of strata (Fig. 5) and the U-Pb zircon ages (Fig. 7; Kähkönen *et al.*, in press) agree with Simonen's concept (1953a) of two volcanic units separated by the Veittijärvi conglomerate. The units are here named the Lower Volcanic Unit and the Upper Volcanic Unit at Ylöjärvi.

Some adjustments of Simonen's scheme are warranted. Contrary to the view of Simonen (1953a), the pillow basalt-bearing Haveri Formation seems to lie below the greywackes-mudstones to the south (Fig. 7 with references).

The greywackes-mudstones at Aitoniemi represent the lowermost strata near Lake Näsijärvi (Figs. 4 and 5), but there are also volcanic rocks at low stratigraphic levels (Seitsaari, 1951; Simonen & Kouvo, 1951; Fig. 7). Furthermore, the Aitoniemi greywackes abound with clasts derived from volcanic rocks and from granitoids (Ojakangas, 1986; observations by the author). In fact, Sederholm (1897, p. 87) described clasts of porhyritic volcanic rocks in these greywackes, and Simonen and Kouvo (1951, p. 103) noted a few fragments of basic rocks with blasto-ophitic texture. The greywackes contain detrital zircon with a $^{207}Pb/^{206}Pb$ age of about 2.3 Ga (Kouvo & Tilton, 1966; Simonen, 1980a). This figure may be derived either from crustal sources 2.3 Ga old, from resetting of Archaean zircon, or from mixing of Archaean zircon with younger zircon. The ε_{Nd} values of -0.3 — -1.1 (Huhma, 1987) for the Tampere sedimentary rocks indicate that the predominating sources were separated from the mantle during the early Proterozoic. It is evident that the Svecofennian terrain contains igneous rocks which are slightly older than, or contemporaneous with, the greywackes at Aitoniemi.

The northern limb of the syncline at Orivesi is divided into four major units of volcanic origin: the Intermediate Unit (the northernmost and lowermost one), the Subalkaline Basaltic to Rhyolitic Unit, the Shoshonitic Unit, and the Trachytic Unit (Fig. 7; Appendix I). The Shoshonitic Unit and the Trachytic Unit are exposed also in the southern limb. The Trachytic Unit is overlain by sedimentary rocks. The Intermediate Unit, 1.904 Ga in U-Pb zircon age (Fig. 7 with references), is the oldest volcanic unit in the Tampere Schist Belt dated so far by the U-Pb zircon method.

The strata underlying the Shoshonitic Unit and the Trachytic Unit in the southern limb of the syncline at Orivesi are dominated by greywackes-mudstones. The greywackes resemble certain greywackes at Aitoniemi because they are rich in clasts of polycrystalline quartz/quartzite and also contain clasts derived from volcanic and granitoid sources (observations by the author). The sedimentary rocks contain interbeds of volcanic

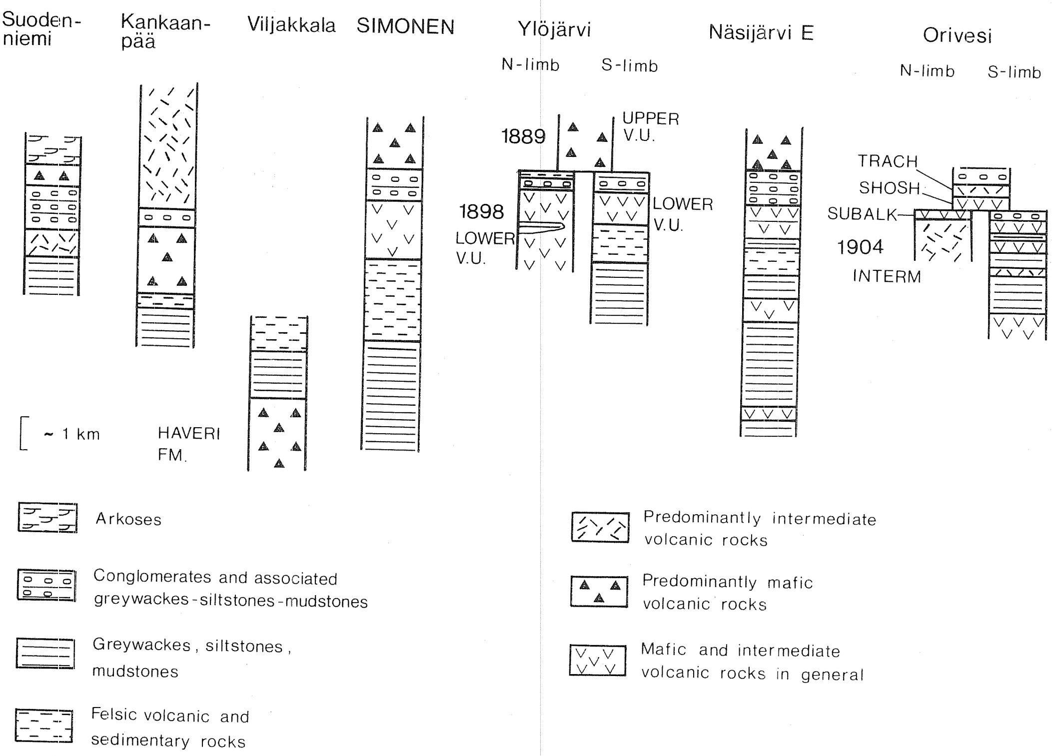


Fig. 7. Stratigraphic sections of the Tampere Schist Belt, after Simonen (1953a, 1980a), Söderholm (1978), Mäkelä (1980), Perttula (1982), Rautio (1987), Nironen (in press) and observations by the author. Thickness of some strata as shown are exaggerated. SIMONEN = generalized stratigraphy after Simonen (1953a, 1980a); INTERM = Intermediate Unit at Orivesi; SUBALK = Subalkaline Basaltic to Rhyolitic Unit at Orivesi; SHOSH = Shoshonitic Unit at Orivesi; TRACH = Trachytic Unit at Orivesi; LOWER V.U. = Lower Volcanic Unit at Ylöjärvi; UPPER V.U. = Upper Volcanic Unit at Ylöjärvi; HAVERI FM. = Haveri Formation. The figures 1904, 1898, and 1889 give U-Pb zircon ages in Ma (Kähkönen *et al.*, in press). 2-sigma error limits are 4—5 Ma. The Pb-Pb whole-rock age of the mafic volcanic rocks of the Haveri Formation is 1990 ± 25 Ma (Vaasjoki and Huhma, 1987).

rocks and seem to be underlain by volcanic rocks (Figs. 4—7 with references). The relation of the Intermediate Unit in the northern limb to these sedimentary and volcanic rocks is not known.

Outside the present study area, the stratigraphic position of the Mauri arkose is not clear. It contains clastic zircon with a U-Pb age of about 1.9 Ga and the provenances are dominated by uplifted aplite granites (Matisto, 1968). Arkoses comprise the uppermost unit at Suodenniemi (Fig. 7 with references).

Tectonomagmatic affinities

Sederholm (1897, p. 41) indicated that the porphyritic rocks in the conglomerates of the Tampere belt form an association which bears resemblances to young andesites. Simonen (1953a, p. 35) emphasized similarities to eugeosynclinal belts and suggested that the mafic volcanic rocks ”. . .have accumulated probably on the volcanic arch system rising from the geosyncline”.

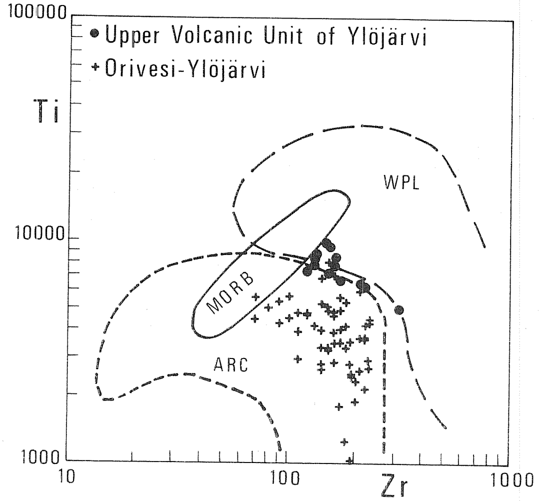


Fig. 8. Ti-Zr diagram of the volcanic rocks of the Tampere Schist Belt between Ylöjärvi and Orivesi. Data from Table I. MORB (mid-ocean ridge basalts), ARC (arc volcanics) and WPL (within-plate lavas) fields from Pearce (1982). Ti and Zr in ppm.

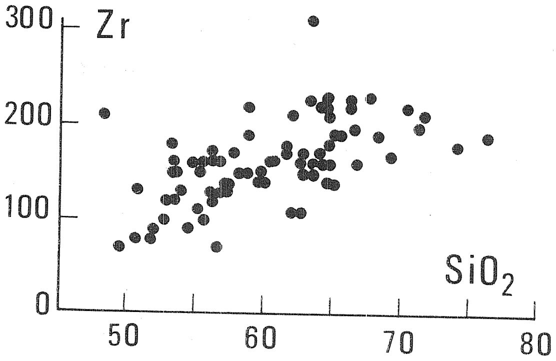


Fig. 9. Covariation of Zr and SiO_2 in the volcanic rocks of the Tampere Schist Belt between Ylöjärvi and Orivesi. Data from Table I. SiO_2 in weight %, Zr in ppm.

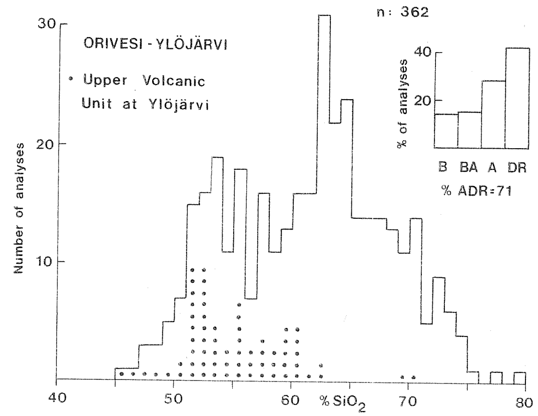


Fig. 10. SiO_2 frequency diagram of the volcanic rocks of the Tampere Schist Belt between Ylöjärvi and Orivesi. The data consist of 18 wet-chemical analyses from Sederholm (1897), Seitsaari (1951) and Simonen (1953a), and 344 XRF analyses made by Outokumpu Oy (this study). Sample 285 is not included because it is from a post-D_1 dyke. SiO_2 represents values for which the total of oxides was calculated to 100%. Class interval 1%. The inset right up: B-BA-A-DR diagram displays the frequencies of basalts, basaltic andesites, andesites and dacites-rhyolites. Class boundaries are here from Leeman (1983). %ADR indicates the proportion of andesites, dacites and rhyolites of the total.

Most of the volcanic rocks of the Tampere Schist Belt resemble those of present-day mature island arcs or active continental margins (Kähkönen, 1987). This is so because the Tampere volcanic rocks are dominated by calc-alkaline intermediate rocks, the mafic rocks are mostly low in Ti, and the rocks occur mostly in the arc field in the Ti-Zr diagram (Fig. 8). Since the general increase in Zr with increasing Si (Fig. 9) does not indicate extensive changes in the Si content, approximations based on silica frequencies are warranted. In the Ylöjärvi—Orivesi area the percentage of andesites-dacites-rhyolites (percentage of ADR) is about 70 (Fig. 10). Intermediate rocks are so abundant that bimodal affinities are not pronounced. In other parts of the belt the percentage of ADR often exceeds 50 (Kähkönen, 1987). Therefore, when considering percentage of ADR and crustal thickness in modern arc settings (Leeman, 1983), the crust could have been relatively thick during most of the volcanic activity. This indicates, in the absence of Archaean crust in the Svecofennian terrain, that significant early Proterozoic crustal evolution preceded most of the Proterozoic volcanic activity now observable near Tampere.

The arc affinities are not unequivocal throughout the belt. The basalts of the Haveri Formation, certain mafic rocks at Kankaanpää, and the rocks of the Upper Volcanic Unit at Ylöjärvi are relatively rich in Ti (Mäkelä, 1980; Kähkönen, 1987; Fig. 8). Thus they resemble those young basalts which, although situated near or within volcanic arcs, have high Ti contents (Hörmann *et al.*, 1973; Gill, 1976; Luhr & Carmichael, 1981; Innocenti *et al.*, 1982; Tarney *et al.*, 1982; Briggs & Coles, 1984; Nelson & Carmichael, 1984). These young basalts derive from areas or periods of extensional tectonics at convergent plate margins. Similar environments are possible for the high-Ti mafic rocks near Tampere.

PETROGRAPHY, GEOCHEMISTRY AND PETROLOGY

General

Based on lithological, geochemical and magnetic properties, the areas studied are divided into units. In each unit, petrographic and geochemical properties and their relations to each other are described. The reasons for the compositional variation within each unit are discussed. The units are not given formal stratigraphic names because (1) thorough mapping outside the study profiles was not done, (2) lateral extensions and regional significance of several units are not known, and (3) some units are so thin in the study areas that locality names could not be used (cf. Ayres, 1977).

The main emphasis in the petrography is placed upon major minerals, upon igneous and sedimentary structures and textures, and upon pseudomorphs of phenocrysts and clasts. Metamorphic features and minor and accessory minerals are treated only incidentally.

Nomenclature and classification used

Classifications of volcanic rocks are numerous and, like Gill (1981, p. 3) writes, "...nomenclature is the Pandora's Box of igneous petrology". Because of glassy or fine-grained groundmass in fresh rocks and recrystallization in metamorphic rocks, classifications based on chemical composition are preferred over those based on modal compositions. The classifications may use major elements and their abundance ratios (e.g. Taylor, 1969; Middlemost, 1972, 1975; Peccerillo & Taylor, 1976; Cox *et al.*, 1979; De la Roche *et al.*, 1980; Gill, 1981; Ewart, 1982; Le Bas *et al.*, 1986) or normative compositions (Streckeisen, 1978). Irvine and Baragar (1971) utilized both major element abundance ratios and normative compositions.

The classification in this study is based on the contents and ratios of SiO_2, K_2O, Na_2O, FeO* and MgO (Fig. 11). In the $Na_2O + K_2O$ vs. SiO_2 diagram, the rocks are classified as basalts, basaltic andesites, etc. The boundary between basaltic andesites — andesites — dacites and basaltic trachyandesites — trachyandesites — trachydacites approximates the boundary between subalkaline and alkaline rocks of, for example, Miyashiro (1978). In the K_2O-SiO_2 diagram, the rocks occur in low-K, medium-K, high-K, very high-K and ultra-K fields. In the FeO*:MgO vs. SiO_2 and AFM diagrams the associations show pronounced or less pronounced enrichment of Fe over Mg (iron-enrichment or no iron-enrichment). According to these diagrams, subalkaline

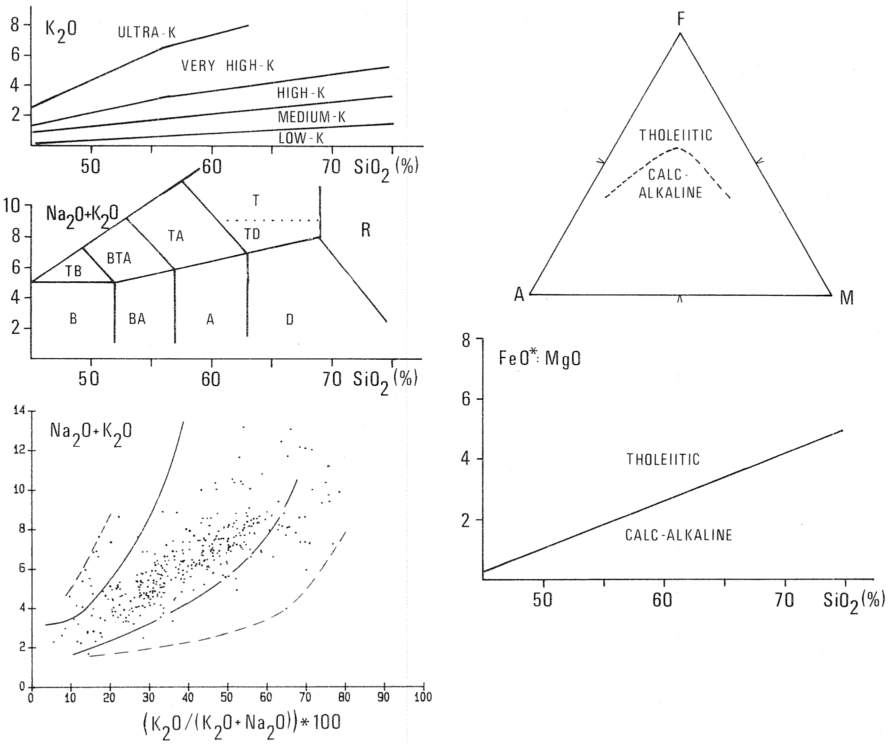


Fig. 11. Classifications in the Harker-type and AFM diagrams and a revision of the igneous spectrum. In the K_2O-SiO_2 diagram, the boundaries between the low-K, medium-K, high-K and very high-K fields are based on Gill (1981) and Ewart (1982), and the boundary between the very high-K and ultra-K fields is based on Foden and Varne (1980), Morrison (1980) and Keller (1983). The lines pass points $K_2O = 0.18\%$, $SiO_2 = 45\%$; $K_2O = 1.54\%$, $SiO_2 = 75\%$; $K_2O = 0.93\%$, $SiO_2 = 45\%$; $K_2O = 3.38\%$, $SiO_2 = 75\%$; $K_2O = 1.40\%$, $SiO_2 = 45\%$; $K_2O = 3.20\%$, $SiO_2 = 56\%$; $K_2O = 5.40\%$, $SiO_2 = 75\%$; $K_2O = 2.50\%$, $SiO_2 = 45\%$; $K_2O = 6.50\%$, $SiO_2 = 56\%$; $K_2O = 8.00\%$, $SiO_2 = 63\%$. In the $Na_2O + K_2O$ vs. SiO_2 diagram, the fields are after Le Bas *et al.* (1986): B = basalt, BA = basaltic andesite, A = andesite, D = dacite, R = rhyolite, TB = trachybasalt, BTA = basaltic trachyandesite, TA = trachyandesite, TD = trachydacite, T = trachyte. The dotted line between trachytes and trachydacites is based on the approximation that 20% quartz in QAPF diagram equals to 9% $Na_2O + K_2O$ (Le Bas *et al.*, 1986). The boundaries between the tholeiitic and calc-alkaline fields are after Irvine and Baragar (1971; AFM diagram) and Miyashiro (1974; FeO*:MgO vs. SiO_2 diagram). In the $(K_2O + Na_2O)$ vs. $((K_2O)/(K_2O + Na_2O))*100$ diagram, the continuous line shows the igneous spectrum of Hughes (1973). The points are averages and representative analyses from Joplin (1968), Nicholls and Carmichael (1969), Morrison (1980), Baker (1982) and Ewart (1982); the hatched line is the modified igneous spectrum based on these points.

associations have tholeiitic or calc-alkaline affinities, respectively. Disadvantages of classifications such as these are that they are sensitive to changes in the K, Na and Si contents.

The K_2O-SiO_2 classification used in this study is an expansion of that of Gill (1981). The rocks are not classified as tholeiitic or calc-alkaline according to this diagram (cf. Peccerillo & Taylor, 1976; Basaltic Volcanism Study Project, 1981, p. 193; Ewart, 1982). The medium-K group corresponds to the calc-alkaline series and the very high-K group corresponds to the shoshonitic series of Ewart (1982). The ultra-K group corresponds to the leucitites, leucite tephrites and K-rich rocks of Foden and Varne (1980), Ewart (1982) and Keller (1983).

Miyashiro (1974) rejected the classical AFM diagram as the criterion for distinguishing between tholeiitic and calc-alkalic series. He defined tholeiitic and calc-alkalic series as having steeper and gentler slopes, respectively, than the boundary line in the FeO*:MgO vs. SiO_2 diagram. Gill (1981) chose the FeO*:MgO value of 2.25 at 57.5% SiO_2 to separate tholeiitic andesites from calcalkaline andesites although even he stressed the significance of the rate of change in the FeO*:MgO ratio with increasing Si. In this study the slope of the FeO*:MgO vs. SiO_2 trend is the major criterion when the rocks of a certain unit are considered having tholeiitic or calc-alkaline affinities. The AFM diagram is shown because it still is an effective means in describing the geochemistry of igneous rocks. In some instances, individual rocks are described according to their position in these diagrams.

The igneous spectrum (Hughes, 1973) is used to identify altered rocks and compositions which are not common in fresh volcanic rocks. The generalized trend of the plots in Fig. 11 slopes more gently than the original spectrum of Hughes (1973), and a modification of the spectrum is justified.

In felsic volcanic rocks, the K_2O:Na_2O ratio is discussed because Svecofennian felsic rocks show a wide variation in this ratio. The range from Na-enriched to K-enriched Svecofennian felsic volcanic rocks is thought to be caused by hydrothermal metasomatic alteration (Lagerblad & Gorbatschev, 1985; Vivallo & Claesson, 1987).

The Intermediate Unit at Orivesi

General description and petrography

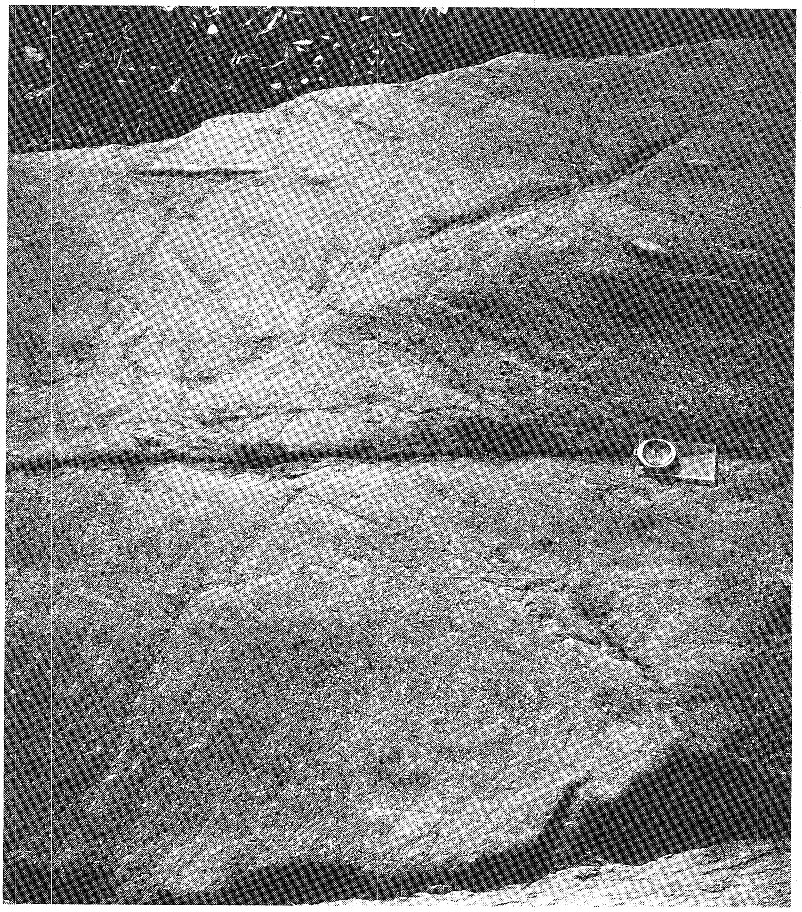
The Intermediate Unit at Orivesi (Fig. 7) is nearly 1 km thick and, based on magnetic maps (Geological Survey of Finland, 1978, 1979, 1982), up to 10 km long. It was sampled in two profiles; along highway 9 and near Lake Teerijärvi (Appendix I). The unit is dominated by plagioclase-phyric pyroclastic intermediate rocks. It comprises also pyroclastic and redeposited felsic rocks. Mafic rocks are rare and mostly of dyke origin by highway 9, but near Lake Teerijärvi pyroclastic mafic rocks are more common.

The dacites, trachydacites and andesites of the Intermediate Unit are often massive tuffs with sparse fragments (Figs. 12.a,b). When observable, individual strata tend to be 4—5 m, or more, thick. One stratum with an erosional base and eutaxitic structure (Figs. 12.c,d) is a pyroclastic flow deposit. Samples 35—37 are from a volcanic breccia which thickens to the west. A dolomitic stratum in a drill core 100—200 m west of samples 20—33 (Mäkelä, 1979) indicates deposition in a shallow-water environment.

The groundmass of the intermediate rocks is granoblastic and more or less oriented. The major minerals include mostly plagioclase + quartz + biotite ± potassium feldspar. Muscovite is a major mineral in samples 23—25 and 28, and chlorite, epidote and hornblende in the area of samples 9—12. A few mafic fragments are pseudomorphs after glass shards, scoria or rock fragments. Several aggregates rich in biotite seem to be pseudomorphs after phenocrysts of hornblende (Fig. 12.e) or, less frequently, of biotite.

Plagioclase phenocrysts vary in form, size, amount, and composition. Several samples contain both euhedral and broken phenocrysts. The phenocrysts range typically from 0.5 to 3 mm, rarely up to 7 mm, in diameter. Phenocrysts amount mostly to 10—25 vol.% with maximum values being 35—40 vol.%. The phenocrysts are mostly oligoclase or andesine but in samples 23—33 often albite. The content of epidote within the phenocrysts is mostly less than 5 vol.% but in some cases up to 50—100 vol.%. Apparently, the original plagioclase phenocrysts were partly high in An.

a



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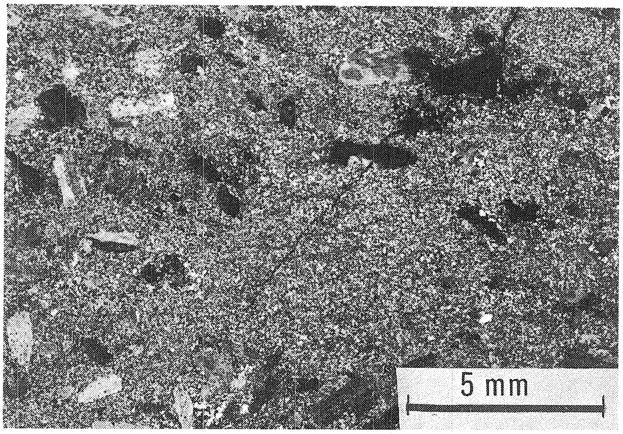
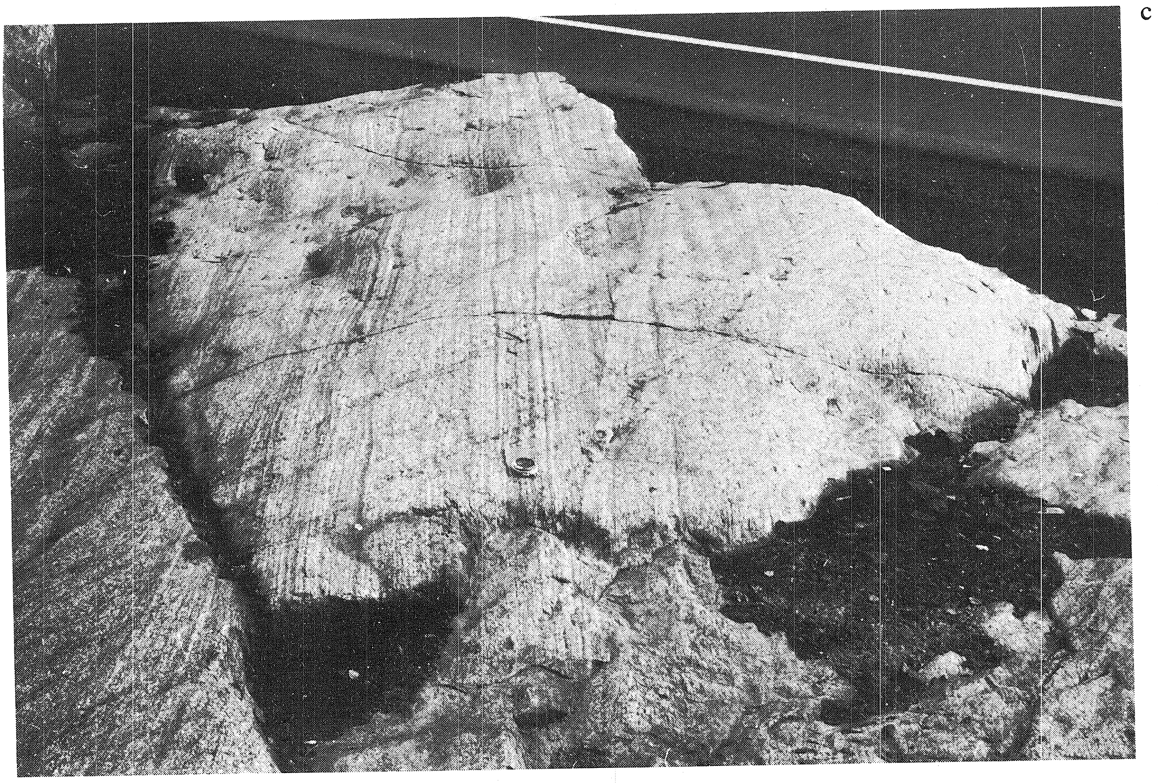
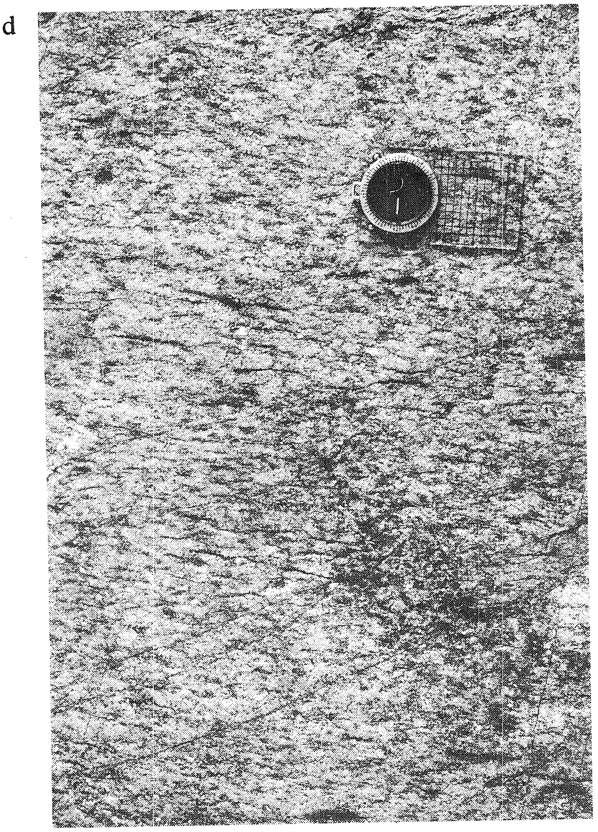






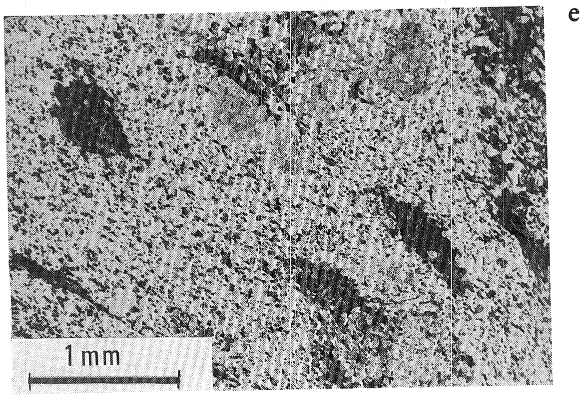


Fig. 12. Structures and textures of the Intermediate Unit at Orivesi. a. Plagioclase-phyric tuff with sparse rock fragments. The area near sample 12; b. Plagioclase-phyric dacite with a non-porphyritic fragment (the even-grained area central-down). Sample 2, crossed nicols; c. Pyroclastic flow with an erosional base. The area of samples 24—25, looking east, top of strata to the south, compass for scale; d. Eutaxitic structure in the pyroclastic flow of Fig 12.c; e. Biotite aggregates, pseudomorphs after phenocrystic hornblende. Sample 46, parallel nicols. Photomicrographs by J. Väätäinen.

Potassium feldspar replaces phenocrystic plagioclase in some samples. Within individual phenocrysts it amounts mostly to less than 5 vol.% but up to 95 vol.% in samples 2 and 15.

The felsic rocks of the Intermediate Unit are mostly stratified tuffs and tuffites. Rhyolite samples 47, 48, 52, 53 are from a 10 m thick stratum which shows hazy folded banding. They contain less than 5 vol.% small (in general ø <0.5 mm), partly embayed phenocrysts of feldspars and quartz. The major minerals include quartz + albite + potassium feldspar + muscovite ± biotite. Samples 21 and 26 are from stratified pyroclastic strata. They accentuate the relatively felsic character of the nearby dacitic samples 23—25 and 28. Sample 49/82 contains 5—10 vol.% plagioclase phenocrysts and a few pseudomorphs after phenocrysts of quartz.

The Intermediate Unit contains few mafic rocks near highway 9. They are typically 0.05—2 m thick dykes or strata. Sample 27 is a from dyke which shows chilled margins and cuts a veinlet of quartz. Most of the mafic rocks near highway 9 are probably dykes, but equally convincing evidence for or against this interpretation is absent. The major minerals include plagioclase + quartz ± biotite (not in sample 34) ± hornblende ± chlorite ± epidote. Some of the rocks contain 5—10 vol.% plagioclase phenocrysts. Hornblende, when present, occurs partly as poikiloblasts, and amphibolite-facies metamorphism is evident. Sample 44, an intermediate rock, is from an apparent dyke. Sample 29 is from a segregation vein filling a fissure, and it is rich in green and greenish amphiboles.

In the profile near Lake Teerijärvi there are two horizons rich in mafic rocks. To judge from magnetic maps (Geological Survey of Finland, 1978, 1979, 1982; Mäkelä, 1979), the northern one is less than 150 m thick and 0.5—1 km long while the southern one is 150—200 m thick and up to 5 km long.

The northern horizon with abundant mafic rocks is dominated by polymictic clast-supported volcaniclastic rocks. In the mafic matrix there are mostly roundish, but partly angular, fragments of mafic (the dominant type), intermediate, felsic and ultramafic rocks. Sample 43/82 is from a single fragment in this area.

The southern horizon with abundant mafic rocks is rich in basalts, basaltic andesites and andesites but more silicic rocks are also abundant. Agglomerates, tuff breccias and lapilli tuffs dominate, but fine-grained, often laminated volcaniclastic rocks are also common, among the silicic types in particular. The samples from this horizon (samples 50—53/82) are from agglomerates or tuff breccias. The major minerals include plagioclase + quartz + hornblende ± epidote ± biotite. Phenocrysts of plagioclase (ø up to 2x4 mm) amount to 10—30 vol.%.

Geochemistry

The Intermediate Unit is dominated by calc-alkaline high-K dacites, trachydacites and andesites (Fig. 13). They range from low-K types to very high-K types and certain rocks have a slight iron-enrichment tendency. Most of the rocks are within the igneous spectrum of Hughes (1973). Being low in K, samples 31, 33 and 35 are to the left of the spectrum while sample 15 occurs to the right. The dispersion in Na and K is partly caused by compositional changes; sample 31 is rich in albite, and in sample 15 up to 95 vol.% of certain plagioclase phenocrysts have been replaced by potassium feldspar. The rather low K_2O content in sample 46 (Table 1) indicates that biotitization of hornblende (Fig. 12.e) did not cause marked increase in K. The Ca, Fe, Ti and P contents decrease with the increasing Si content but the dispersions are wide. The intermediate rocks near Lake Teerijärvi show dispersions as wide as those near highway 9, although the sampling density in the former area was lower (Appendix I).

The intermediate rocks display a wide dispersion in the Zr-SiO_2 diagram, but the pattern may be interpreted as a general increase in Zr with increasing SiO_2 followed by a decrease in Zr in the rhyolites (Fig. 14). The Cr, Ni and Ti contents do not display a coherent decrease with increasing Zr. V shows a general, but dispersed, decrease with increasing Zr. The Sr-Zr and Ba-Zr trends are rising. These two trends are enchanced when the albitized sample 31 is excluded. The K_2O-Zr diagram shows a rising, rather than horizontal, slope but the dispersion is wide. Samples 2 and 31 deviate from the general trend. In sample 2 this is attributed to replacement by potassium feldspar and in sample 31 to albitization. Compositional changes less severe than those in samples 2 and 31 may have caused dispersion in the K_2O-Zr diagram.

Samples 23—25 and 28 deviate from the other intermediate rocks in having relatively high FeO*:MgO ratios and in regularly containing muscovite as a major mineral. The high FeO*:MgO ratio is petrographically explained by muscovite, occurring largely as a fine-grained network. This might indicate alteration, but the K content is not particularly high.

Intermediate sample 44, from a dyke, deviates from the typical rocks of the Intermediate Unit due to its high FeO*:MgO ratio.

The rhyolitic rocks of the Intermediate Unit are very high-K (samples 47, 48, 52, 53), high-K and medium-K rocks. The K_2O:Na_2O ratios vary widely but are mostly close to or in excess of unity. The rhyolites occur mostly in calc-alkaline fields, but sample 26 agrees with the slight iron-enrichment shown by the dacites nearby. The rhyolites occur within or near the modified igneous spectrum. Samples 47, 48, 52 and 53 are lower in Na than the other rhyolites. Sample 53 is relatively low in Sr and Zr.

The mafic rocks by highway 9 are mostly trachybasalts or basaltic trachyandesites. They occur in high-K (samples 29 and 34), very high-K (samples 27, 41 and 43), and ultra-K (samples 22 and 49) fields. The TiO_2 contents are about 1%. Sample 22 occurs far outside the modified igneous spectrum and has hardly any original composition. The high P_2O_5 of 0.4—0.75% in samples 27, 41, 43 and 49 support a primarily alkaline character for these rocks.

The five samples from the mafic horizons near Lake Teerijärvi are subalkaline and low in Ti. The range in K is wide. Sample 43/82, from the northern horizon, is a medium-K basalt. In the southern horizon, samples 50—51/82 occur in or near the low-K field, whereas samples 52—53/82 are high-K rocks. Since the differences reflect variations in the modes of biotite, not of sericite or potassium feldspar, the range in K is regarded as original.

Petrology

The mafic rocks near highway 9 are not parental rocks of the dacites-andesites of the Intermediate Unit because they are partly dykes and often too high in K. Sample 27 is also too low in Cr and Ni. Because of differences in K, samples 22, 29 and 34 are probably not comagmatic with the other mafic rocks near highway 9. Samples 41, 43 and 49 may belong to the same set of dykes as sample 27 although sample 49 is rich in P.

In the dacites-andesites of the Intermediate Unit, the Sr content increases with the increasing Zr content. This feature is not caused by alteration because Zr is a less mobile element than Sr. In the rocks with highest Sr, i.e., in samples 23 and 24, plagioclase phenocrysts amount to only 10—20 vol.%. The highest Sr values are not caused by accumulation of plagioclase. Although the intermediate rocks always contain plagioclase phenocrysts, low-pressure fractional crystallization with Zr as an incompatible element and plagioclase as a major constituent in the crystallized assemblage is not a proper explanation since it yields horizontal (Fig. 15) or descending Sr-Zr trends. Fractional crystallization of plagioclase and zircon may explain a part of the Sr-Zr correlation. For example, the low Sr and Zr contents in the fairly silicic sample 37 are attributable to this process. However, fractionation of plagioclase and zircon does not explain most of

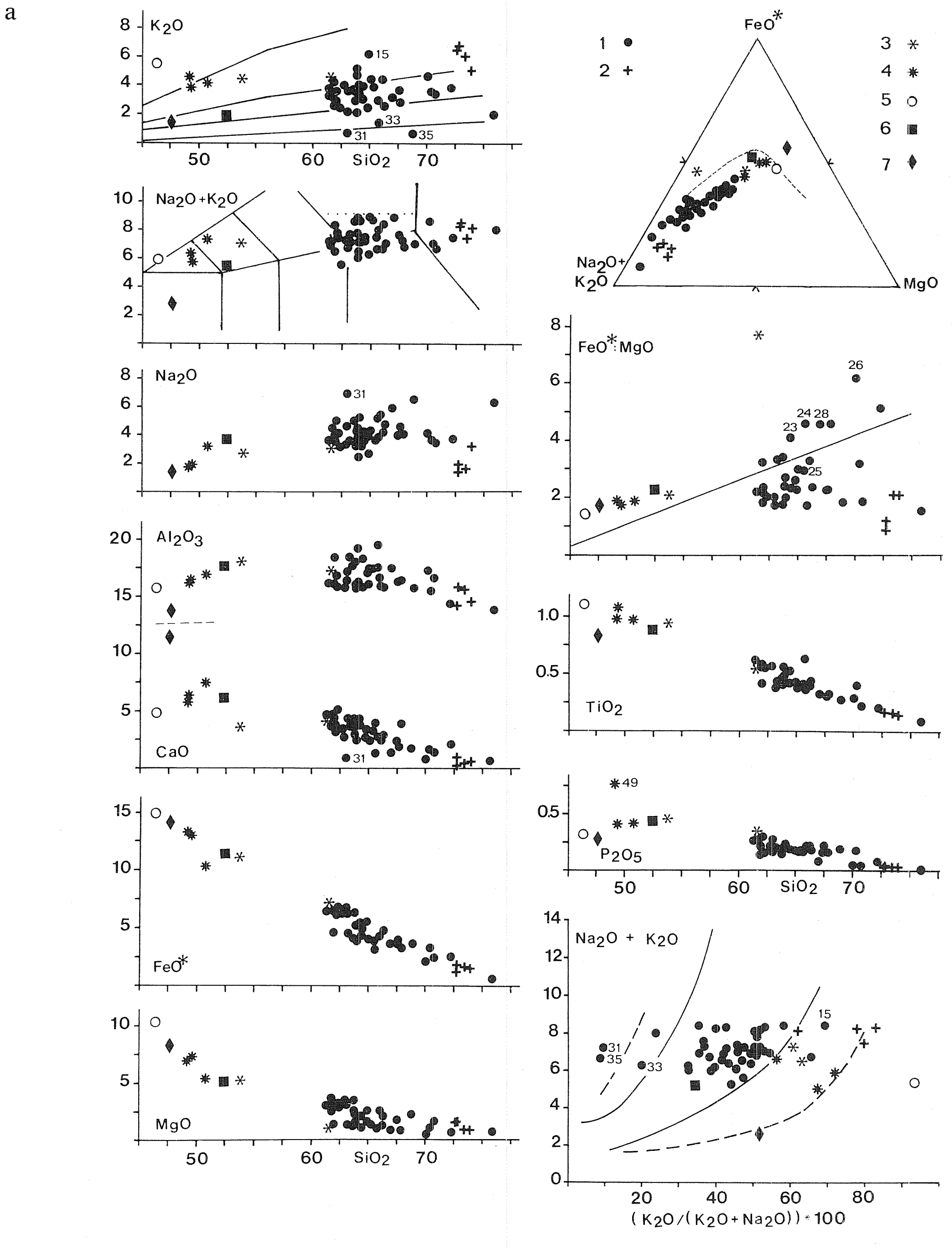
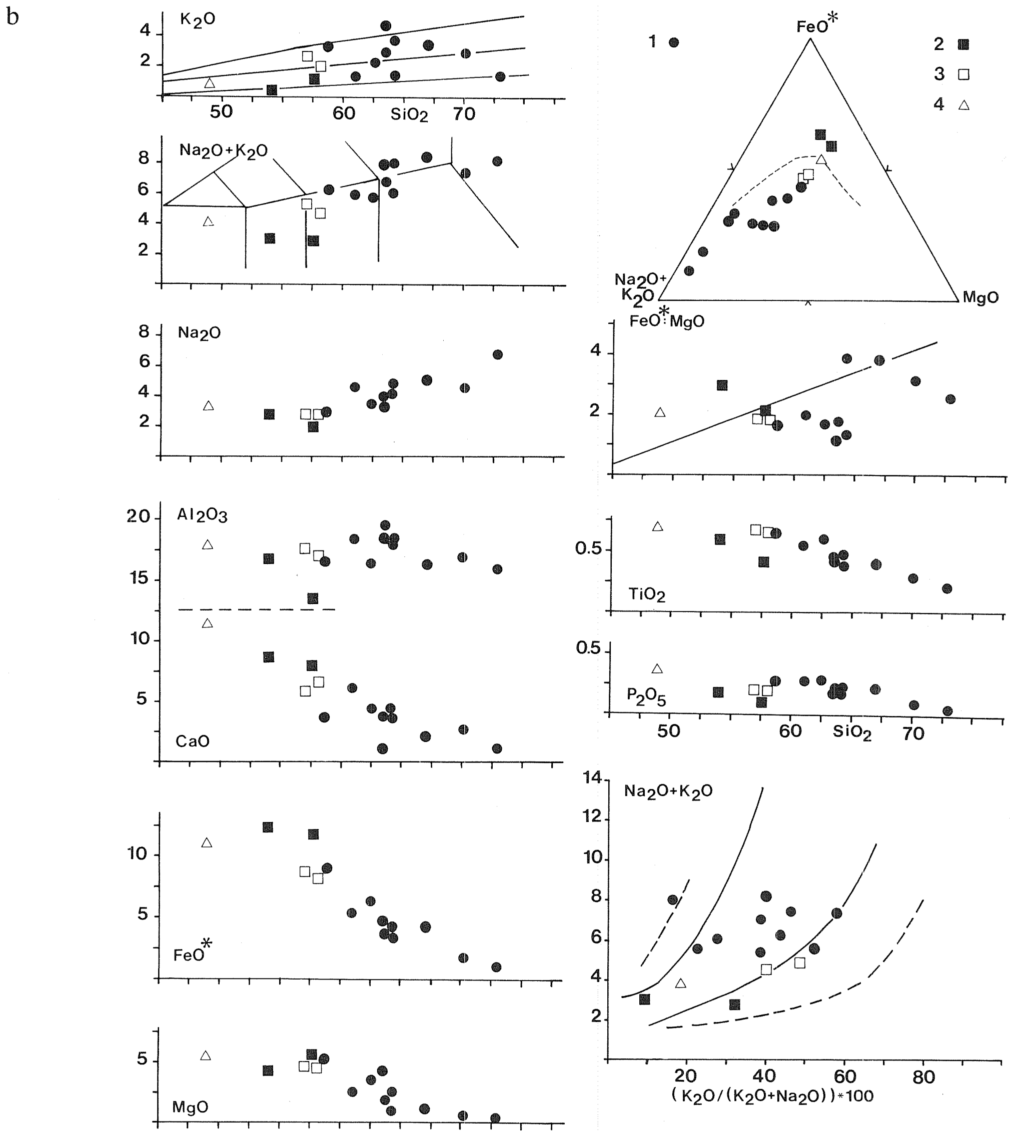


Fig. 13. Harker-type and AFM variation diagrams and igneous spectrum of the Intermediate Unit at Orivesi. Analyses by Outokumpu Oy. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. A. The profile near highway 9. 1. intermediate and rhyolitic rocks in general, some individual samples are shown as numbers; 2. samples 47, 48, 52 and 53; 3. samples 27 and 44 (metamorphosed dykes); 4. samples 41, 43 and 49 (probable metamorphosed dykes); 5. sample 22; 6. sample 34; 7. sample 29. B. Teerijärvi profile. 1. samples 42/82, 44/82, 46—49/82 and 54—57/82; 2. samples 50—51/82; 3. samples 52—53/82; 4. sample 43/82.



the Sr-Zr correlation because the rocks high in Sr and Zr (e.g., sample 23) are rather silicic and so felsic that they cannot be parental rocks of the less silicic rocks (e.g., samples 10 and 11) lower in Sr and Zr. Mixing of mafic and felsic magmas is probably not the reason because rhyolites are not rich enough in Sr; Sr averages in Recent rhyolites are frequently below 500 ppm (Ewart, 1979). Liquid-state differentiation yields both rising and descending Sr-Zr trends (Hildreth, 1981). It might be possible that this process can produce the rising Sr-Zr trend. Variation in the degree of

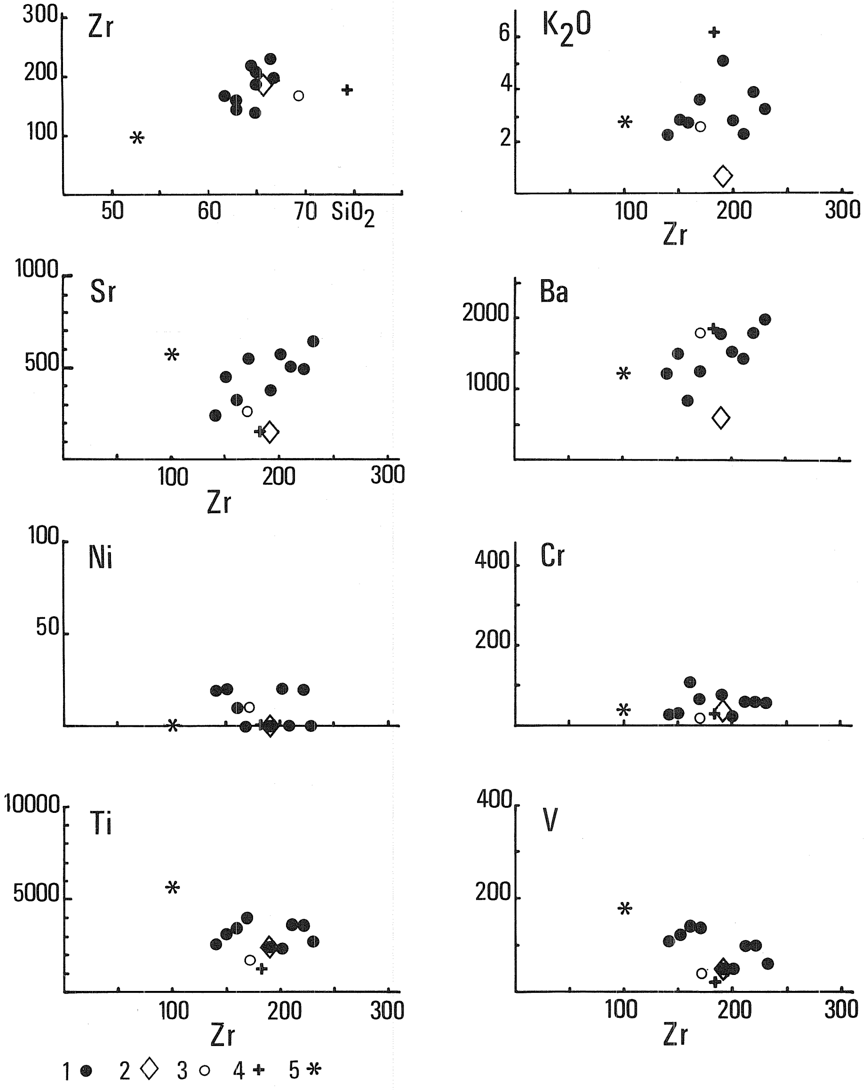


Fig. 14. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Intermediate Unit at Orivesi. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. 1. intermediate rocks in general; 2. sample 31; 3. sample 37; 4. sample 53; 5. sample 27.

partial melting or fractional crystallization at depths where plagioclase is not stable produces rising Sr-Zr trends (Fig. 15). The scarcity of mafic rocks in the Intermediate Unit would suggest that partial melting is to be preferred over fractional crystallization. Mixing of dacitic melts high in Sr and Zr with less silicic melts low in Sr and Zr is another possibility; certain Tertiary-Recent volcanic rocks with 66—69% SiO_2 have Sr and Zr averages of 790—820 ppm and 180—300 ppm, respectively (Ewart, 1979). The dispersions in the Sr-Zr, K_2O-Zr, Ba-Zr, Ti-Zr and V-Zr diagrams might be attributed to subsequent fractional crystallization, liquid-state differentiation and compositional changes.

The rhyolitic samples 47, 48, 52 and 53 are relatively low in Na, Al, P, Fe and Ti. Sample 53 has rather low Sr, Zr, V and Ni contents. These features may be explained by fractional crystallization of sodic plagioclase, hornblende, magnetite, apatite and zircon, starting from some type of dacite or trachydacite of the Intermediate Unit. The Cr content of sample 53 is too high to allow significant surface-equilibrium fractional crystallization of hornblende and magnetite. This could be attributed to the occurrence of mafic phases. Mixing with high-Cr material during redeposition is not probable because petrographic signs of reworking were not observed. Other explanations might be open-system fractionation (O'Hara, 1977), or total equilibrium crystallization instead of surface-equilibrium crystallization (Arth, 1976; Luhr & Carmichael, 1980).

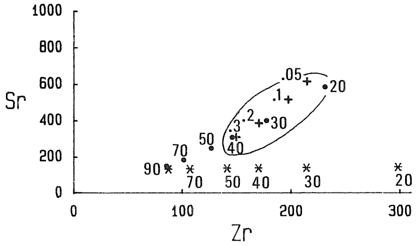


Fig. 15. Sr vs. Zr trends based on model calculations of batch melting and fractional crystallization. Equations (1) and (3) (p. 9). +: Batch melting, the solid residue comprises 60% hornblende and 40% clinopyroxene ($\mathrm{HBL_{0.6}CPX_{0.4}}$), the source has 80 ppm Zr and 130 ppm Sr, figures .05—.3 give the proportion of melt. Largely similar trends may be obtained if hornblende is replaced with garnet or if the proportions of the minerals are changed; •: Surface-equilibrium fractional crystallization of assemblage $\mathrm{HBL_{0.6}CPX_{0.4}}$. Figures 90—20 give the percentage of residual liquid; *: Surface-equilibrium fractional crystallization of assemblage $\mathrm{PLG_{0.5}HBL_{0.35}CPX_{0.15}}$. Figures 90—20 give the percentage of residual liquid. In the crystallization models the parental melt contains 80 ppm Zr and 130 ppm Sr. D values are from Gill (1981). The continuous line defines the field of andesites and dacites of the Intermediate Unit at Orivesi. The altered sample 31 is omitted.

The shear zone between the Intermediate Unit and the Subalkaline Basaltic to Rhyolitic Unit at Orivesi

General description and petrography

The area between the Intermediate Unit and the Subalkaline Basaltic to Rhyolitic Unit is a 200 m wide zone of pronounced deformation and alteration. It is a part of the northern shear zone described by Nironen (in press). The rocks are relatively silicic. Sulphide minerals are common both as disseminations and in quartz veins.

The northern parts of the zone are characterized by plagioclase-phyric rocks with hazy fragmental structures. The phenocrysts (albite) have often been highly replaced by quartz and potassium feldspar. Polycrystalline aggregates of quartz are abundant. Originally these rocks were similar to the dacites-andesites of the Intermediate Unit but were subject to silicification and potassium metasomatism.

In the southern parts of the zone the rocks are tuffs, lapilli tuffs and tuff breccias. They are often rich in sericite. Potassium feldspar is in certain parts abundant, occurring both as phenocrysts (up to 30 vol.% in sample 62) and in groundmass. Quartz aggregates amount mostly to less than 5 vol.%. The phenocrysts of plagioclase are often albite and amount up to 15 vol.%.

Geochemistry and petrology

The original chemical composition of the rocks of the shear zone has been disturbed by compositional changes. In the classification used the rocks are high-K and very high-K rhyolites, dacites and trachydacites (Fig. 16). Calc-alkaline affinities are apparent because of the low FeO*:MgO ratios. The rocks tend to occur outside the igneous spec-

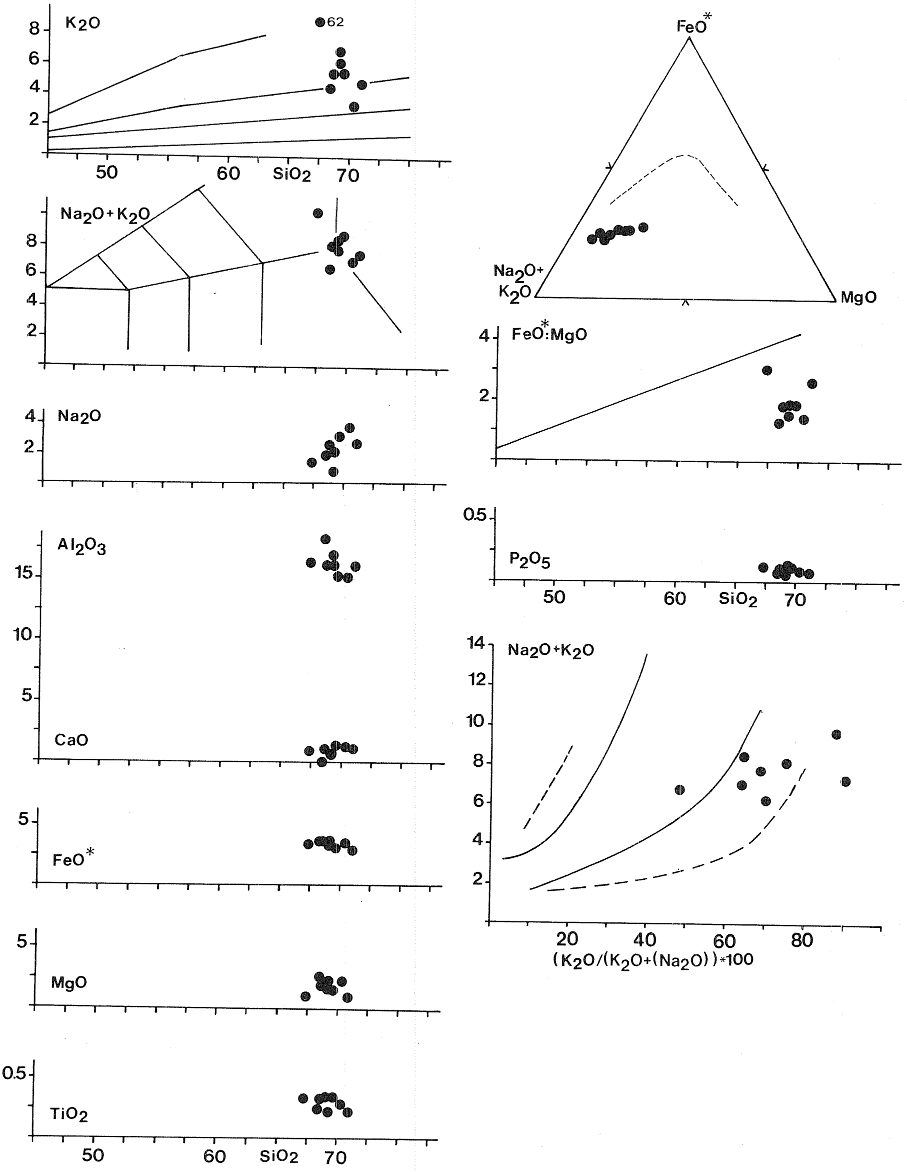


Fig. 16. Harker-type and AFM variation diagrams and igneous spectrum of the rocks of the shear zone between the Intermediate Unit and the Subalkaline Basaltic to Rhyolitic Unit. Analyses by Outokumpu Oy. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines.

trum of Hughes (1973) but are mostly within the modified spectrum. Although the samples are highly variable in Na and K, the ranges of the other elements are narrow. Alteration has mainly affected the contents of alkali metals and silica.

Their petrographic properties indicate that the rocks were originally intermediate or rhyolitic. The percentage of ADR given in Fig. 10 is valid even though these rocks have been altered.

The Subalkaline Basaltic to Rhyolitic Unit at Orivesi

General description and petrography

Magnetic anomalies corresponding to those of the Subalkaline Basaltic to Rhyolitic Unit, Shoshonitic Unit and Trachytic Unit extend for tens of kilometers in the E-W direction (Geological Survey of Finland 1978, 1979, 1982). These units have thus a considerable regional significance although the Subalkaline Basaltic to Rhyolitic Unit is only 150 m thick in the profile studied.

The Subalkaline Basaltic to Rhyolitic Unit is characterized by stratified, fine-grained to lapilli-sized volcaniclastic rocks which range from basalts to rhyolites in composition (Fig. 17). The rocks are in part non-reworked pyroclastic rocks but there are also signs of redeposition (Fig. 17.a). The thinly bedded character, fine grain size, and occurrence of ripped-up mud chips and pelitic strata indicate subaqueous deposition largely in distal environments. Temporary quiescent periods in volcanic activity are also evident. In the area of samples 73—76, mafic and felsic strata alternate repeatedly and there the unit is bimodal (Fig. 17.b). In general, however, intermediate rocks are so frequent that bimodality is not pronounced.

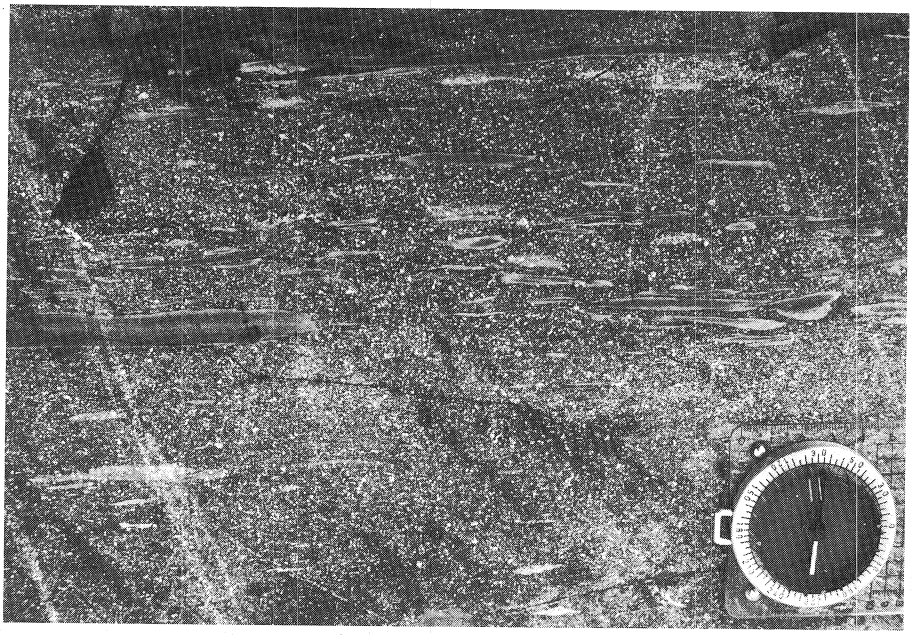
Most basalts of the Subalkaline Basaltic to Rhyolitic Unit have stratified or fragmental structures; they are tuffs, lapilli tuffs and redeposited tuffs. These mafic strata vary from 10 cm to 7 m in thickness, and the thick strata display internal bedding. The 15 m thick massive uralite-plagioclase-phyric stratum of samples 66 and 67 is out of the ordinary. The major minerals in the basalts include plagioclase (oligoclase to andesine) + quartz + hornblende ± chlorite ± epidote ± carbonate. Muscovite amounts to about 5 vol.% in sample 76. Hornblende is mostly blue-green but, in pseudomorphs after pyroxene, partly pale green. Chlorite is Fe-rich. It is cut by the non-oriented poikiloblasts of hornblende.

The intermediate rocks of the Subalkaline Basaltic to Rhyolitic Unit are tuffs, lapilli tuffs (Fig. 17.c; sample 58/82) and volcanic greywackes. Samples 79 and 80 are from massive tuffs. The strata of sample 70 (Fig. 17.d) are either crystal tuffs or volcanic greywackes. The thickness of individual strata varies from lamination to the 5—10 m thick strata of samples 79 and 80. The major minerals include plagioclase + quartz ± hornblende (in andesites only) ± chlorite (mostly Fe-rich) ± epidote ± biotite (in sample 58/82 only) ± cummingtonite (in sample 79 only). The phenocrysts and clasts of plagioclase amount up to about 15—20 vol.%. Chlorite in sample 70 is an alteration product of biotite.

The northernmost parts of the Subalkaline Basaltic to Rhyolitic Unit are dominated by rhyolitic rocks (samples 63—65 and 68) which are layered or laminated, very fine-grained, and even-grained or slightly plagioclase-phyric tuffites. The layering is partly attributed to deformation. Some laminae are rich in epidote.

In the central and southern parts of the Subalkaline Basaltic to Rhyolitic Unit, the rhyolites are partly fine-grained and laminated tuffs and tuffites but lapilli tuffs are also frequent. The fragmental structure is megascopically not distinct, but is evident under the microscope. Individual felsic strata vary from 5 cm to 5 m in thickness. The thick strata display internal bedding. The two samples with 67—69% SiO_2 (Fig. 18) are felsic enough to be considered rhyolites.

The major minerals in the rhyolites include quartz + plagioclase + potassium ± feldspar ± muscovite ± biotite ± chlorite ± rarely carbonate. The lapilli tuffs of the central and southern parts contain up to 10 vol.% small (ø < 1 mm mostly) phenocrysts of plagioclase which partly are broken crystal fragments. A few of the phenocrysts have been slightly replaced by potassium feldspar. Muscovite, and to a lesser extent carbonate, occur as small poikiloblasts.



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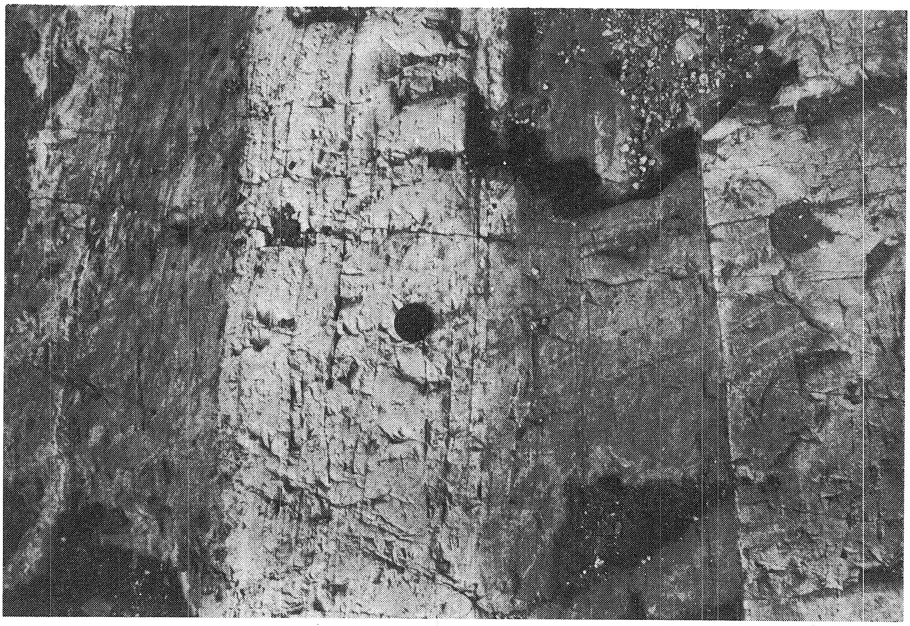
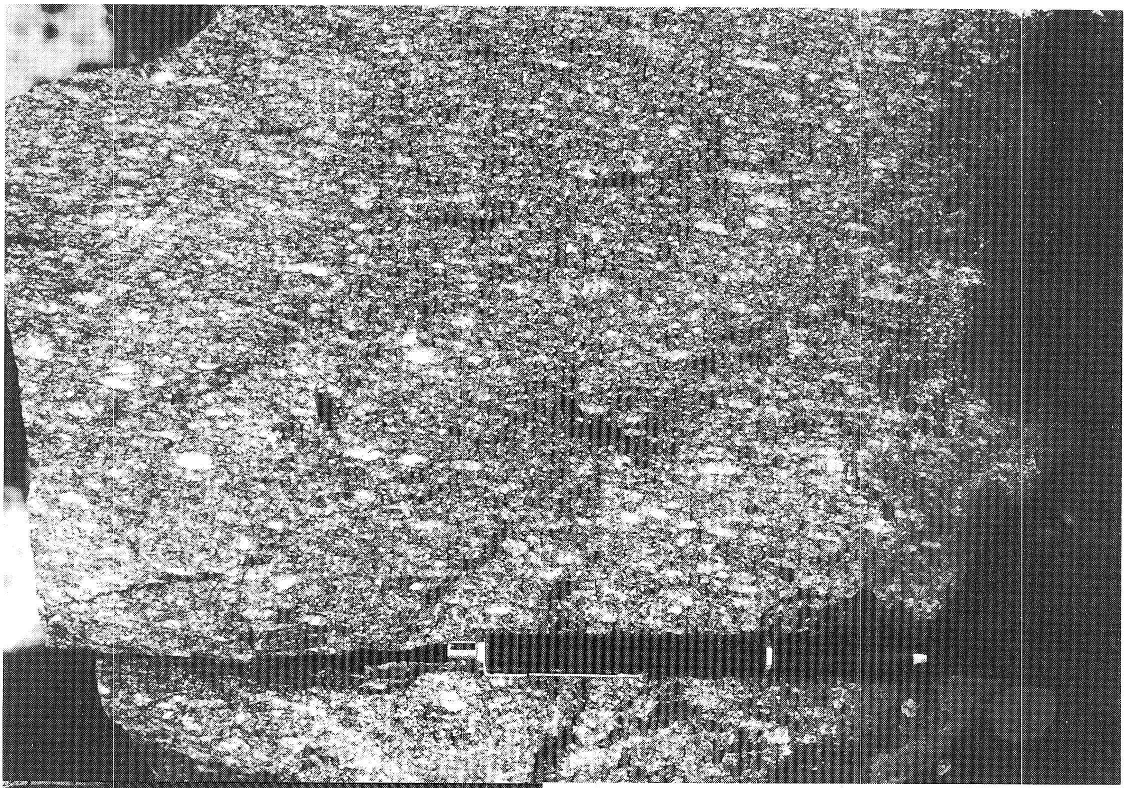
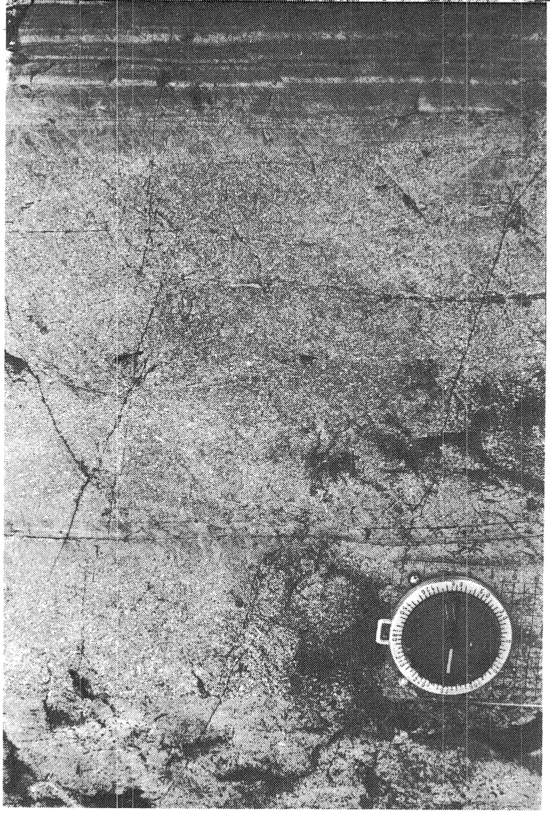


Fig. 17. Structures of the Subalkaline Basaltic to Rhyolitic Unit at Orivesi. a. Mud chips in a redeposited stratum. The area between samples 70 and 72; b. Abrupt changes from rhyolites to basalts and vice versa. Strata of samples 75 and 76 on the eastern side of highway 9, the lens cap is 6.2 cm in diameter; c. Lapilli tuff. The stratum of sample 58/82; d. Grading in crystal tuffs or volcanic greywackes, the felsic laminae are distal fallout deposits. Strata of sample 70.





Between the Subalkaline Basaltic to Rhyolitic Unit and the overlying Shoshonitic Unit occur silty and pelitic strata. This indicates temporary waning of volcanic activity.

Geochemistry

The rocks of the Subalkaline Basaltic to Rhyolitic Unit define calc-alkaline trends although the basalts and some of the andesites occur in tholeiitic fields (Fig. 18). They are high-K and medium-K rocks with one low-K andesite and one very high-K rhyolite. The rocks show more or less coherent trends such as decrease in Ca, Fe, Mg, P, Ti, V, Cr, Ni and Sr, as well as general increase in Zr, Ba and K from basalts to rhyolites (Figs. 18 and 19). In intermediate rocks Na has a maximum content, and K a minimum content. Some ranges of, for instance, K, Na, Al, Ca and Mg with an equal content of Si are wide. Some of the rocks are outside the modified igneous spectrum.

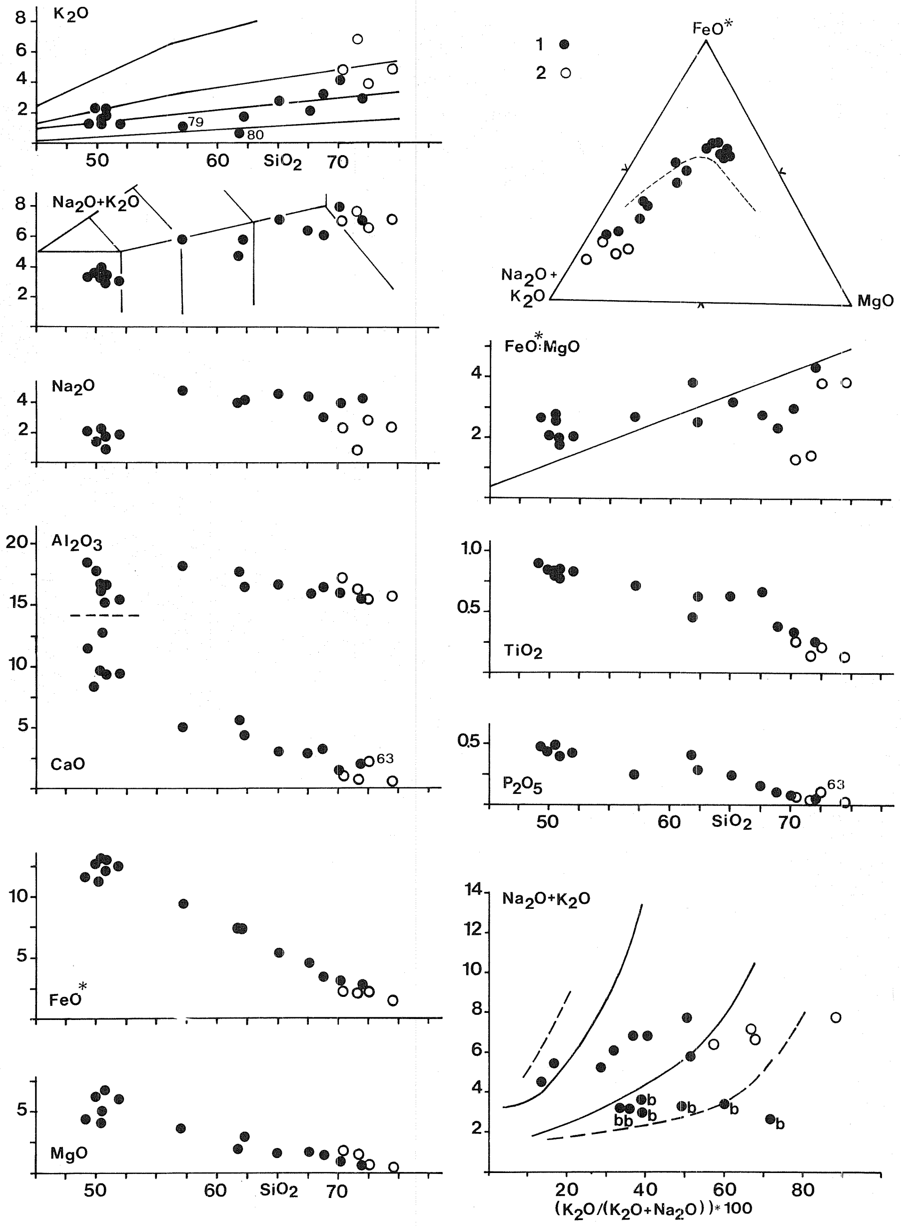


Fig. 18. Harker-type and AFM variation diagrams and igneous spectrum of the Subalkaline Basaltic to Rhyolitic Unit at Orivesi. Analyses by Outokumpu Oy. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples of the unit in general; 2. samples 63—65 and 68 (tuffites from the NE parts). b in the igneous spectrum diagram indicates basalts.

The basalts are of both medium-K and high-K types but occur mostly near the boundary of the two fields. Al_2O_3 varies between 15% and 19%. Being low in Ti the basalts resemble arc basalts. The Sr and Zr contents are similar to those in young medium-K and high-K arc basalts.

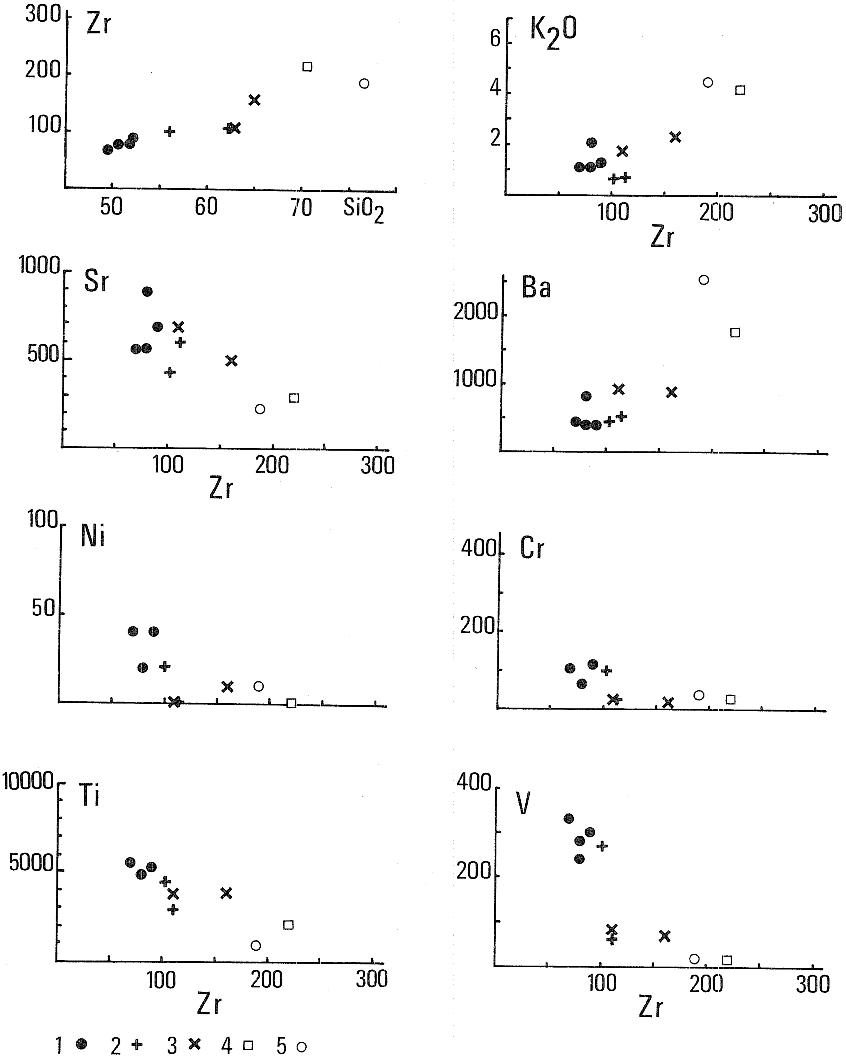


Fig. 19. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Subalkaline Basaltic to Rhyolitic Unit. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. 1. samples 67, 72, 74, 76 and 78; 2. samples 79 and 80; 3. samples 70 and 58/82; 4. sample 73; 5. sample 65.

The P_2O_5 contents resemble more the averages of high-K arc basalts than those of medium-K arc basalts (see Ewart, 1982).

Samples 66 and 67, from the thick massive stratum, are similar to the other basalts of the unit but sample 67 is slightly higher in Cr and Zr. The Cr content is attributed to minor accumulation of phenocrysts of clinopyroxene.

Sample 76 is relatively high in K, Ba and Sr and low in Na. It is the basalt occurring fairly outside the modified igneous spectrum. Alteration in this sample is petrographically indicated by the abundance of muscovite.

The andesites and dacites of the Subalkaline Basaltic to Rhyolitic Unit are mostly medium-K rocks. Samples 79 and 80 are lower in K than the basalts of the unit. They are the two which occur slightly to the left of the igneous spectrum of Hughes (1973). In thin sections, the low K contents of these rocks are indicated by the fact that biotite is only a minor constituent. The P contents are higher than those in low-K arc andesites and approach averages in high-K arc andesites, but the Zr contents are more like those in low-K andesites than those in medium-K and high-K andesites (Ewart, 1982). The data cannot be used to decide whether the low K content is primary or caused by alteration.

The rhyolites, including the two samples with 67—69% SiO_2 (p. 39), vary in alkali metal contents; they range from medium-K types to very high-K types and from 0.8 to 4.5% in Na_2O. The K_2O:Na_2O ratios are close to or in excess of unity. One of the samples is outside the modified igneous spectrum. Samples 65 and 73 have Cr and Ni contents close to those in the intermediate samples 70 and 58/82.

Secondary increase in K is not probable in the rhyolites because any pronounced sericitization was not observed. Metasomatism due to the occurrence of small poikiloblasts of muscovite is probably minor. Fine-grained muscovite, when present, follows the boundaries of laminae and indicates differences in the composition of thin strata. The laminated samples are mixtures of redeposited strata and their composition is partly a result of mixing.

Petrology

The basalts of the Subalkaline Basaltic to Rhyolitic Unit are relatively poor in Cr and Ni. Their FeO*:MgO ratios exceed unity. The basalts are not primary mantle melts but fractional crystallization of olivine + Cr-spinel ± clinopyroxene is probable (cf. Pearce, 1982).

The andesitic samples 79 and 80 are lower in K than the basalts. This indicates that they are not derived from the basalts by fractional crystallization, but the possible alteration makes definite conclusions difficult.

Samples 70 (62% SiO_2) and 58/82 (65% SiO_2) are medium-K rocks and could have been derived from the basalts of the unit. However, the difference in the Zr contents of the basalts and sample 70 is minute (Table I). Given that bulk $\bar{D}_{Zr}$ approached zero, the degree of fractionation (indicated as F) approximated from the Zr contents, and using Eq. 1 (p. 9) would be about 0.65—0.85. These are figures markedly higher than the F values of 0.4—0.2 calculated by Gill (1981) and Grove and Kinzler (1986) for deriving dacites from basalts by crystal fractionation. The derivation of sample 70 from the basalts is unlikely. Similar constraints do not concern sample 58/82, higher in Zr.

The low Sr, Ti and V contents in the rhyolites indicate fractional crystallization of plagioclase and mafic minerals. The relatively high Cr content in sample 73 could be caused by the presence of minor mafic phases rich in Cr, by open-system crystallization, or by a process of total equilibrium type (p. 9). The relatively high Cr and Ni content in sample 65 is attributed to mixing during redeposition. The laminae rich in epidote have contributed to the relatively high Ca and P content in sample 63. They indicate the deposition of thin P-bearing calcareous strata during quiescent periods in volcanic activity.

In general, the predominantly thin beds, the distal fallout laminae, and the pelites and other redeposited rocks indicate deposition in a basin between vents rather than near a vent. The massive strata of samples 66—67, 79 and 80 are less distal than the other strata. The pelitic strata indicate quiet intervals in volcanic activity, and the time of deposition of the unit was possibly long. The unit contains rocks which are not related to one another through fractional crystallization and were possibly tapped from separate vents or magma chambers. With the data available, it was only possible to group all of these rocks as a single unit.

The Shoshonitic Unit at Orivesi

General description and petrography

In the profile studied, the Shoshonitic Unit at Orivesi is about 130 m thick in the northern limb and about 80 m thick in the southern limb of the major syncline. Individual strata vary largely in thickness; internal beds in the area of sample 88 are 0.2—30 cm thick (Fig. 20.a) while the massive stratum of samples 104—106 is about 30 m thick.

The Shoshonitic Unit comprises partly indisputable pyroclastic rocks such as tuffs and tuffites (samples 81, 85, 88; Fig. 20.a), lapilli tuffs, and agglomerates or tuff breccias (samples 82, 83 and 84). The rocks are partly porphyritic with both massive (samples 104—106, 109) and fragmental structures (Fig. 20.b). The matrix of the fragmental rocks is partly laminated. Samples 89, 90, 107 (from porphyritic fragments) and 108 (from fine-grained matrix near sample 107) represent the fragmental type. The non-fragmental porphyritic stratum of sample 87 shows patchy variations in the proportion of mafic minerals. The porphyritic rocks are originally lava flows or ash flow tuffs. The laminated matrix represents tuffs and tuffites ripped up by the flows.

Sample 86 resembles the rocks of the overlying Trachytic Unit. It is discussed on pp. 50—53.

The major minerals in the Shoshonitic Unit include plagioclase (mostly albite/oligoclase) + quartz ± biotite (only a minor constituent in sample 87) ± epidote ± hornblende (generally blue-green) ± chlorite (mostly Mg-rich). Pseudomorphs after phenocrysts of plagioclase amount up to 25—30 vol.% in the porphyritic rocks and are mostly <3 mm in diameter. They are often clear but also those rich in epidote are frequent. This may indicate variations in the composition of the original phenocrysts. Pseudomorphs after phenocrysts of pyroxene amount up to about 10 vol.%, and their diameter is characteristically 0.2—2 mm. Besides hornblende, they often contain chlorite and epidote. A few mafic aggregates seem to be pseudomorphs after hornblende. Sample 109 contains about 10 vol.% biotite aggregates many of which are probably pseudomorphs after phenocrystic mica (Fig. 20.c). Similar aggregates, though less frequent, were observed in samples 88, 90 and 107. The porphyritic rocks often contain poorly discernible microscopic fine-grained fragments.

Geochemistry

The Shoshonitic Unit is characterized by very high-K basaltic trachyandesites and trachyandesites (Fig. 21). The K_2O:Na_2O ratios are near unity, and the rocks are within the modified igneous spectrum. The K content tends to decrease with the increasing Si content. Samples 84 and 87 fall below the general K_2O-SiO_2 trend and are medium-K basaltic andesites. This may be attributed to the heterogeneous character of these strata. The FeO*:MgO ratios are largely constant. The TiO_2 contents are less than 1.0%. The Fe and Ti contents decrease with the increasing Si content, but the trends for Mg and Ca are less coherent. The Al_2O_3 content ranges mostly between 14% and 18%, and the P_2O_5 content between 0.3% and 0.6%; both elements display a slight but dispersed decrease with increasing Si. Like K, also Zr decreases with increasing Si (Fig. 22). The K content increases with the increasing Zr content, but the Ba-Zr and Sr-Zr trends are dispersed. The Ti content increases with the increasing Zr content while the V-Zr trend is horizontal. The generalized Ni-Zr and Cr-Zr trends tend to be steeply descending.

The rocks of the Shoshonitic Unit resemble shoshonites of Recent volcanic arcs in being high in K, Sr and Zr, low in Ti, and in having K_2O:Na_2O ratios close to unity (Morrison, 1980; Baker, 1982; Ewart, 1982; Pearce, 1982). In addition, the low FeO*:MgO ratios indicate similarities. A difference is caused by the descending

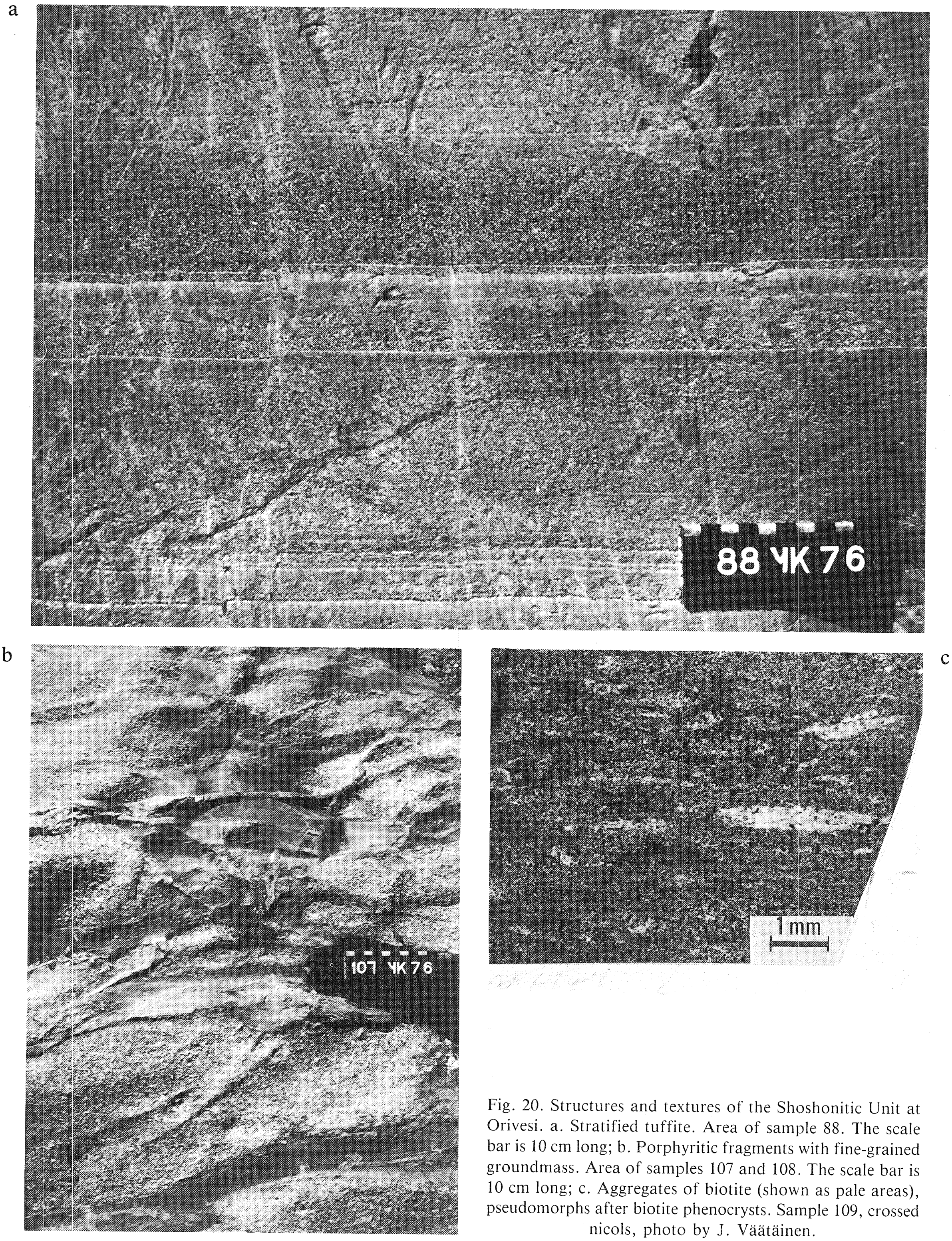


Fig. 20. Structures and textures of the Shoshonitic Unit at Orivesi. a. Stratified tuffite. Area of sample 88. The scale bar is 10 cm long; b. Porphyritic fragments with fine-grained groundmass. Area of samples 107 and 108. The scale bar is 10 cm long; c. Aggregates of biotite (shown as pale areas), pseudomorphs after biotite phenocrysts. Sample 109, crossed nicols, photo by J. Väätäinen.

K_2O-SiO_2 and Zr-SiO_2 trends because these trends are mostly rising in young shoshonites. However, horizontal or descending K_2O-SiO_2 trends are known in young and ancient shoshonitic associations (Jakeš & Smith, 1970; Déruelle, 1978; Brooks *et al.*, 1982). The P_2O_5 content is somewhat lower than the P_2O_5 averages in young shoshonitic basalts typically, but not lower than those in Mediterranean shoshonitic basaltic andesites (see Ewart, 1982). Similarities are also observed in phenocrysts; certain biotite aggregates are pseudomorphs after phenocrysts of mica (Fig. 20.c) and the presence of epidote in the pyroxene pseudomorphs indicates that clinopyroxene was partly rich in Ca and Al. Clinopyroxenes in shoshonites are relatively rich in Ca (Morrison, 1980) and clinopyroxenes in Vulsinian tephritic leucitites contain up to 13% Al_2O_3 (Barton *et al.,* 1982).

The geochemistry of the Shoshonitic Unit is well reflected by mineral composition. The high K contents are indications of biotite occuring frequently as a major phase. This is corroborated by the medium-K sample 87 which contains biotite only as a minor constituent. The relatively high Na contents are attributed to the presence of albitic-oligoclasic plagioclase. Considering also the oligoclase-andesine plagioclase in the mafic rocks of the Subalkaline Basaltic to Rhyolitic Unit, the composition of plagioclase is not controlled by only metamorphic grade, but the total chemical composition was also influential. The low FeO*:MgO ratios and the high Cr and Ni contents are attributed partly to the Mg-rich chlorite. These features must be partly attributed to the composition of the other mafic minerals because chlorite is absent in sample 88 high in Cr and Ni.

The properties of the Shoshonitic Unit can be observed more clearly when they are compared with those in the mafic rocks of the Subalkaline Basaltic to Rhyolitic Unit. The latter rocks are medium-K and high-K basalts with relatively low Na and Ca contents and high FeO*:MgO ratios; they have biotite only as a minor constituent, and contain Fe-rich chlorite and oligoclase/andesine. A fundamental difference between the mafic rocks of the two units is shown by Cr, Ni and Zr; the Cr and Ni contents in the Shoshonitic Unit tend to be higher than those in the basalts of the Subalkaline Basaltic to Rhyolitic Unit, even though the latter are lower in Zr.

Petrographic signs of secondary increase in K, such as sericitization and replacement by potassium feldspar, are not shown by the rocks of the Shoshonitic Unit. Because Zr is a less mobile element than K, the correlation between K_2O and Zr is difficult to explain by compositional changes. Furthermore, Cr and Ni are relatively immobile elements. For these reasons the high K, Sr, Zr, Cr and Ni contents largely reflect the original composition of magmas.

Sample 108 (47.5% SiO_2) is from the matrix of porphyritic fragments and might have been altered more readily than the rocks from the fragments. The K_2O-SiO_2 and Zr-SiO_2 trends could thus be attributed partly to alteration, but the trends are indisputable even if sample 108 is ignored. Sample 107, from a porphyritic fragment, is the one second to highest in Zr and second to lowest in SiO_2 in Fig. 22. Therefore, alteration in matrix cannot alone explain the Zr-SiO_2 and K_2O-SiO_2 trends. The K_2O-SiO_2 and Zr-SiO_2 trends of the Shoshonitic Unit are probably primary features.

The trachyandesite near Lake Mastosjärvi, Ylöjärvi, underlies stratigraphically the Veittijärvi conglomerate. It is a very high-K rock and resembles the rocks of the Shoshonitic Unit in chemical composition (Fig. 21).

Petrology

The Ni and Cr contents in the Shoshonitic Unit are mostly lower, and the FeO*:MgO ratios higher than those in primary mantle melts (Basaltic Volcanism Study Project, 1981; Pearce, 1982). This indicates fractional crystallization of olivine + Cr-spinel ± pyroxene. The high Cr and Ni contents in some of the rocks indicate that the

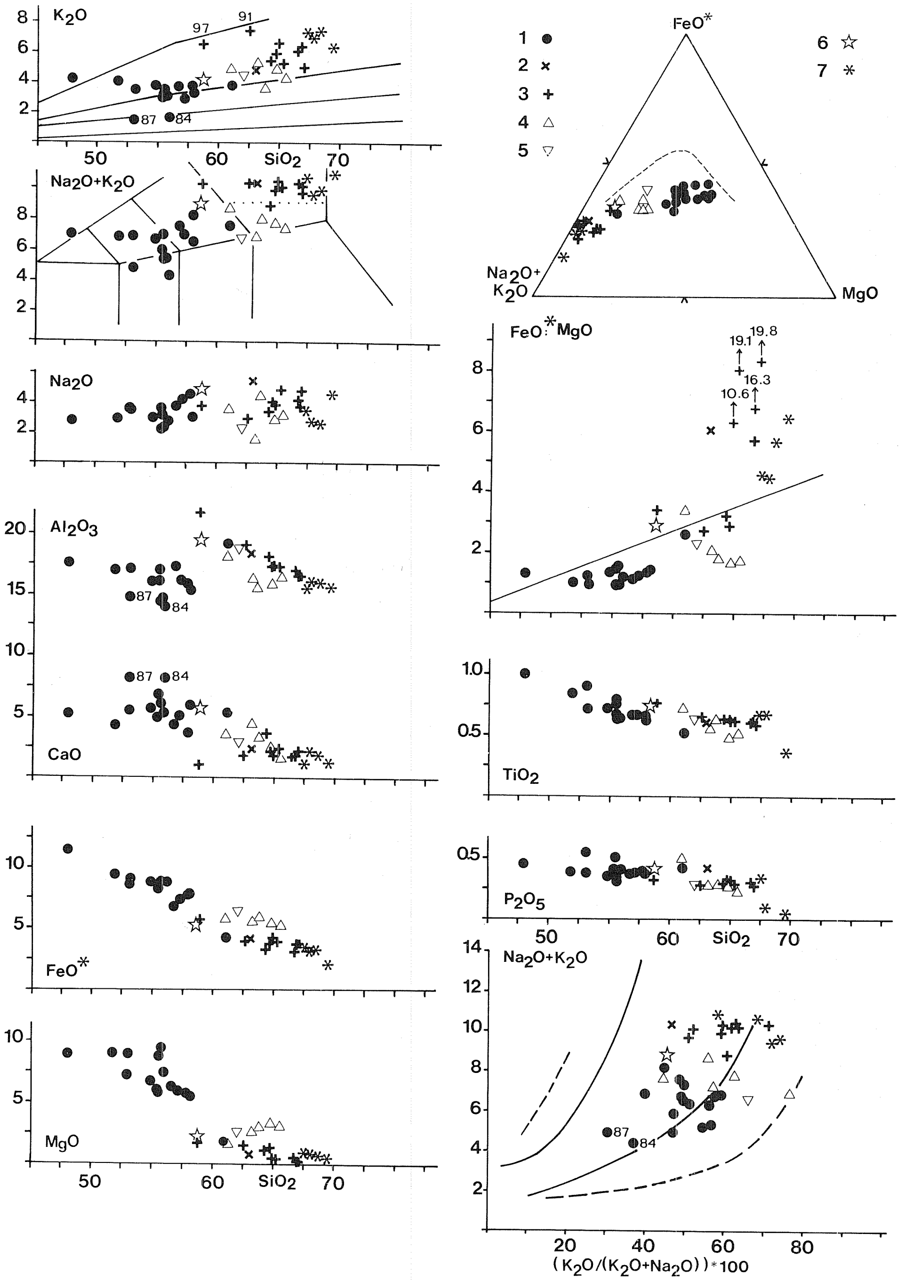


Fig. 21. Harker-type and AFM variation diagrams and igneous spectrum of the Shoshonitic Unit, Trachytic Unit and the overlying sedimentary rocks at Orivesi. Some earlier analyses on very high-K volcanics from the Tampere Schist Belt are included. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 81—85, 87—90 and 104—109 of the Shoshonitic Unit; 2. sample 86 from the area of the Shoshonitic Unit; 3. samples 91—97, 102 and 103 of the Trachytic Unit; 4. samples 98—101 and 293 from the overlying conglomerates; 5. sample 294 from the overlying pelites; 6. a trachyandesite near Mastosjärvi, Ylöjärvi (analysis 29 in Table IV of Simonen, 1953a); 7. K-rich felsic porphyries from Valkeajärvi, 1—2 km west of the highway 9 profile (analysis 2 in Table I of Seitsaari, 1951), from Lielahti, Tervakivi and north of Vaavujärvi (analyses 38—40 in Table IV of Simonen, 1953a).

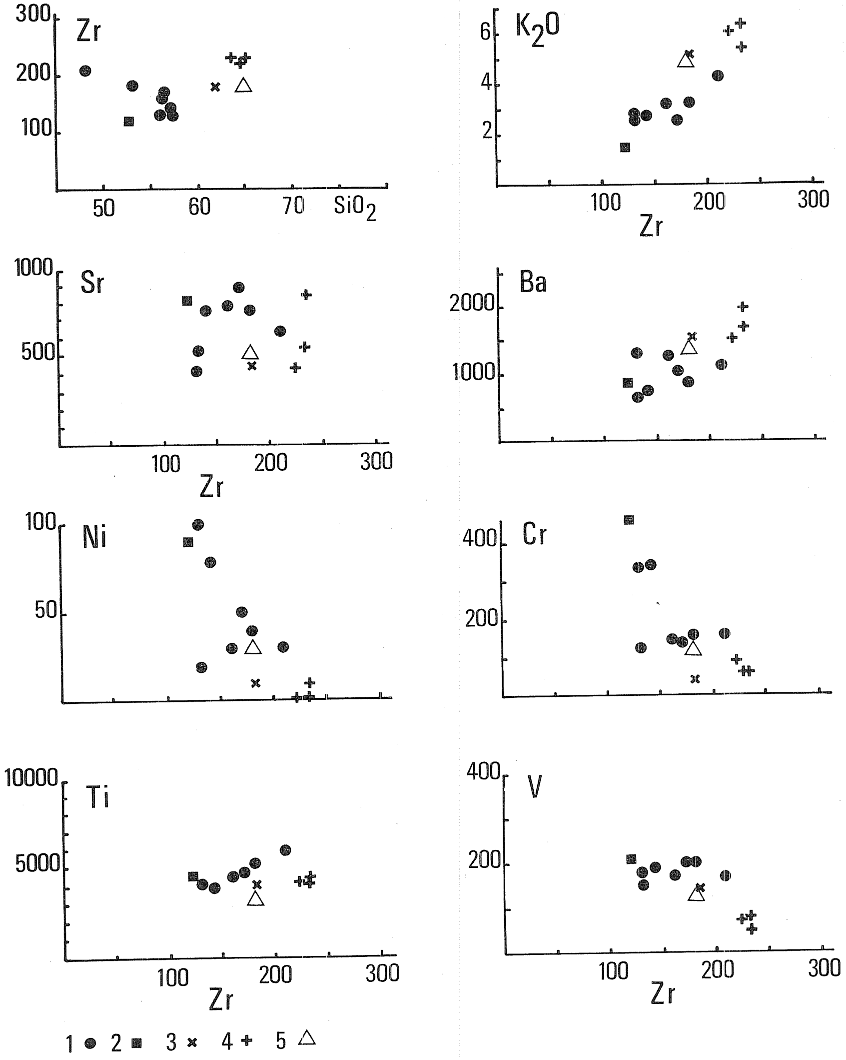


Fig. 22. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Shoshonitic Unit, Trachytic Unit and overlying sedimentary rocks at Orivesi. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. 1. samples 81, 88, 90, 104 and 107—109 of the Shoshonitic Unit; 2. medium-K sample 87 of the Shoshonitic Unit; 3. trachytic sample 86 from the area of the Shoshonitic Unit; 4. samples 94, 95 and 103 of the Trachytic Unit; 5. sample 98 from the conglomerates overlying the Trachytic Unit.

degree of fractionation was not always high. Fractional crystallization of olivine cannot, however, explain the descending K_2O-SiO_2 and Zr-SiO_2 trends or the constant FeO*:MgO ratios.

The original phenocrysts in the Shoshonitic Unit contain plagioclase, clinopyroxene, hornblende and mica. Fractional crystallization of this assemblage yields descending K_2O-SiO_2 trends presuming that the proportion of mica is great enough. Given that D_K^{bt} was 2.7 (Cox *et al.*, 1979) the amount of biotite in the assemblage should have exceeded 30—40%. This figure is considerably greater than the petrographically approximated amount of biotite in the phenocrystic assemblage of the Shoshonitic Unit. In mafic and intermediate melts, D^{bt}_{Zr} is about 1.2, while D^{cpx}_{Zr}, D^{plg}_{Zr} and D^{hbl}_{Zr} are below unity (Pearce & Norry, 1979; Luhr & Garmichael 1980; Gill, 1981). Thus the bulk $\overline{D}_{Zr}$ of the assemblage should have been below unity and, consequently, the Zr-SiO_2 trend should slope risingly. The descending K_2O-SiO_2 and Zr-SiO_2 trends of the Shoshonitic Unit were probably not produced by fractional crystallization of the phenocrystic assemblage observed.

Fractional crystallization of dry basaltic magma at pressures of 10—15 kb enrichs the residual liquid in K, while Si may rise, be constant, or fall during continued crystallization (Meen, 1987a). This explanation is not warranted because the K_2O-SiO_2 trends shown by Meen (1987b) are much steeper than those of the Shoshonitic Unit.

The fluids causing metasomatism and enrichment of LIL elements in the mantle are poorly known (Gill, 1981). The K_2O-SiO_2 and Zr-SiO_2 trends might be caused by the fluids, but probably the fluids were rich in both K and Si.

The K_2O-SiO_2 and Zr-SiO_2 trends may be explained by the mixing of very high-K trachybasalts or basaltic trachyandesites with high-K intermediate magmas. Magma mixing might explain the variation in the composition of pyroxene and plagioclase phenocrysts. Assimilation of pre-existing crust low enough in K and Zr by trachybasalts might be another possibility. The pooled I_{Sr} ratio of the Shoshonitic Unit and the Trachytic Unit is so low (Aro, 1983; Kähkönen, *et al.*, in press) that the possible assimilated material did not comprise Archaean crust.

The Trachytic Unit at Orivesi

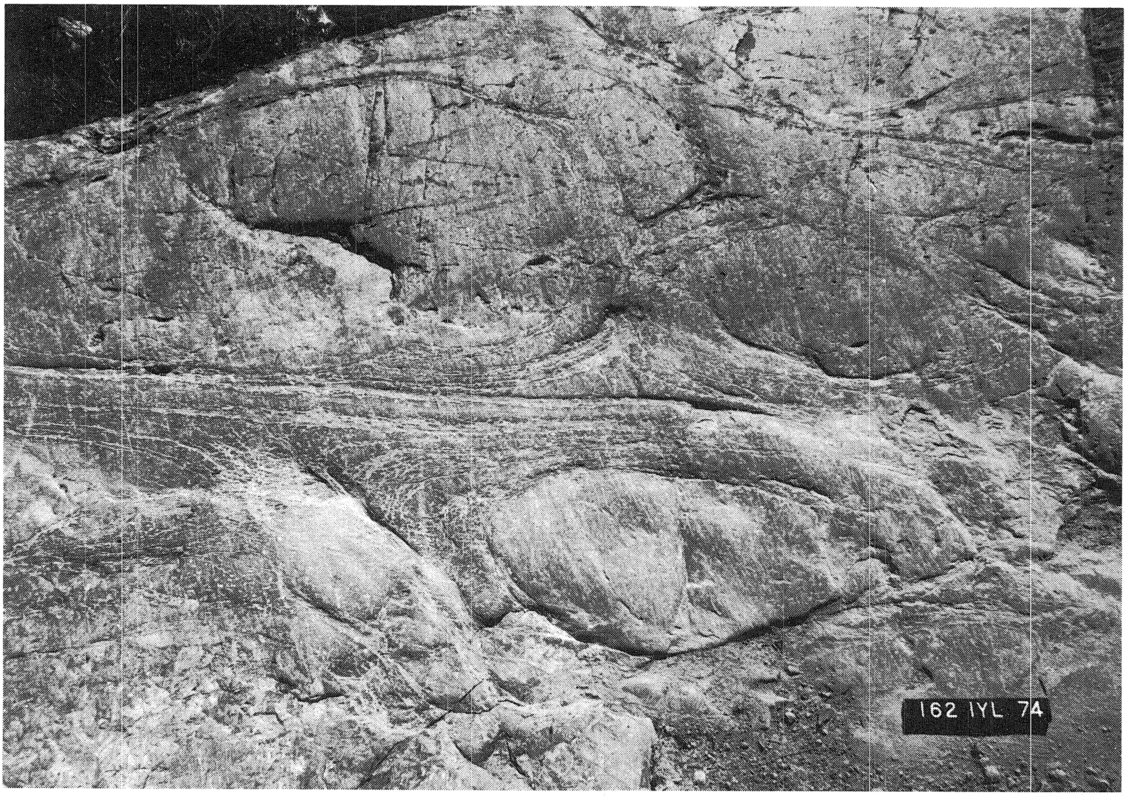
General description and petrography

The Trachytic Unit is about 100 m thick in the northern limb and about 10 m thick in the southern limb of the major syncline near highway 9. The Trachytic Unit, known by Seitsaari (1951) as feldspar porphyry, extends for 10—11 km in an E-W direction. This, and the long magnetic anomalies corresponding to those of the Trachytic Unit, Shoshonitic Unit and Subalkaline Basaltic to Rhyolitic Unit (p. 39) indicate a considerable areal extent for this unit also.

The rocks of the Trachytic Unit are pink and feldspar-phyric. They often have a pillow-like structure (Fig. 23.a) which is thought to be a result of primary flow. Sample 97 is from the matrix of large fragments while the other samples are from fragments. The rocks display microscopic fragmentation visible as variations in grain size, texture and mode of major minerals such that in places the rocks resemble ignimbrites (Fig. 23.b). The unit contains a few polymictic interbeds which indicate variation in the character of activity or temporary sedimentary reworking.

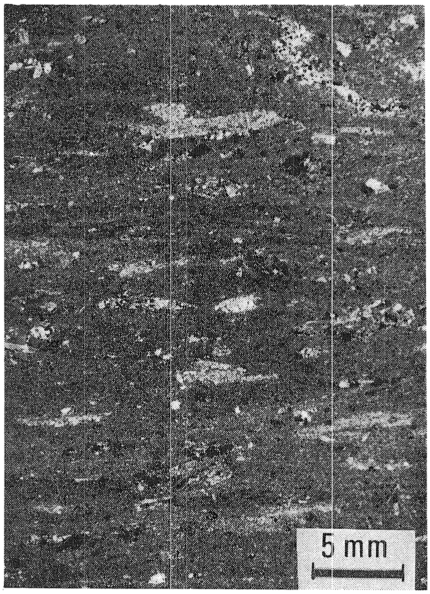
The rocks of the Trachytic Unit contain plagioclase (oligoclase/albite) + quartz + potassium feldspar ± biotite ± muscovite as major minerals. Besides these, oxide minerals (often about 5 vol.%) and sometimes epidote are abundant. The rocks are mostly porphyritic with phenocrysts of oligoclase (ø up to 4 mm) amounting to 5—10 vol.%. In certain samples, some of the phenocrysts are composed of potassium feldspar. Signs of metasomatism, such as elongated aggregates or veinlets of quartz ± potassium feldspar, were observed in the sheared sample 91. However, the texturally well-preserved sample 94 displays no replacement of oligoclase phenocrysts.

Sample 86, from a 5 m thick stratum within the Shoshonitic Unit, resembles the rocks of the Trachytic Unit in chemical and mineral composition. The massive pyroclastic stratum comprises



a

Fig. 23. Structures and textures of the Trachytic Unit at Orivesi. a. Pillow-like structure of the feldspar-phyric trachytes. The area of sample 96. The scale bar is 12 cm long. Photo by I. Laitakari; b. Variation in grain size in an ignimbrite. Sample 103, crossed nicols. Photo by J. Väätäinen.



b

lapilli-sized fragments. The oligoclase phenocrysts are often broken fragments of larger grains.

The stratum of sample 86 indicates that at Orivesi there are trachytes at more than one stratigraphic level. This conception is supported by the presence of pink feldspar-phyric pebbles in a volcanic conglomerate stratigraphically below the Shoshonitic Unit in the southern limb of the syncline.

Geochemistry

The rocks of the Trachytic Unit are mostly very high-K trachytes (Fig. 21). The $K_2O:Na_2O$ ratios are near unity, and most of the rocks occur in the igneous spectrum. The FeO*:MgO ratios vary greatly and are often high. The decrease in the Al, Fe, Mg, Ti and P content with the increasing Si content is evident. The three samples analyzed for trace elements display narrow ranges for most trace elements but the variation in Sr is wide (Fig. 22).

Sample 86, from a stratum within the Shoshonitic Unit, is similar to the typical rocks of the Trachytic Unit in most elements but is slightly lower in Zr and Si, and higher in P and V.

The chemical properties of the Trachytic Unit are largely primary because the rocks, in general, do not show signs of significant compositional changes. Sample 91 is a sheared rock and contains elongated aggregates or veinlets of quartz ± potassium feldspar (p. 50). Its high K_2O content is attributed to metasomatism. The low Si and Ca content in sample 97 is possibly caused by compositional changes in the matrix of fragments. The characteristics and the major element trends described above, however, are evident even if samples 91 and 97 are ignored.

The high alkali metal contents in the Trachytic Unit reflect mainly the abundance of feldspars. The high FeO*:MgO ratios are attributed to oxide minerals which often amount to 5 vol.%.

Fig. 21 also shows felsic porphyries from other parts of the Tampere belt. They are relatively silicic rocks. The most silicic one is from the Trachytic Unit 1—2 km W of the profile now studied. Except being higher in Si, it is similar to the rocks of the Trachytic Unit. The other three samples are from stratigraphically lower strata. They, too, resemble the rocks of the Trachytic Unit.

The rocks of the Trachytic Unit are similar to the potassic trachytes of Ewart (1979) but their Zr content tends to be lower and Cr content higher than the averages in the latter trachytes. In young volcanic arcs, very high-K rocks with SiO_2 in excess of 60% have mostly low FeO*:MgO ratios, but a few trachytes-latites with high FeO*:MgO ratios are known (Ewart, 1979, 1982; Morrison, 1980; Baker, 1982; see also analyses in Joplin, 1965, 1968; Nicholls & Carmichael, 1969; Joplin *et al.*, 1972; Colley & Warden, 1974; Heming, 1979). Alkaline rocks with high FeO*:MgO ratios and resembling the Trachytic Unit are rare but not absent in young volcanic arcs. The Zr contents less than 300 ppm cause the Trachytic Unit to show arc affinities in the Ti-Zr diagram of Pearce (1982). In having high FeO*:MgO ratios, high alkali metal contents and $K_2O:Na_2O$ ratios near unity, the Trachytic Unit also shows similarities to the granitoid complex of central Finland (Front & Nurmi, 1987). The Trachytic Unit resembles in these contexts even A-type granitoids (Anderson, 1983) but the unit is lower in Si and higher in Al. Certain syenites associated with A-type granites have SiO_2 contents of 60—65% and Al_2O_3 contents up to 17—18%, but they have Zr contents exceeding 400 ppm and Sr contents below about 150 ppm (Whalen *et al.*, 1987).

Petrology

The Trachytic Unit is related to the Shoshonitic Unit in place and time. The two units have high alkali metal contents and $K_2O:Na_2O$ ratios close to unity. They, however, are not related to each other by the same process because the Trachytic Unit has higher K, Ti and Zr contents than the K_2O-SiO_2, TiO_2-SiO_2 and Zr-SiO_2 trends of the Shoshonitic Unit would suggest. The differences in the FeO*:MgO ratios are also noteworthy. Furthermore, if sample 86 is included to the Trachytic Unit, the Zr-SiO_2, K_2O-Zr and Ti-Zr trends do not indicate a common origin.

Dry melting of mafic rocks yields trachytic liquids when the degree of fusion is low (Green, 1982), and the melts tend to show iron-enrichment (Green & Ringwood, 1968; Stern & Wyllie, 1978). Thus the Trachytic Unit might imply dry conditions during melting. This is supported by the similarities with A-type granitoids also interpreted to result from dry melting. When compared with A-type granitoids, higher degrees of melting or less silicic sources are implied. The relatively high Sr content in the Trachytic Unit might indicate the absence of plagioclase in the solid residue.

The sedimentary rocks overlying the Trachytic Unit at Orivesi

General description and petrography

The Trachytic Unit changes upwards first to clast-supported polymictic volcanic conglomerates. Pebbles similar to the rocks of the Trachytic Unit are present (Fig. 24), but those from other intermediate volcanic sources dominate. Upwards in the sequence, the pebbles decrease in size and amount while the matrix and finer-grained interbeds increase until the rocks are graded pelites-siltstones (Fig. 6.c). Samples 98—101 and 293 are from conglomerates and sample 294 represents the mudstones.

Geochemistry and petrology

The samples from the sedimentary rocks overlying the Trachytic Unit are mostly very high-K or high-K dacites and trachydacites (Fig. 21). A few occur outside the igneous spectrum of Hughes (1973) but are within the modified igneous spectrum. Calc-alkaline affinities are evident because of the low FeO*:MgO ratios. The pelitic sample 294 is similar to the conglomerate samples in composition, and pronounced weathering is not probable.

The conglomerates contain pebbles resembling

Fig. 24. Feldspar-phyric trachyte pebble in the volcanic conglomerate overlying the Trachytic Unit at Orivesi. The area of sample 101. The scale bar is 10 cm long.

the rocks of the Trachytic Unit, but the samples analyzed are distinguished from the latter because they are frequently lower in K, Na, Al and Ti, as well as higher in Fe and Mg at equal SiO_2. From the Shoshonitic Unit they differ in being more silicic and in having higher K and Zr contents than those suggested by the K_2O-SiO_2, Zr-SiO_2 and K_2O-Zr trends of the Shoshonitic Unit.

The southern limb of the major syncline at Orivesi

General description and petrography

The southern limb of the major syncline at Orivesi is dominated by greywackes-mudstones but there also occur volcanic strata. The rocks considered in this section lie high in the sequence of the southern limb, but below the Shoshonitic Unit (Figs. 4 and 7). On the basis of magnetic maps (Geological Survey of Finland, 1978, 1979, 1982), they more resemble the Shoshonitic Unit and the Subalkaline Basaltic to Rhyolitic Unit than the Intermediate Unit. The interpretation of these rocks is inadequate because the outcrops studied are less frequent than those in the northern limb. The samples comprise both volcanic and sedimentary rocks. Volcanic provenances for the sedimentary rocks are evident.

The rocks analyzed from the southern limb range between 53% and 73% in SiO_2 content. They contain up to 20 vol.% phenocrysts of plagioclase. Samples 112 and 113 are petrographically similar to the porphyritic rocks of the Shoshonitic Unit. Sample 117 is from a relatively homogeneous plagioclase-phyric stratum. Rocks resembling it are common east and west of the area now discussed. Sample 114 is a volcanogenic greywacke with rock fragments in a matrix rich in epidote; both plagioclase-phyric and even-grained clasts were observed. The rhyolites are layered or laminated, even-grained or slightly plagioclase-phyric tuffs or tuffites.

Geochemistry and petrology

The samples analyzed from the southern limb form a heterogeneous group. They range from medium-K to very high-K types and from subalkaline to alkaline rocks (Fig. 25). The FeO*:MgO ratios are mostly low but are high in two rhyolites. The rocks are mostly in the igneous spectrum of Hughes (1973). The rhyolites are high-K rocks with K_2O:Na_2O ratios close to or in excess of unity.

Samples 112 and 113 are very high-K basaltic trachyandesites with low FeO*:MgO ratios and high Cr and Ni contents (Table I). Thus they are like the rocks of the Shoshonitic Unit. This indicates that there are in addition to trachytes (p. 51) shoshonites in more than one stratigraphic horizon.

Sample 114, a high-K greywacke, has low Fe and Mg contents for a rock with about 54% SiO_2, and its Al_2O_3 content is high. The composition is attributed to the matrix rich in epidote and biotite, i.e. the matrix was originally a calcareous pelite.

The rocks containing 62—64% SiO_2 often occur near the medium-K/high-K boundary. They probably do not represent the provenances of the sedimentary rocks overlying the Trachytic Unit.

The Vaavujärvi sill

General description and petrography

The Vaavujärvi sill is about 400 m thick at maximum and can be traced for about 6 km in a WSW-ENE direction (Seitsaari, 1951). Because the younging directions south and north of the

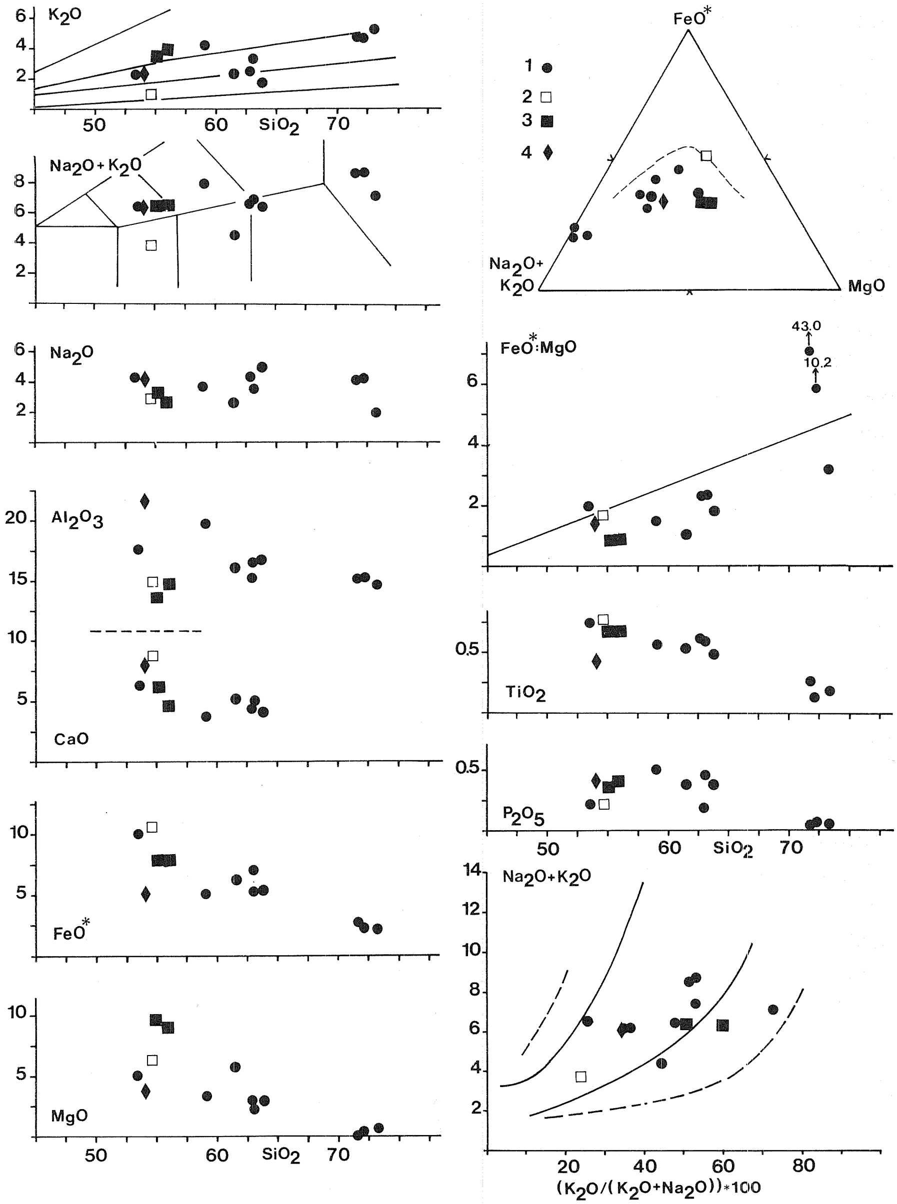


Fig. 25. Harker-type and AFM variation diagrams and igneous spectrum of the rocks in the southern limb of the syncline at Orivesi. Oxides in weight%. FeO^*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 110, 111, 115, 116 and 118—122; 2. sample 117; 3. samples 112 and 113; 4. sample 114.

sill are both northerly (Fig. 5; observations by the author), the thickness is not caused by folding. Instead, volcanic doming may have produced a thick sill.

The major parts of the sill are composed of massive rocks (samples 2/82 and 5—8/82) with abundant phenocrysts of oligoclase (30—50 vol.%; ø up to 7 mm, mostly 1—3 mm). Pseudomorphs after phenocrysts of pyroxene and hornblende both amount up to 5—10 vol.%. The rocks are massive but darkish inclusions do occur. The groundmass is granoblastic, more or less oriented, and relatively coarse-grained. There is a small percentage of quartz-rich pressure shadows, veinlets and aggregates. The major minerals include albite/oligoclase + quartz + biotite ± hornblende ± epidote. Potassium feldspar amounts to about 5 vol.% in some samples.

In the northern and southern margins of the sill there exist fine-grained contact zones, a few m thick (samples 3—4/82). These rocks display a well-preserved pilotaxitic texture with an abundance of oriented albite laths (p. 15 in Seitsaari, 1951). Plagioclase phenocrysts (ø up to 2.5 mm) amount to 10—20 vol.%. They are albitic but in places rich in epidote; apparently the primary An contents were partly high. A few aggregates of biotite and hornblende are, because of their form, pseudomorphs after phenocrysts of amphibole. Some accumulations of hornblende + carbonate + biotite, and of epidote + quartz are amygdules. The major minerals include albite + biotite + hornblende ± epidote ± quartz.

Sample 1/82 is a plagioclase-phyric volcaniclastic rock from the area south of, and stratigraphically below, the sill. In addition to the mineral grains (about 30 vol.%), there are fine-grained rock fragments.

Geochemistry and petrology

The rocks of the Vaavujärvi sill are mostly high-K trachyandesites (Fig. 26). The samples from the contact zones are higher in Na, Al, Fe, Ti and P but, even though lower in Si, also lower in Mg than the samples from the major parts. The FeO*:MgO vs. SiO_2 trend is descending. The Zr, Ba, Sr and Cr contents are lower in sample 3/82, which represents the contact zones, than in sample 7/82 from the major parts (Table I). The sample described by Seitsaari (1951) from the northern contact zone is similar to the two samples of the contact zones analyzed here.

The K_2O content varies in the major parts of the sill between 2.3% and 3.2%. A petrographic study indicates that the dispersion is not caused by sericitization or replacement by potassium feldspar, but by the variation in the abundance of biotite occurring partly as aggregates of unknown origin.

The increases in the Mg, Cr and Sr contents, as well as the abrupt decrease in the Na content and the FeO*:MgO ratio with the increasing Si and Zr contents are peculiar features which cannot be attributed to fractional crystallization or partial melting. Various factors can be considered as the reason. The high Na content in the contact zones is petrographically visible as abundant albite. Reactions with water or wet sediments probably caused alteration. An associated decrease in Mg is possible because Na-enriched volcanic rocks may be either enriched or depleted in Mg (Lagerblad & Gorbatschev, 1985). The alteration might also have affected the contents of Sr and Ca. In the major parts of the sill, accumulation of plagioclase, pyroxene and hornblende phenocrysts and mafic aggregates may have contributed to the Ca, Sr, Mg and Cr contents. The presence of quartz-rich pressure shadows, veinlets and aggregates indicates silicification in the major parts.

Sample 1/82, a volcaniclastic rock south of the sill, is a high-K dacite of calc-alkaline fields. Together with the Vaavujärvi sill this sample indicates that high-K intermediate rocks are common in the southern limb near Lake Vaavujärvi.

The Kämmenniemi area

General petrography and description

The strata in the Kämmenniemi area form an anticline north of the hinge zone of the major syncline (Fig. 5). The relatively open folding with subhorizontal fold axes and subvertical axial

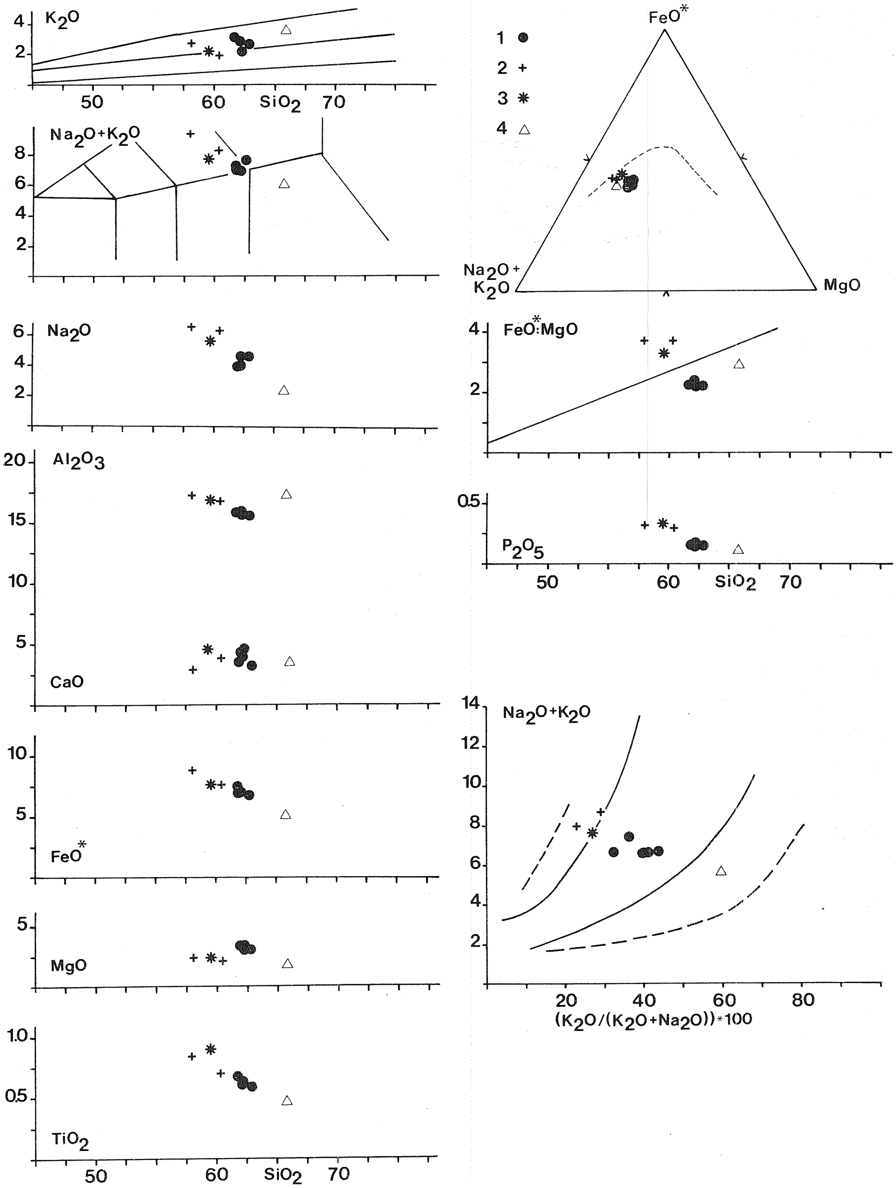


Fig. 26. Harker-type and AFM variation diagrams and igneous spectrum of the Vaavujärvi sill and of a volcaniclastic rock nearby. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 2/82 and 5—8/82 from the major parts of the sill; 2. samples 3—4/82 from the contact zones; 3. a sample from the northern contact zone (analysis 1 in Table I of Seitsaari, 1951); 4. sample 1/82, a volcaniclastic rock from the strata south of the sill.

planes is visible in the road cutting south of the new bridge over the strait Aunessillansalmi (Fig. 6). The area is dominated by intermediate and felsic rocks of both volcanic and sedimentary origin.

The dacitic and trachydacitic rocks display stratified, massive and fragmental structures. Massive and fragmental rocks dominate, although in the road cutting stratified rocks are common. Plagioclase phenocrysts or clasts (ø < 1 mm) amount characteristically to 10—20 vol.%. They have been replaced by potassium feldspar to some degree in certain samples. The major minerals include quartz + plagioclase ± potassium feldspar ± biotite ± chlorite ± muscovite. The stratified rocks are mostly volcanogenic greywackes or siltstones. The massive rocks contain up to 30—40 vol.% large (ø to 5 mm) phenocrysts of plagioclase, as well as pseudomorphs after phenocrysts of quartz and hornblende. They may in part be subvolcanic. The fragmental rocks are partly of pyroclastic origin, but the fragmental structures are partly caused by deformation of stratified rocks.

The rhyolitic rocks are mostly even-grained laminated tuffs or tuffites.

Mafic rocks amount to < 5 vol.% in the area studied at Kämmenniemi. Their abundance is exaggerated in the data of this study. However, the percentage of ADR given in Fig. 10 is valid even though these rocks are included to the data. They occur as narrow interbeds among more silicic rocks. Stratified tuffs or tuffites dominate but sample 31/82 is from a fragmental rock. The stratified basaltic andesites are mostly even-grained, but some contain phenocrysts of plagioclase (up to 20—30 vol.%; ø up to 1.5 mm) and rare pseudomorphs after pyroxene. The major minerals include oligoclase/andesine + quartz + hornblende ± chlorite ± biotite ± sericite (in sample 15/82).

Geochemistry and petrology

The Kämmenniemi area is dominated by calc-alkaline high-K rocks (Fig. 27). Most of the rocks occur in the igneous spectrum of Hughes (1973) and, in general, extensive changes in composition are not evident. The K_2O:Na_2O ratios in felsic rocks are mostly close to or in excess of unity.

Samples 30/82 and 31/82 are relatively low in K. The latter sample (with about 53% SiO_2) is also a deviating basaltic andesite in being low in Al and showing fragmental structure. The other samples display rather coherent groupings on most variation diagrams, but Na is dispersed.

The basaltic andesites have low TiO_2 contents of 0.7—1%. The P content (about 0.2% P_2O_5) is lower than in young high-K basaltic andesites of volcanic arcs on an average (Ewart, 1982). The P content tends also to be lower than in the basalts and basaltic andesites of the Subalkaline Basaltic to Rhyolitic Unit at Orivesi and the Lower Volcanic Unit at Ylöjärvi, although the two groups mentioned contain less K. Therefore, the high-K feature of the stratified basaltic andesites at Kämmenniemi is not necessarily primary but may be attributed to mixing with pelitic material during redeposition, and to alteration in sample 15/82 with sericite as a major mineral.

A part of the range of K in the dacites and trachydacites at Kämmenniemi is attributable to metasomatism because plagioclase phenocrysts in certain samples have been replaced by potassium feldspar. However, because petrographic signs of metasomatism are not ubiquitous, the high-K feature in the Kämmenniemi rocks is probably not caused by compositional changes alone. Considering also the narrow dispersion in the K content, most intermediate rocks at Kämmenniemi did originally belong to high-K types.

Mafic rocks are rare in the study area at Kämmenniemi, and the high-K character of the few basaltic andesites is probably not a primary feature. The high-K dacites and trachydacites were not produced from the few interbedded mafic rocks through fractional crystallization.

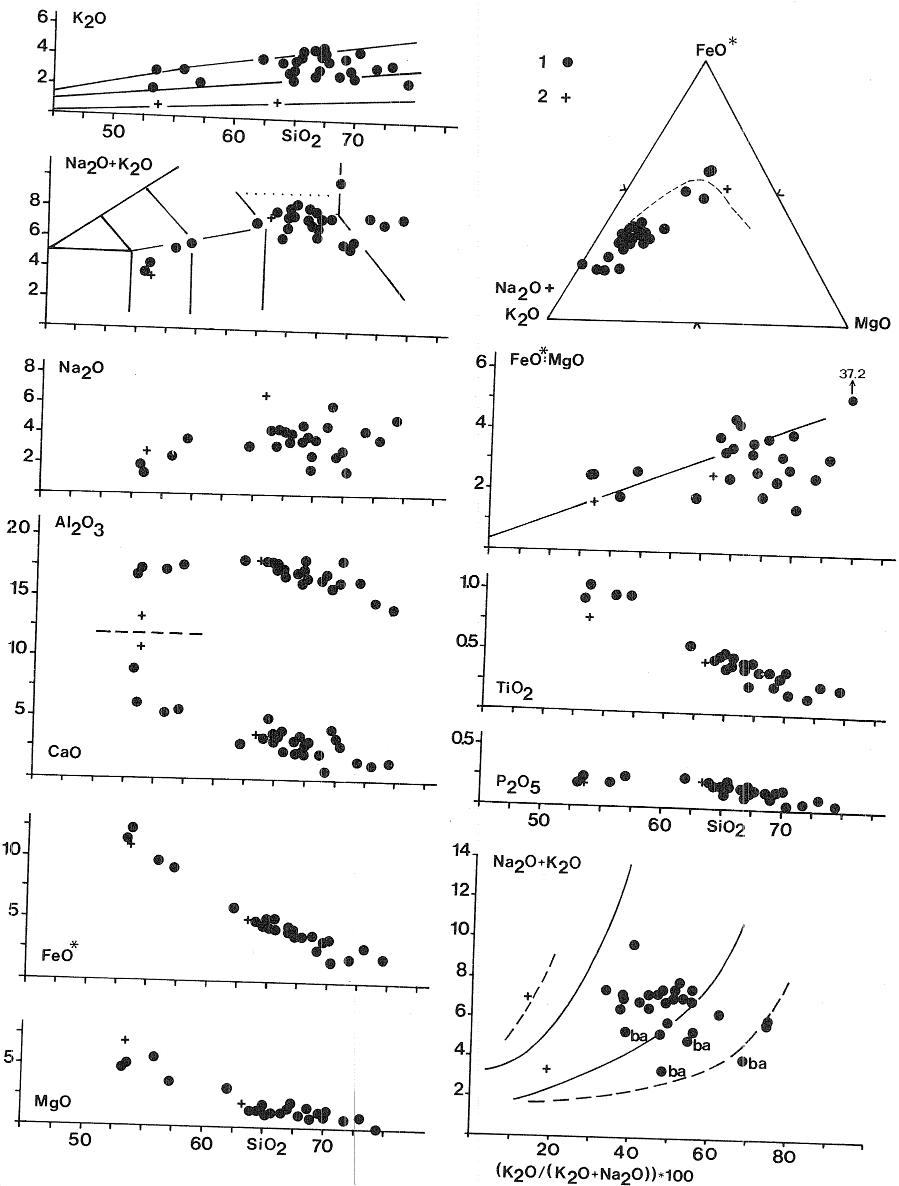


Fig. 27. Harker-type and AFM variation diagrams and igneous spectrum of the rocks of the Kämmenniemi area. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. rocks of the Kämmenniemi area in general; 2. samples 30—31/82.

The Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline

General description and petrography

The Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline is about 100 m thick in the profile investigated. To the east the unit is thicker and contains rock types different from those now considered (p. 68).

The volcanic rocks of the area discussed are

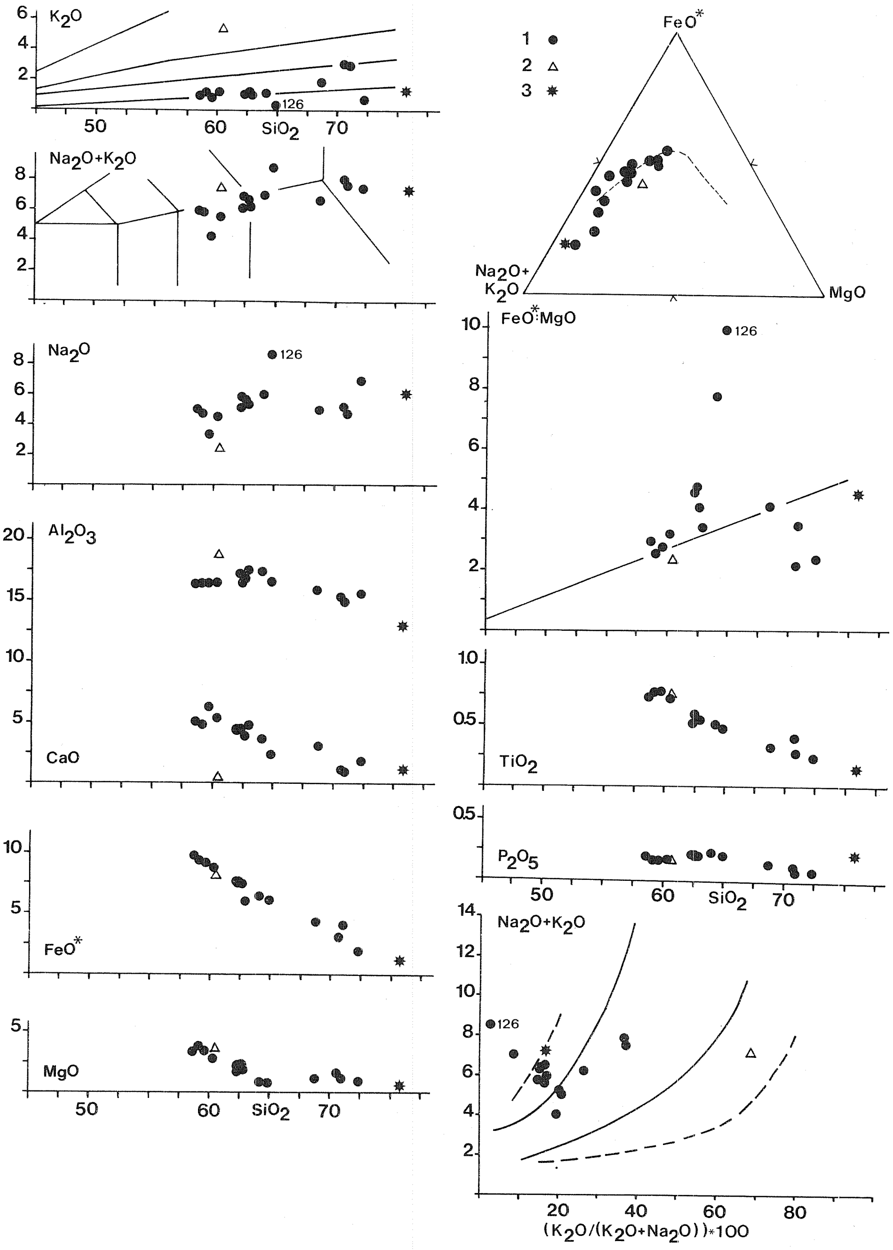


Fig. 28. Harker-type and AFM variation diagrams and igneous spectrum of the Lower Volcanic Unit at Ylöjärvi in the southern limb of the syncline. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. volcanic rocks of the area in general; 2. sample 123 (a mylonitized mica-chlorite schist); 3. a fine-grained felsic rock at Kiviniemenlahti, about 7 km east of the study profile (analysis 15 in Table IV of Simonen, 1953a).

characterized by massive, non-fragmental andesites and dacites. They may be partly subvolcanic. The intermediate rocks contain phenocrysts, or their pseudomorphs, of plagioclase (mostly

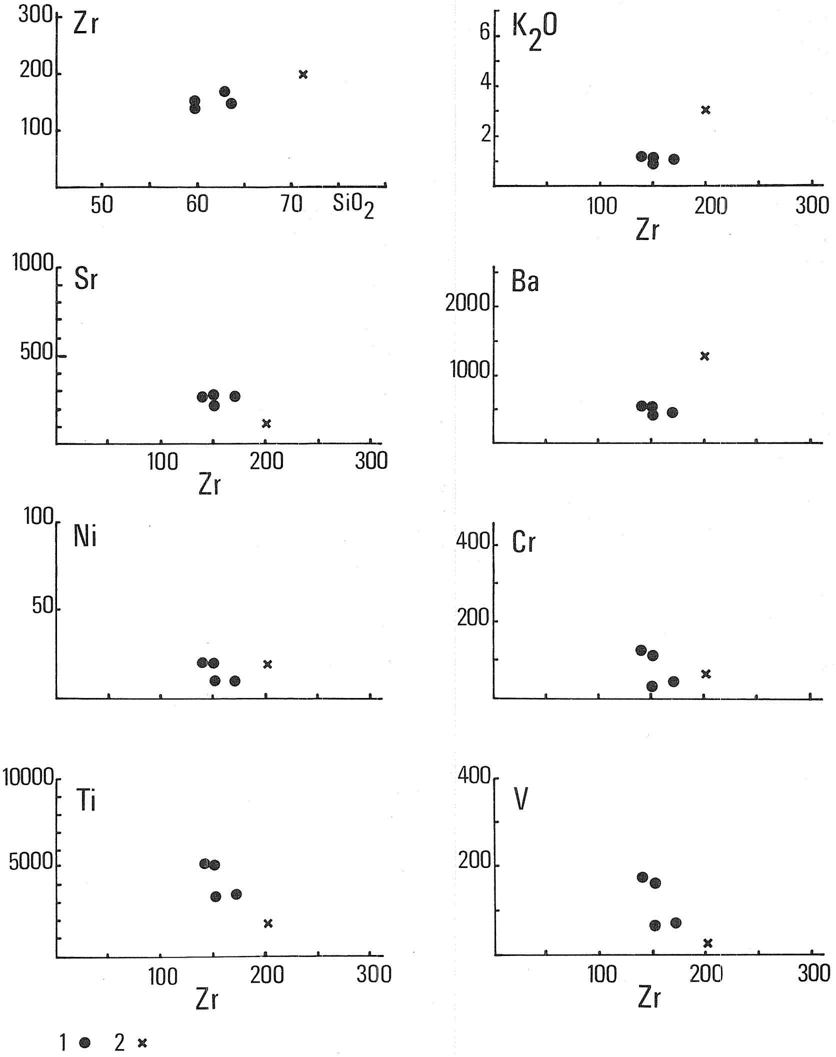


Fig. 29. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Lower Volcanic Unit at Ylöjärvi in the southern limb of the syncline. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. 1. samples 127, 130, 356/79 and 357/79; 2. sample 124.

10—30 vol.%, ø <1 mm), hornblende and, in the types lowest in Si, pyroxene. The major minerals are oligoclase (albite in sample 126) + quartz + hornblende ± biotite.

The rhyolitic rocks are even-grained and very fine-grained laminated or layered tuffites. The major minerals include quartz + plagioclase + potassium feldspar + chlorite.

Sample 123 is a mylonitized chlorite-mica schist.

Geochemistry

The volcanic rocks of the area discussed are mostly subalkaline and behave consistently in most variation diagrams (Figs. 28 and 29). The andesites and dacites straddle the low-K/medium-K boundary, whereas the rhyolitic rocks show a range from low-K to nearly high-K types. The K_2O:Na_2O ratios are below unity. Most rocks are within the modified igneous spectrum. The andesites and dacites have tholeiitic affinities in that the FeO*:MgO ratio increases steeply with increasing Si but the rhyolites occur in calc-alkaline fields. The Zr contents of the andesites and dacites are only slightly higher than, and the P and Sr contents similar to those in young low-K arc andesites and dacites on average (Ewart, 1979, 1982). The relatively low K content is probably a primary feature. The Zr content tends to increase with the increasing Si content (Fig. 29). The Sr-Zr, K_2O-Zr and Ba-Zr trends are horizontal in the andesites and dacites, but the rhyolitic sample analyzed for trace elements is low in Sr and high in K and Ba. The decrease in Ni, Cr, Ti and V with increasing Zr and Si is apparent in the andesites and dacites, but the rhyolite is relatively rich in Ni and Cr.

Sample 123 deviates from the andesites being high in K and Al, and low in Ca and Na.

In Fig. 28, the rhyolitic tuff from Kiviniemenlahti represents the felsic schists some km E-ESE (Fig. 4). It is similar to the rhyolites discussed in that Na_2O dominates over K_2O. Andesites-rhyolites with K_2O:Na_2O ratios below unity are common in parts of the Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline.

The low K content in the andesites and dacites is petrographically attributed to the scarcity of biotite and to the absence of potassium feldspar. The high Na content and the very low K content in sample 126 are indications of the abundance of albite. Alteration is probable in this sample and may have enhanced the high FeO*:MgO ratio because Na-enriched volcanic rocks are partly depleted in Mg (Lagerblad & Gorbatschev, 1985). The general iron-enrichment shown by the andesites-dacites is not, however, caused by similar alteration because most of these rocks contain oligoclase, not albite, as a major mineral.

Petrology

Equilibrium partial melting yields horizontal or gently descending trends in compatible vs. incompatible element diagrams, when the degree of fusion is below about 40% (Pearce, 1982). Thus partial melting is not the reason for the steeply descending Cr-Zr and Ni-Zr trends in the andesites-dacites discussed.

The andesites-dacites display an iron-enrichment, but also the decrease of Ti and V with increasing Zr and Si is indisputable. Fractionation of olivine cannot explain these features because such a process produces concurrent increases in Ti and V and in the FeO*:MgO ratio with increasing Si and Zr. Hornblendes may have FeO*:MgO ratios below unity, and the D_{Ti}, D_V, D_{Cr} and D_{Ni} values of hornblende exceed unity (Pearce & Norry, 1979; Luhr & Carmichael, 1980; Gill, 1981, p. 181). Surface equilibrium fractional crystallization of hornblende would seem to be plausible, especially as pseudomorphs after phenocrysts of hornblende were observed. The pseudomorphs and relicts after pyroxene and plagioclase and the horizontal Sr-Zr trend would imply that the assemblage also contained pyroxene and plagioclase. However, accepting that the K and Ba contents are largely primary, the behaviour of these elements is controversial. The horizontal K_2O-SiO_2, K_2O-Zr and Ba-Zr trends do not support the model of fractional crystallization because the D_K and D_{Ba} values for hornblende, pyroxenes and plagioclase in andesitic systems are mostly below unity (Arth, 1976; Gill, 1981; Hanski, 1983). A possible explanation is mixing, but final conclusions are premature with the insufficient data available.

The predominance of Na_2O over K_2O in the intermediate and rhyolitic rocks indicates that the two groups somehow have a common origin. The decrease of Sr, Ti and V from andesites and dacites to rhyolites may be attributed to fractionation of plagioclase and mafic phases. The relatively high Ni and Cr contents and the low FeO*:MgO ratios in the rhyolites could be caused by mixing with material high in Ni, Cr and Mg. The relatively high K and Ba content in sample 124 indicates that the admixture was rich also in these elements. A possible admixture is material similar to the chlorite-mica schist sample 123.

The sedimentary and volcanic rocks between the Lower Volcanic Unit and the Upper Volcanic Unit in the southern limb of the major syncline at Ylöjärvi

General description and petrography

The sedimentary rocks between the Lower and Upper Volcanic Units at Ylöjärvi in the southern limb of the major syncline are conglomerates (the Veittijärvi conglomerate), greywackes, siltstones and pelites. There also occur volcanic rocks, sills and subvolcanic rocks.

Samples 133—135, south of and underlying the Veittijärvi conglomerate, are mafic greywackes. They contain pseudomorphs after clasts of clinopyroxene (3—30 vol.%, presently actinolite ± hornblende) and plagioclase (up to 20 vol.%, presently andesine), as well as volcanic rock fragments. The amount of clasts smaller than 0.2 mm in diameter is difficult to approximate but it seems to be high in sample 134. Sample 132 is from a redeposited laminated felsic stratum interbedded with siltstones and pelites.

Samples 138—140, 143, 147, 412/79 and 60/82 are from the sedimentary strata 150—250 m north of, and overlying, the Veittijärvi conglomerate. They, like the conglomerate, have predominantly volcanic provenances. Sample 138 is from a 3 m thick massive stratum of greywacke. Samples 139, 147 and 60/82 are from greywackes which are partly graded (Fig. 30.a). They contain clasts of plagioclase and volcanic rock fragments. Sample 412/79 represents the mafic, fine-grained and stratified rocks below the greywackes described above. Samples 140 and 143 are from silty-pelitic strata but have a SiO_2 content exceeding 60%.

Samples 149—152, from the northernmost parts of the area, are stratified rocks with a SiO_2 content of 64—69%. They often display clastic texture and are rich in plagioclase and quartz. Tourmaline is abundant as veins, and occurs also as pseudomatrix in clastic strata.

Samples 141 and 286 are from stratified felsic beds interlayered with the strata of samples 140 and 143. Sample 286 is fine-grained and contains chalcopyrite-bearing veins. Sample 141 is from a partly fragmental 20 m thick stratum which shows internal bedding. The sample contains felsic rock fragments, and the phenocrysts of quartz and feldspar display features resembling embayments.

Sample 145 is from a fragment in a uralite-plagioclase-phyric stratum about 15 m in thickness. The fragmental structure (Fig. 30.b) probably formed by autoclastic brecciation of a subaqueous lava flow. Samples 137 and 148 are from massive uralite-phyric strata which may be sills.

Sample 142 represents a massive, non-stratified pyroclastic rock which contains about 10 vol.% phenocrysts of plagioclase (ø < 1 mm). Under the microscope the rock is seen to comprise felsic and intermediate rock fragments.

Samples 144 and 146 are from a plagioclase-phyric subvolcanic rock which in the area of sample 144 contains schists as inclusions. Sample 146 is from a 30 cm wide sinuous dyke intruding the stratum of sample 145. Phenocrysts of oligoclase (ø up to 5 mm) amount to 30—50 vol.%.

Sample 136 is from a hypabyssal rock. Besides plagioclase phenocrysts (30—35 vol.%, ø up to 2 mm, oligoclase-albite), euhedral phenocrysts of quartz also occur. Both types of phenocrysts are in part embayed. The rock contains about 10 vol.% inclusions rich in amphibole.

Finally, sample 285 is from a 15—30 cm wide

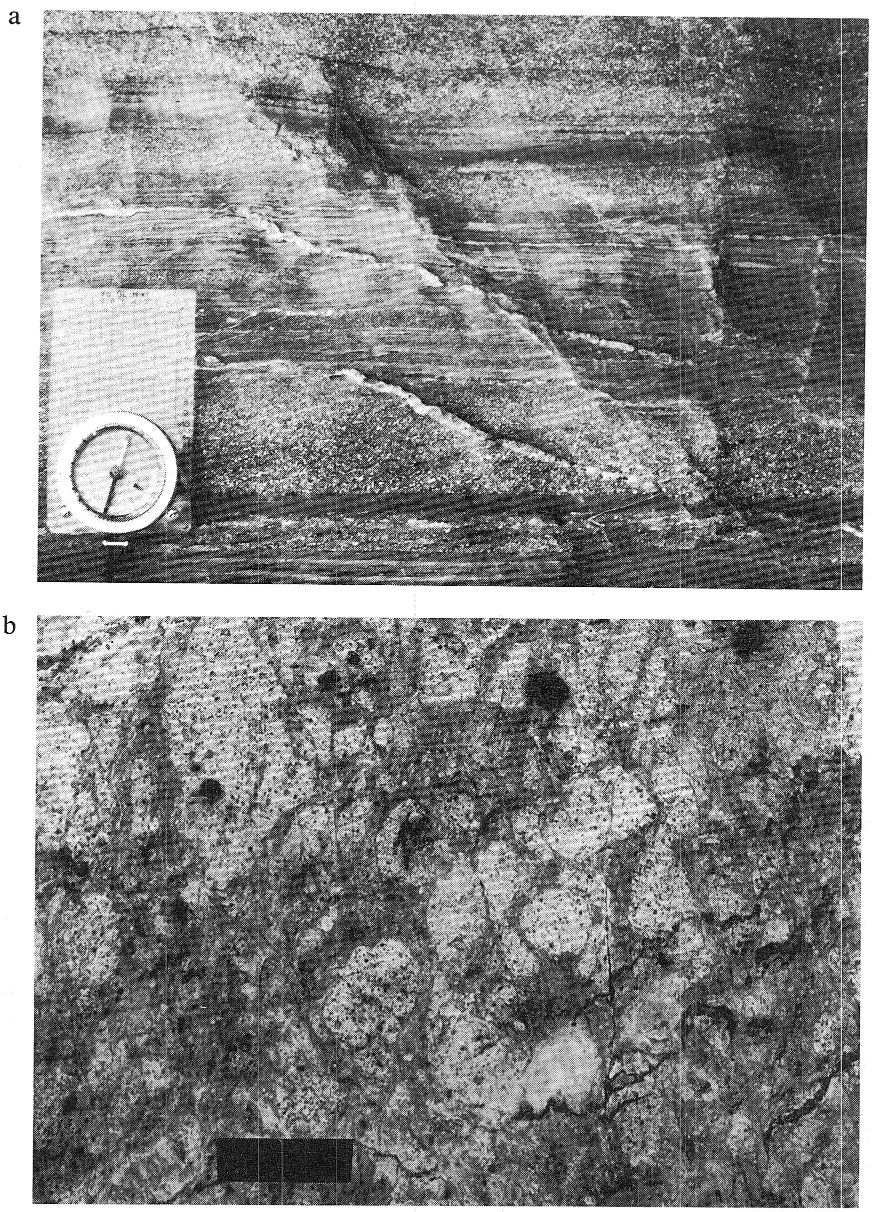


Fig. 30. Structures of the sedimentary and volcanic rocks between the Lower and the Upper Volcanic Unit at Ylöjärvi in the southern limb of the major syncline. a. Graded greywackes. Strata of sample 60/82; b. Fragmental lava. The stratum of sample 145. The scale bar is 10 cm long.

dyke cutting the Veittijärvi conglomerate. It was emplaced after the major D_1 folding but before the development of a later schistosity with a NE strike.

Geochemistry and petrology

The rocks with basaltic to andesitic compositions have low TiO_2 contents (Fig. 31). This indicates arc affinities for the sills, the lava and the provenances of the mafic sedimentary rocks.

The three greywackes below the Veittijärvi conglomerate (samples 133—135) are mostly medium-K and high-K basalts or basaltic andesites. The Mg, Al and Ca contents vary widely. The dispersion in Mg and Al is in part caused by the variation in the proportion of pseudomorphs after pyroxene which in sample 135, with about 13% MgO, amounts to 30 vol.%. The high Cr and Ni contents in sample 134 (Fig. 32) are partly caused by the presence of small pyroxene pseudomorphs and rock fragments rich in hornblende. These greywackes were derived from sources dominated by pyroxene-phyric medium-K/high-K basalts and basaltic andesites.

In having a K_2O:Na_2O ratio near unity, the rhyolitic sample 132 differs from the rhyolitic rocks of the Lower Volcanic Unit discussed on pp. 59—63.

The greywacke samples 139, 147 and 60/82 (SiO_2 54—60%) above the Veittijärvi conglomerate are very high-K trachyandesites. They are mostly in the calc-alkaline fields in the AFM and FeO*:MgO vs. SiO_2 diagrams. The Cr and Ni contents are high in sample 60/82. The fine-grained sample 412/79 (about 54% SiO_2) resembles the three greywackes although it is slightly lower in K. In chemical composition, these four sedimentary rocks resemble the rocks of the Shoshonitic Unit at Orivesi and the trachyandesite at Mastosjärvi, although they are slightly lower in P (cf. Figs. 21 and 31). Despite the difference in P, it is tempting to suggest that they were derived from the Mastosjärvi trachyandesite but more data are needed to make a final conclusion.

Sample 138 (a massive greywacke, about 62.5% SiO_2) occurs near the medium-K/high-K boundary. It deviates from the greywackes just considered and had a separate volcanic provenance.

The fine-grained samples 140 (65% SiO_2) and 143 (62% SiO_2) occur near the high-K/very high-K and alkaline/subalkaline boundaries. Calc-alkaline affinities are evident. Since these silty-pelitic rocks are not high in Al, marked weathering is not probable and the compositions reflect those of their sources.

Samples 149—152 are dacitic rocks straddling the low-K/medium-K boundary. The FeO*:MgO ratios are low but the ratio is high in one sample. This rock, sample 152, might have been altered because it is from a site near the Hämeenkyrö batholith. The Ti contents, about 0.6% TiO_2 at 67% SiO_2, are relatively high and indicate provenances other than the andesites-dacites of the Lower Volcanic Unit discussed on pp. 59—63, although the two groups have low K contents.

Felsic samples 141 and 286 are high-K subalkaline rhyolites or dacites with calc-alkaline affinity. They resemble each other in most elements and may be cogenetic. The relatively high FeO*:MgO ratio in sample 286 is attributed to an increase in Fe caused by the chalcopyrite-bearing veins.

Samples 137 and 148 from the sills, and sample 145 from the fragmental lava, are medium-K basaltic andesites with calc-alkaline affinities. The major element compositions resemble each other and the rocks may be comagmatic. If so, the sills fed the lava higher in the sequence. When compared with the typical basalts and basaltic andesites of the Upper Volcanic Unit at Ylöjärvi (pp. 77—87; Table 1), these three rocks are lower in Al and P. Therefore, the two groups are not comagmatic although they both overlie the Veittijärvi conglomerate. The low Ni content and the FeO*:MgO ratio approaching 2 in sample 145 (Table I) indicate fractionation of olivine after fusion of the mantle. The Cr content of 260 ppm is attributed to minor accumulation of pyroxene.

Sample 142 is a calc-alkaline medium-K trachydacite. It is higher in K, but lower in P and Zr than the subvolcanic samples 144 and 146 nearby and, therefore, not comagmatic with them.

Samples 144 and 146 are calc-alkaline low-K subvolcanic dacites. Because of the abundance

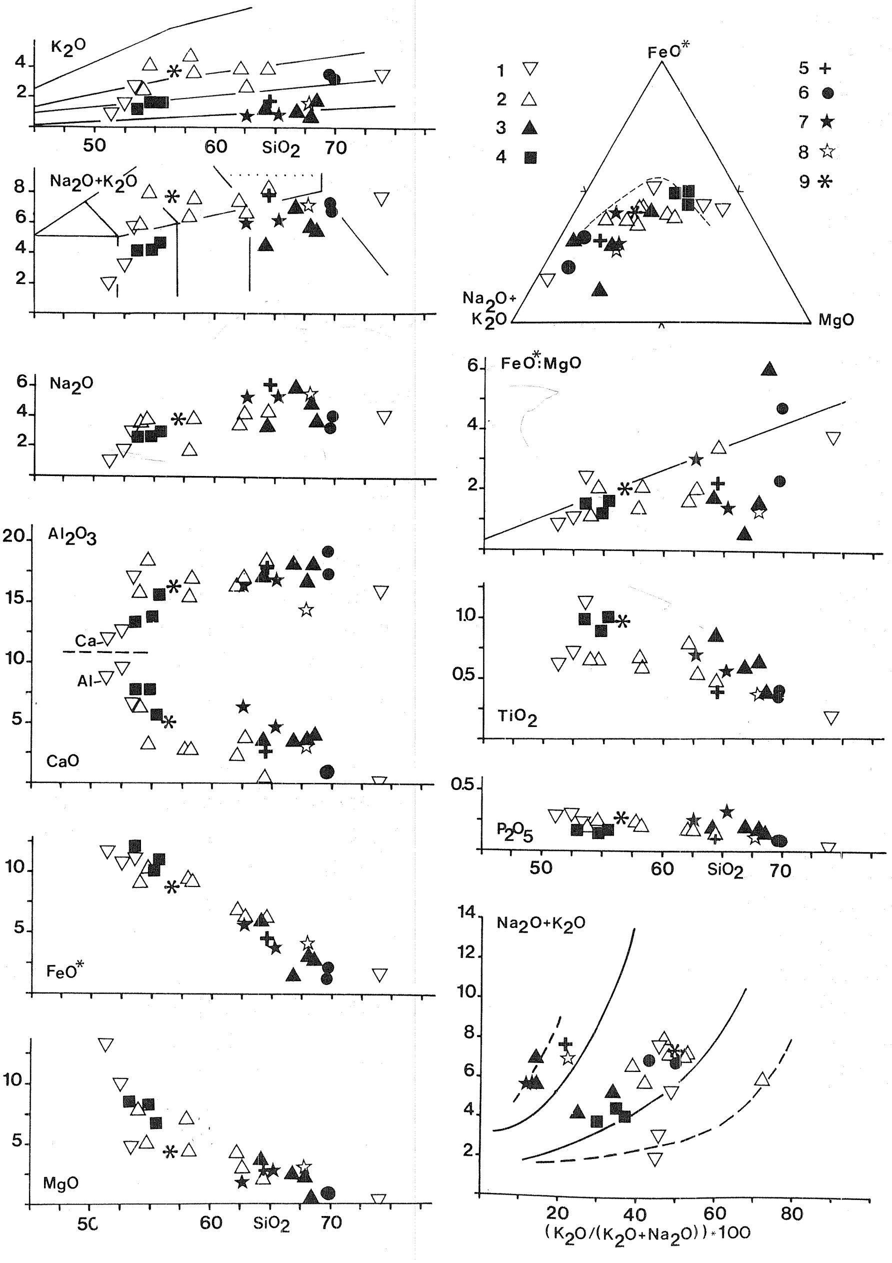


Fig. 31. Harker-type and AFM variation diagrams and igneous spectrum of the sedimentary and volcanic rocks between the Lower and the Upper Volcanic Unit at Ylöjärvi in the southern limb of the syncline. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 132—135 from volcanogenic sedimentary rocks S of the Veittijärvi conglomerate; 2. samples 138—140, 143, 147, 412/79 and 60/82 from volcanogenic sedimentary rocks 70—150 m N of the Veittijärvi conglomerate; 3. samples 149—152 from intermediate schists in the northernmost parts of the area; 4. samples 137, 145 and 148 from sills and a fragmental lava N of the Veittijärvi conglomerate; 5. sample 142 (a non-stratified pyroclastic rock); 6. samples 141 and 286 from stratified rhyolitic rocks; 7. samples 144 and 146 from a subvolcanic dacite; 8. sample 136 from a subvolcanic rock near the Veittijärvi conglomerate; 9. sample 285 from a post-D_1 dyke.

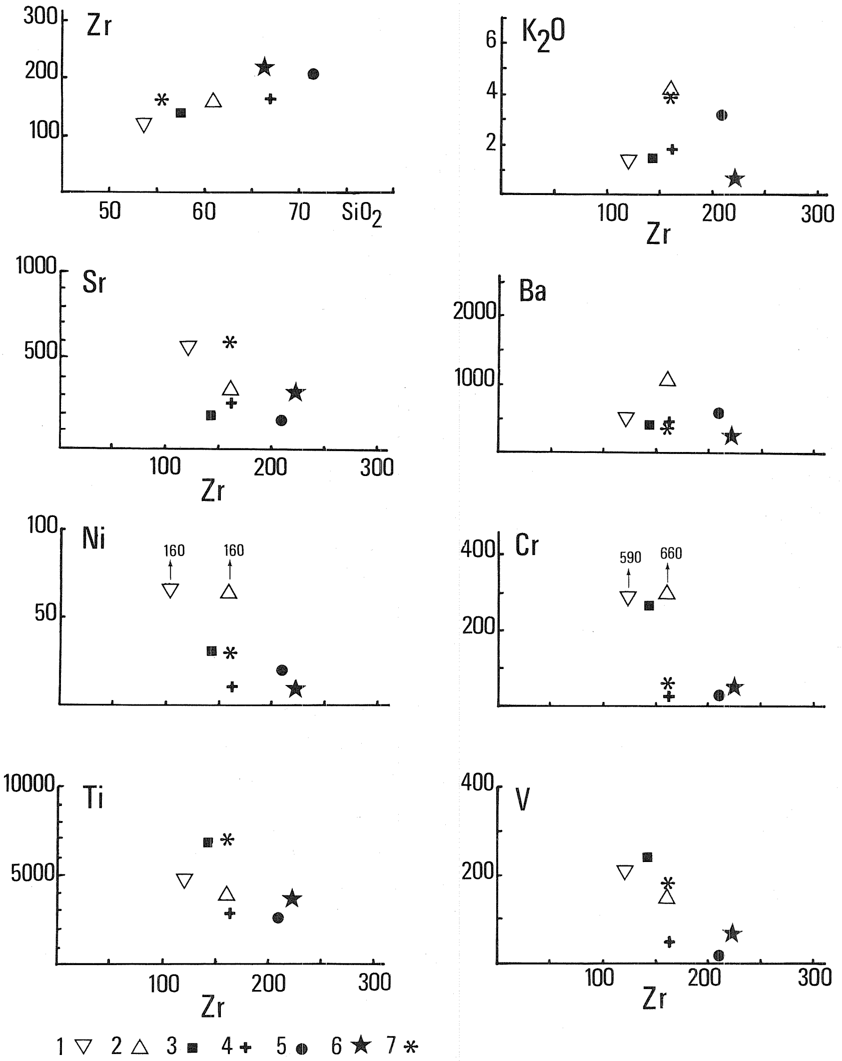


Fig. 32. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the volcanic and sedimentary rocks between the Lower and the Upper Volcanic Unit at Ylöjärvi in the southern limb of the syncline. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. 1. sample 134; 2. sample 060/82; 3. sample 145; 4. sample 142; 5. sample 141; 6. sample 144; 7. sample 285.

of phenocrysts of plagioclase they are not good representatives of the composition of the melt. Sample 136, also from a porphyritic hypabyssal rock, is largely similar in its chemical composition. The relatively high Mg content is attributed to the mafic inclusions.

Sample 285, a post-D_1 dyke, is a very high-K trachyandesite. As for the Na and K contents, it is similar to the least silicic rocks of the Hämeenkyrö batholith (cf. Gaál *et al.*, 1981).

In all, the sedimentary rocks discussed in this section and the volcanic rocks discussed on pp. 59—63 indicate that the Lower Volcanic Unit at Ylöjärvi is heterogeneous in the southern limb of the major syncline. It contains rocks which range from basalts to rhyolites, from nearly low-K types to very high-K types, and show both tholeiitic and calc-alkaline affinities.

The Lower Volcanic Unit at Ylöjärvi in the northern limb of the major syncline

General description and petrography

The Lower Volcanic Unit at Ylöjärvi in the northern limb of the major syncline is about 1 km thick across the strike. Because there are faults and signs of intensive deformation (Fig. 33) it is difficult to say how well this figure agrees with the original thickness. A fault in the valley between samples 239—241 and 242—244 divides the area into two parts. The unit is dominated by volcanic rocks but there are pelitic rocks with pseudomorphs after andalusite porphyroblasts.

The strata display younging to the SW near samples 254—255 and to the NE near samples 258—260 (Fig. 5). Whether this reversal represents the hinge zone of a major fold, or a minor fold in the limb of a major fold is not known with certainty. Since the lithological and geochemical properties north of the reversal are different from those to the south (samples 260—269 and 249—259, pp. 68—73, Fig. 34.a), the latter alternative is preferred. This interpretation is supported by the stratum of sample 258, presuming that the change in grain size (p. see below) is normal grading. In the area of samples 242—269, deformation and brecciation often disturb the identification of the original character of the rocks, and late-stage alteration has in places severely affected the composition.

In the area of samples 260—269, the rocks are intermediate with SiO_2 ranging between 57% and 64%. They are mostly plagioclase-phyric (up to 25 vol.% phenocrysts; ø < 3 mm). Fragmental structures, partly of primary and partly of tectonic origin, are frequent (Fig. 33.a). The major minerals include oligoclase/albite + quartz ± hornblende ± biotite. Sample 267 shows fragmentation on a microscopic scale and contains late veinlets of prehnite.

In the area of samples 249—259, the volcanic rocks vary from basaltic to rhyolitic in composition but basaltic andesites are most frequent. This area comprises stratified, both porphyritic/clastic and even-grained rocks. The rocks are mostly tuffs, crystal tuffs and volcanic greywackes. Fragmental structures occur, but they may be caused partly by transposition (Figs. 33.b,c). In the area of samples 257—259 the volcanic rocks are in part pyroclastic; sample 257 is from a stratified tuff. Sample 258 is from a 5 m thick non-fragmental basaltic stratum in which the pseudomorphs after phenocrysts of pyroxene (up to 30 vol.% in the sample) decrease in size toward the SW. Sample 259 is from a 4 m thick sill which shows regular jointing in the SW part. The pseudomorphs after plagioclase and pyroxene phenocrysts amount to <5 vol.% in total. The basaltic andesites and andesites contain oligoclase/albite + quartz + hornblende/actinolite ± chlorite as major minerals. Prehnite occurs as a minor constituent in sample 250.

Throughout the area of samples 242—269 there are deeply weathered zones which are obvious fault zones. Sample 253, a tectonically brecciated even-grained tuff or tuffite, represents them.

Samples 255 and 256 are laminated, fine-grained and even-grained felsic rocks in which the proportions of muscovite, epidote and chlorite vary from lamina to lamina.

Samples 244—248 lie on the margin of the fault zone toward the SW. In this area there are intensively sheared zones between more solid parts. Samples 244—246 and 248 represent the solid parts. Phenocrysts of plagioclase amount to 10—30 vol.%. Sample 246 contains pseudomorphs after pyroxene (<5 vol.%). A network of aggregates and veinlets of quartz indicates

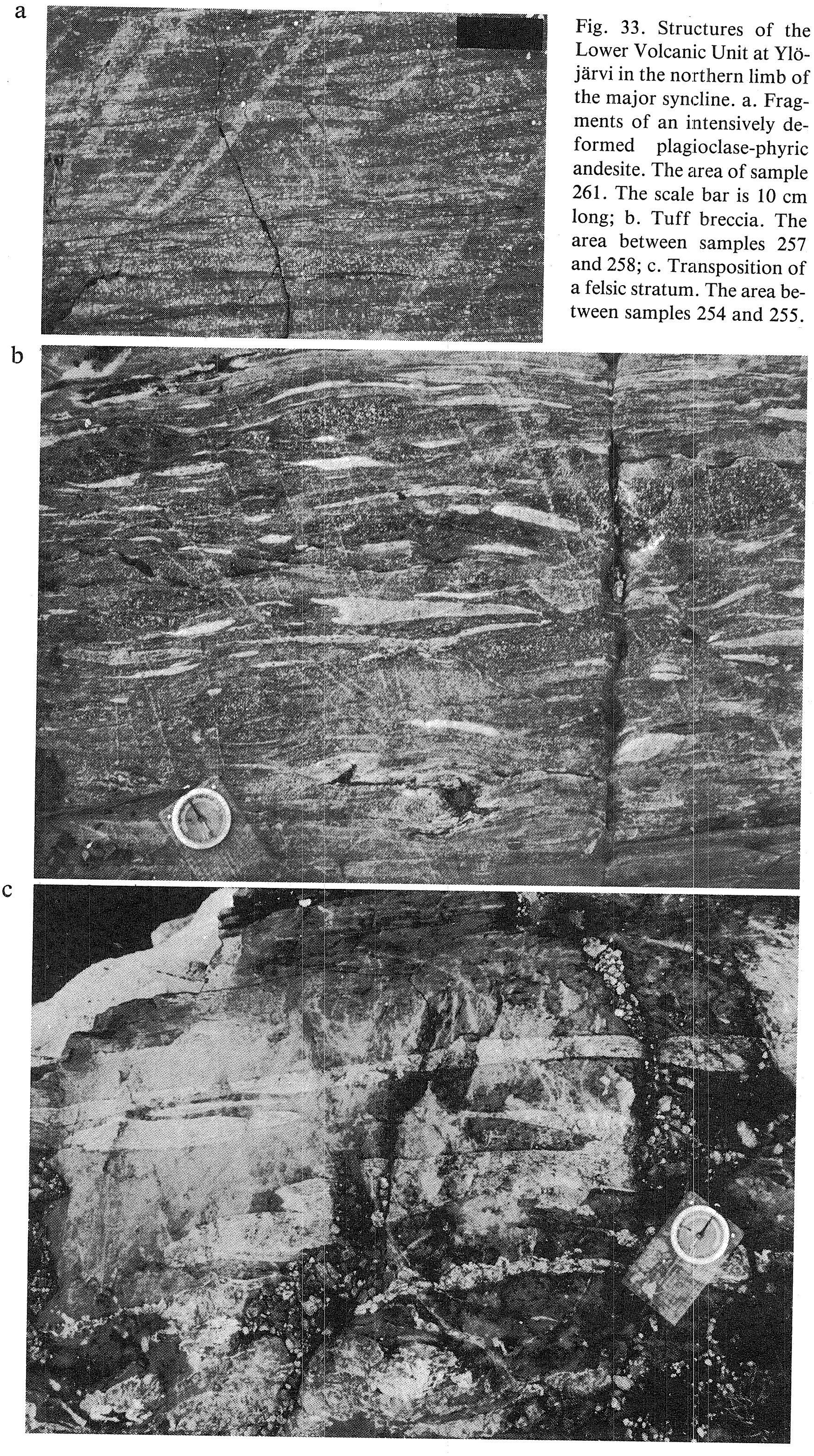


Fig. 33. Structures of the Lower Volcanic Unit at Ylöjärvi in the northern limb of the major syncline. a. Fragments of an intensively deformed plagioclase-phyric andesite. The area of sample 261. The scale bar is 10 cm long; b. Tuff breccia. The area between samples 257 and 258; c. Transposition of a felsic stratum. The area between samples 254 and 255.

secondary silicification. Sample 247 is from an intensively sheared zone. It is rich in prehnite.

Samples 242 and 243 are banded intermediate schists from a separate outcrop NW of samples 244—248.

In the area of samples 224—241, SW of the fault zone, stratified intermediate volcaniclastic rocks dominate. In addition, there are obvious sills and rhyolitic strata.

The andesitic and dacitic rocks are tuffs, tuffites and volcanogenic sedimentary rocks. They often display stratification with internal bedding 0.5—20 cm thick but there are also thicker beds. Both clastic and even-grained types, as well as pelitic interbeds occur. Clasts of plagioclase and volcanic rock fragments are common, but pseudomorphs after pyroxene were observed only near sample 224. Sample 236 is from a massive stratum which is at least 3 m thick. Its plagioclase phenocrysts (ø < 1.5 mm) are partly components of porphyritic rock fragments and amount to 20 vol.% in total.

The rhyolitic rocks of this area are mostly tuffites or tuffs. The strata of samples 227 and 228 comprise even-grained, laminated felsic rocks with pelitic and clastic interbeds.

Among the four basaltic andesites, sample 237 is from a stratified tuff or tuffite. Samples 233, 234 and 241 are from massive, non-fragmental rocks with pseudomorphs after phenocrysts of plagioclase (up to 20 vol.%, ø < 2 mm, andesine) and pyroxene (5—10 vol.%, ø < 2 mm, now hornblende). Sample 234 displays an ophitic-like texture, and the three rocks may derive from sills.

Samples 239 and 240 are from an outcrop relatively near the fault zone. They show pronounced schistosity. Sample 239 contains about 30 vol.% phenocrysts of albite and a few veins of prehnite.

Geochemistry and petrology

The volcanic rocks of the Lower Volcanic Unit at Ylöjärvi in the northern limb of the major syncline are predominantly medium-K and high-K basaltic andesites, andesites and dacites (Fig. 34). Calc-alkaline affinities are evident although the basalt and some of the basaltic andesites are in tholeiitic fields. Most of the rocks occur in the modified igneous spectrum. The trends in the major element variation diagrams are partly coherent, but the dispersions are partly wide. The Zr content increases with the increasing Si content but the K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr and Ti-Zr diagrams display non-regular patterns (Fig. 35).

The dispersions in the variation diagrams are often attributed to certain samples or sample groups. For instance, among the rocks with about 60% SiO_2, samples 250 and 252 tend to be higher in P and Al than samples 244—246 (Fig. 34.a.). The two groups tend to be higher in P and K than samples 260—269. Since the differences are shown by an element such as P they are probably primary.

Samples 260—269 define a narrow range in SiO_2 but range from the low-K/medium-K boundary to the high-K/very high-K boundary. Furthermore, the scattering of Na, Ca, Mg and Ti is wide and non-systematic with increasing silica. The dispersion is caused by compositional changes such as silicification, prehnitization and replacement by potassium feldspar.

Being dominated by plagioclase-phyric calc-alkaline intermediate rocks, samples 260—269 resemble the Intermediate Unit at Orivesi. They tend, however, to be lower in Si and K and higher in Ni and Cr (Figs. 13, 14, 34.a, 35; see also Table I). Because the rocks are not stratified the relatively high Cr and Ni contents are not caused by mixing with pelites or tuffites high in Cr and Ni. Rather, they are features of the magmas erupted.

The area of samples 249—259 is characterized by basaltic andesites. The basalt and the basaltic andesites are mostly medium-K rocks. The low Ti content (0.6—0.9% TiO_2) indicates arc affinities. The P_2O_5 content is about 0.25—0.35%, the Zr content 70—110 ppm and the Sr content about 300—1000 ppm. These values are close to the averages in young medium-K basaltic andesites (Ewart, 1982). The Sr-Zr trend of the four samples is steeply rising but dispersed. The variations in the CaO, Al_2O_3 and Cr contents are wide.

Sample 253, from a deeply weathered shear zone, is a high-K rock low in Ca. Metasomatism in the brecciated rock now rich potassium feldspar has contributed to the composition.

Samples 249 and 251 are relatively high in Mg. Sample 251 is rich in Sr, Cr and Ni (Fig. 35; Table I). It abounds with even-grained nematoblastic hornblende, and accumulation of mafic phenocrysts is not evident. Plagioclase phenocrysts amount to no more than about 20 vol.%. Accordingly, the magma from which it crystallized was high in Cr and Ni, and possibly also in Sr. Samples 249 and 251 are probably not related to the other basaltic andesites of samples 249—259 through fractional crystallization.

Samples 250 and 252 are andesites relatively high in K, Al and P. Sample 250 is rich in Sr, Ni and Cr (Table I; Fig. 35). Since the rock contains about 70 vol.% phenocrysts or clasts of plagioclase, the abundance of Sr is explained by the accumulation of plagioclase. Thus the increase in Sr with increasing Zr shown by samples 250, 251, 257 and 259 is in part attributed to accumulation of plagioclase. Instead, pseudomorphs after mafic phenocrysts to explain the high Ni and Cr content in sample 250 are absent. The andesitic samples 250 and 252 were probably not derived from the basaltic andesites nearby through fractional crystallization.

Samples 255 and 256 are the two high-K/very high-K calc-alkaline felsic rocks with 68—78% SiO_2. The K_2O:Na_2O ratio exceeds unity. Since the rocks comprise laminae alternatingly rich in chlorite and muscovite, their composition represents a mixture rather than the composition of a single magma.

Petrographic studies indicate that samples 244—246 (60—62% SiO_2) have been silicified (p. 70). Sample 247 was excluded from the variation diagrams because of its anomalous Ca content (about 18.5% CaO at 54% SiO_2) caused by pronounced prehnitization.

In the area of samples 224—241, south of the fault zone, rocks with SiO_2 exceeding 60% are more frequent than in the area north of the fault zone (Fig. 34). In addition, the andesites and dacites of the former area tend to be higher in Al than those of the latter.

Samples 233, 234, 237 and 241 are medium-K basaltic andesites. Sample 237, a stratified tuff or tuffite with about 52.5% SiO_2, is similar to the three samples from the sills but is lower in Ti and P. When the four rocks are considered together they show increases in the FeO*:MgO ratio and in the Ti content with the increasing Si content, but more data are necessary for corroborating the tholeiitic affinity so obtained.

Among samples 224—241, the intermediate rocks with a SiO_2 content exceeding 60% show wide dispersions from the generalized variation trends for many elements. This is partly caused by compositional changes. For instance, sample 239 is rich in Na and albite. The dispersions are not restricted to alkali metals; the Cr content ranges from 40 to 140 ppm and the Al_2O_3 content from 15 to 20%. These scatterings reflect the character of the rocks; i.e., the samples are from reworked volcanogenic strata derived from various sources. As indicated by the pelitic interbeds and by the Al_2O_3 contents approaching 20%, mixing with pelitic material also occurred. The high Cr content in sample 235 is attributed to mixing with material rich in Cr.

The two very high-K rhyolitic rocks are samples 227 and 228. Their K_2O:Na_2O ratios exceed unity. The composition of these rocks is a result of sedimentary mixing.

In conclusion, the Lower Volcanic Unit at Ylöjärvi in the northern limb of the major syncline is dominated by medium-K and high-K basaltic andesites, andesites and dacites with calc-alkaline affinities. The Cr content in the ande-

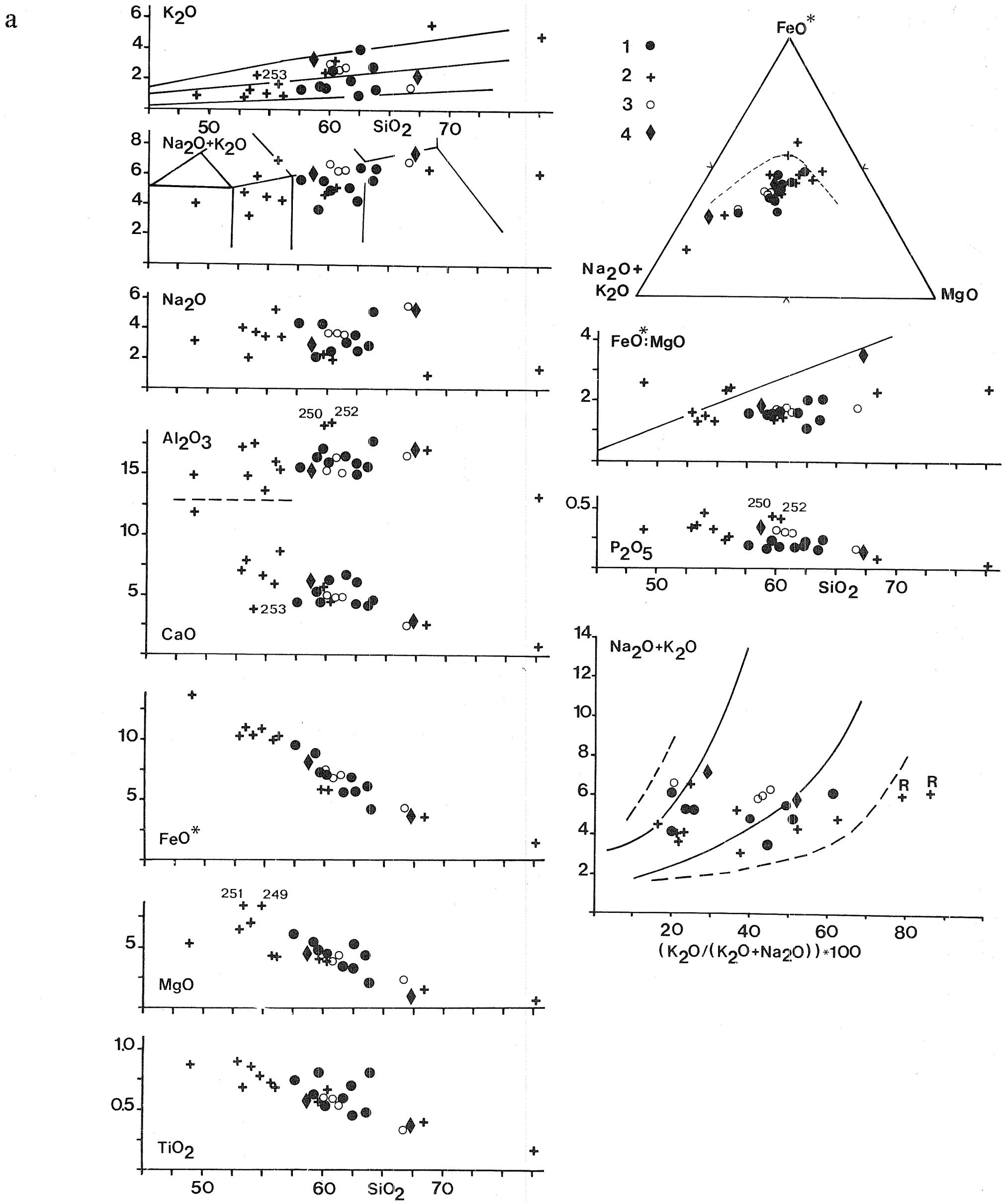
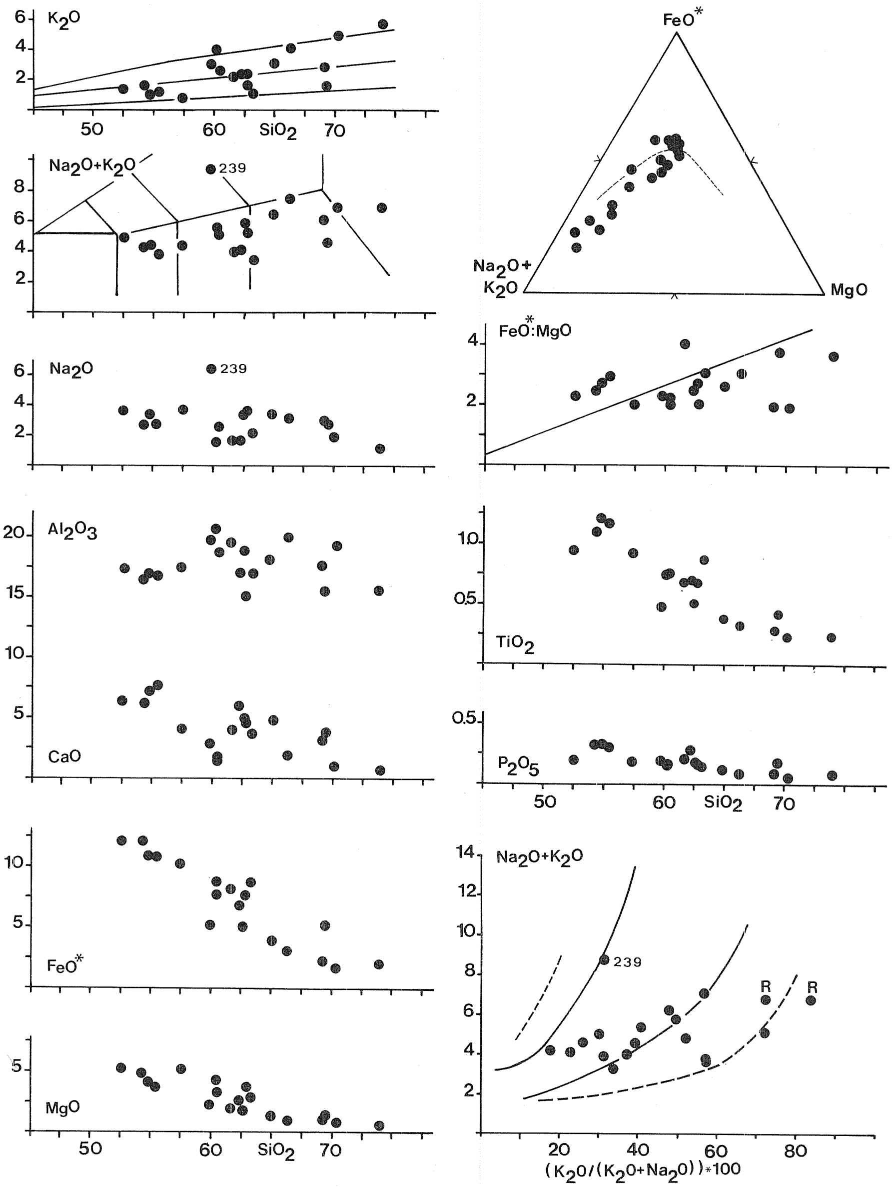


Fig. 34. Harker-type and AFM variation diagrams and igneous spectrum of the Lower Volcanic Unit at Ylöjärvi in the northern limb of the syncline. Oxides in weight%. FeO^*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. A. 1. samples 260—264 and 266—269; 2. samples 249—259; 3. samples 244—246 and 248; 4. samples 242 and 243. B. Samples 224—241 and 275. R in the igneous spectrum diagrams indicates felsic rocks.

sites and dacites is rather high. High in the sequence this is attributed to mixing during redeposition, but low in the sequence (samples 260—269) it is probably a primary feature of magma. The andesites-dacites with relatively low K contents and tholeiitic affinities and the very b



high-K trachybasalts-trachyandesites known to exist in the Lower Volcanic Unit in the southern limb of the syncline were not identified here. The Lower Volcanic Unit at Ylöjärvi may, no doubt, be disassembled into smaller units in future studies.

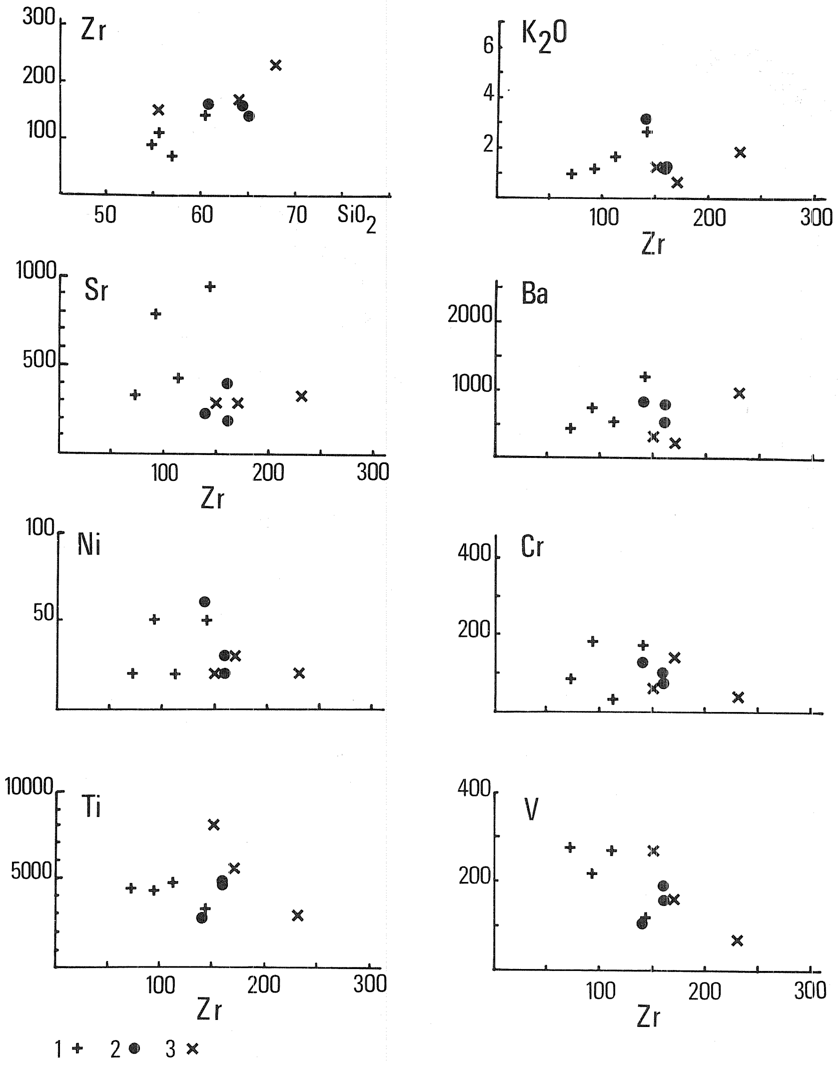


Fig. 35. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Lower Volcanic Unit at Ylöjärvi in the northern limb of the syncline. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. 1. samples 250, 251, 257 and 259; 2. samples 261, 266 and 267; 3. samples 234—236.

The felsic and intermediate rocks between the Lower Volcanic Unit and the Upper Volcanic Unit in the northern limb of the major syncline at Ylöjärvi

General description and petrography

The sedimentary rocks between the Lower Volcanic Unit and the Upper Volcanic Unit in the northern limb of the syncline at Ylöjärvi comprise pelites, siltstones, greywackes and conglomerates. Sample 413/79 represents the pelitic-silty strata. These are overlain by felsic and intermediate rocks which often show signs of compositional changes and intensive deformation.

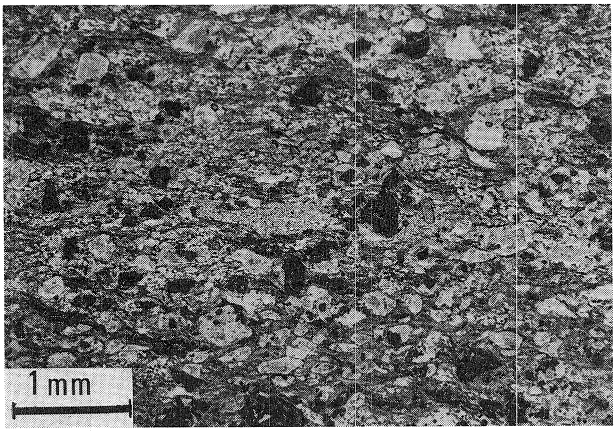


Fig. 36. A fine-grained fragment (in the centre), possibly a glass shard in origin. Most of the dark patches are aggregates of epidote. Sample 217, parallel nicols. Photo by J. Väätäinen.

Samples 221—223 are from fragmental pyroclastic strata with pronounced deformation. Sample 221 contains 30—40 vol.% small (ø <1 mm) phenocrysts of albite many of which are components of porhyritic rock fragments. The strata of samples 219 and 220 display fine banding, but it is not clear whether this is primary lamination or a result of deformation. These rocks are very fine-grained and contain about 5 vol.% small (ø <0.7 mm) phenocrysts of alkali feldspars.

Samples 282, 283, 218 and 417/79 are from felsic rocks interbedded, and partly mixed, with pelites-greywackes. Samples 218 and 417/79 are from fragmental rhyolitic strata. Sample 218 contains sphalerite in the matrix. Sample 284 is from a pure felsic rock brecciated by quartz veins.

The strata of samples 217 and 281 do not contain pelitic interbeds. Internal bedding varies from 1—2 cm to <1 m in thickness. Sample 217 contains clasts of albite, quartz/quartzite and fine-grained felsic fragments (Fig. 36). The degree of deformation here is lower than that in the area of samples 219—223.

The major minerals include quartz + albite + muscovite ± potassium feldspar ± carbonate. Biotite approaches 5 vol.% in sample 221. Epidote, partly as pseudomorphs after plagioclase, amounts to about 5 vol.% in sample 217.

Geochemistry and petrology

Sample 413/79, from the underlying pelites and siltstones, differs in many respects from the other rocks considered in this section. It has more similarities with the intermediate rocks of samples 224—241 (cf. Figs. 34.b and 37) and is omitted from the following discussion.

Most of the intermediate and felsic rocks discussed are subalkaline (Fig. 37). They range from very high-K types to low-K types, but high-K rocks dominate. The Al and Na contents and the FeO*:MgO ratios display wide dispersions. Most of the rocks occur in the igneous spectrum of Hughes (1973).

If these rocks were considered as a group, the variation diagrams would display peculiar features such as the general decrease in Al and K with increasing Si, and more or less convex FeO-SiO_2, TiO_2-SiO_2 and CaO-SiO_2 patterns. These characteristics are largely caused by compositional changes.

Samples 219 and 220 are high in K and Al. They enhance the peculiarities described. Their composition is attributed to alteration observed in the abundant presence of sericite. Some increase in K is possible as indicated by the occurrence of phenocrysts of potassium feldspar. The reason of the sericite-related alteration might be weathering or hydrothermal decomposition but,

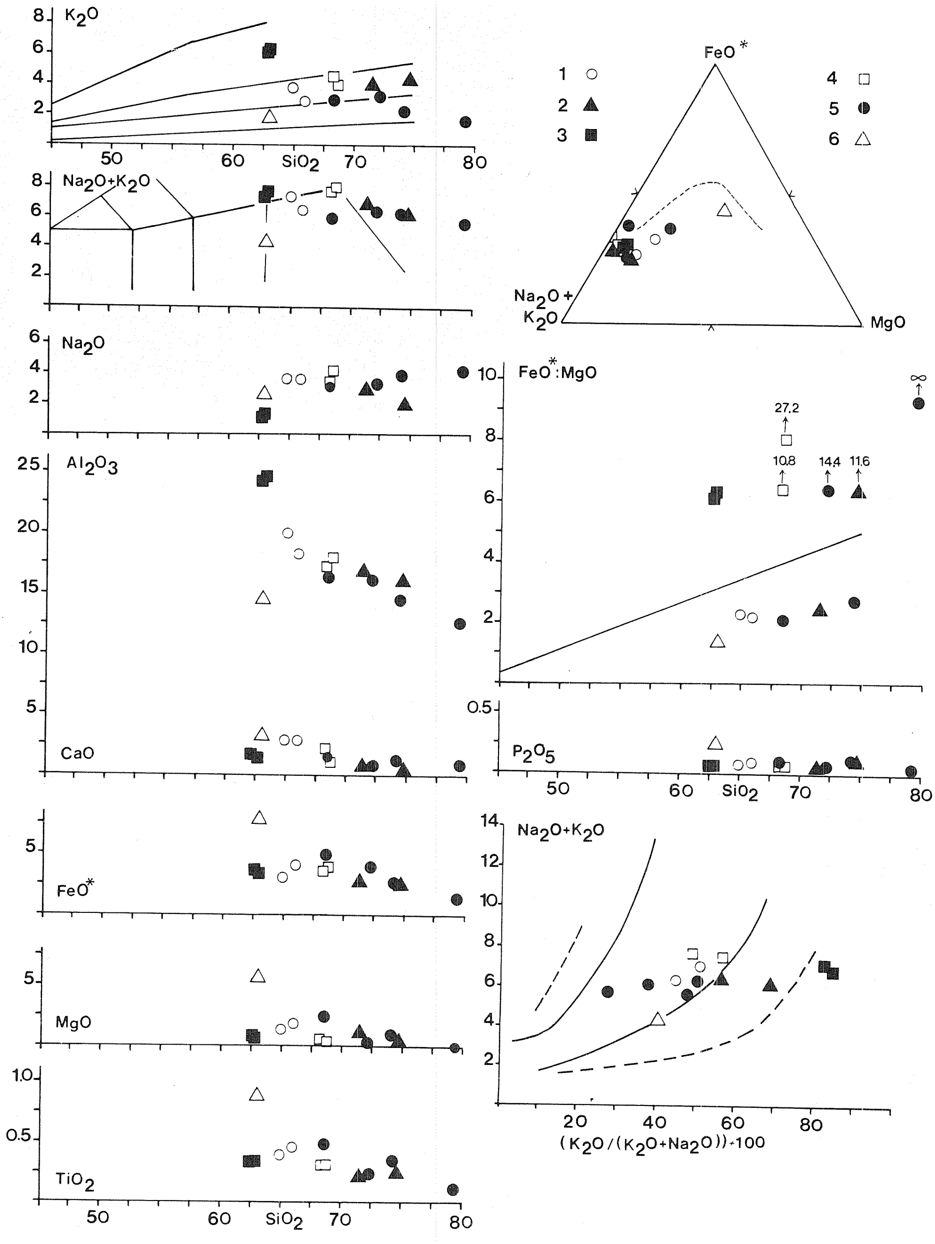


Fig. 37. Harker-type and AFM variation diagrams and igneous spectrum of the felsic and intermediate rocks between the Lower and the Upper Volcanic Unit at Ylöjärvi in the northern limb of the major syncline. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 217 and 281 from the southernmost part of the area; 2. samples 218 and 417/79 from fragmental rhyolitic rocks; 3. samples 219 and 220; 4. samples 221 and 222; 5. samples 223 and 282—284; 6. sample 413/79.

being intensive, deformation may have also contributed to alteration.

Interbeds of pelites-greywackes are common in the area of samples 282 (68% SiO_2) and 283

(74% SiO_2). Sedimentary mixing has affected the composition of these rocks but was not influential in sample 284 (80% SiO_2).

Samples 217 and 281 have not been mixed with pelites because their strata do not contain pelitic interbeds or clasts. Alterations similar to those in samples 219—220 are not apparent. Samples 217 and 281 better represent primary compositions than most of the other rocks of the area now discussed.

The Upper Volcanic Unit at Ylöjärvi in the southern limb of the major syncline

General description and petrography

The Upper Volcanic Unit at Ylöjärvi is characterized by mafic rocks in the southern limb of the major syncline. Near Lake Hirvijärvi, outside the area now discussed, there occur felsic rocks and sericite schists. Samples 164 (rich in sulphide minerals) and 165 (57% SiO_2) are from an outcrop near Lake Hirvijärvi.

The mafic rocks are partly massive and partly fragmental (Fig. 38.a). There seem to be both lavas and pyroclastic rocks. The major minerals include plagioclase + chlorite ± quartz ± epidote ± carbonate ± biotite ± magnetite ± rarely muscovite. Sphene and tourmaline, among others, occur as minor and accessory constituents.

Plagioclase occurs partly as small phenocrysts ($\varnothing < 0.5$ mm) which amount to 0—30 vol.%. Some aggregates of epidote ± carbonate may be pseudomorphs after larger phenocrysts. Plagioclase varies from labradorite-andesine to albite-oligoclase even in single grains. In certain samples, the centres of plagioclase microphenocrysts (about An_{50}) are brownish and display oscillatory zoning (Fig. 38.b). These centres seem to have escaped complete recrystallization. In places the plagioclase laths are oriented in a manner resembling a pilotaxitic texture. In some instances the zoning of plagioclase is cut by grain boundaries and the grains are parts of broken crystals.

Chlorite is mostly Mg-rich but in some samples both Mg- and Fe-rich varities are present. Quartz and carbonate (the latter may approach 15 vol.%) occur both as evenly distributed grains and as aggregates. Magnetite (up to 20 vol.%) is frequently present as small porphyroblasts (see Simonen, 1952). Biotite occurs as small non-oriented porphyroblasts and cuts older chlorite. It has partly altered to chlorite. In sample 176 the late-stage character of biotite is clearly observed; muscovite-rich layers with metamorphic fabric have been crenulated, and biotite has grown parallel with the axial plane.

Geochemistry and petrology

The rocks of the Upper Volcanic Unit at Ylöjärvi in the southern limb of the syncline are mostly medium-K or low-K basalts and basaltic andesites (Fig. 39). Most are in the tholeiitic fields but the trends are dispersed. When the deviating samples 164, 165 and 174—177 (see below) are ignored, tholeiitic affinities are more pronounced than calc-alkaline affinities. The Ti-Zr diagram (Fig. 40) does not unanimously indicate tholeiitic affinities, but the trace element data are sparse. The Al_2O_3 contents, exceeding mostly 17%, are high. Most of the rocks are in the modified igneous spectrum. The ranges in the Ca, Fe, Mg and Ti contents are wide even within a limited interval of SiO_2. The TiO_2 content often exceeds 1.2% and tends to be higher than in typical young arc basalts. The P_2O_5 contents of 0.2—0.3% and the Zr contents of 130—160 ppm are higher than in young low-K mafic rocks of volcanic arcs but approach or slightly exceed those in medium-K basaltic andesites (Ewart, 1982). The Cr and Ni contents are low. The Sr content is below 400 ppm. The average Sr contents close to these are found in low-K and medium-K arc

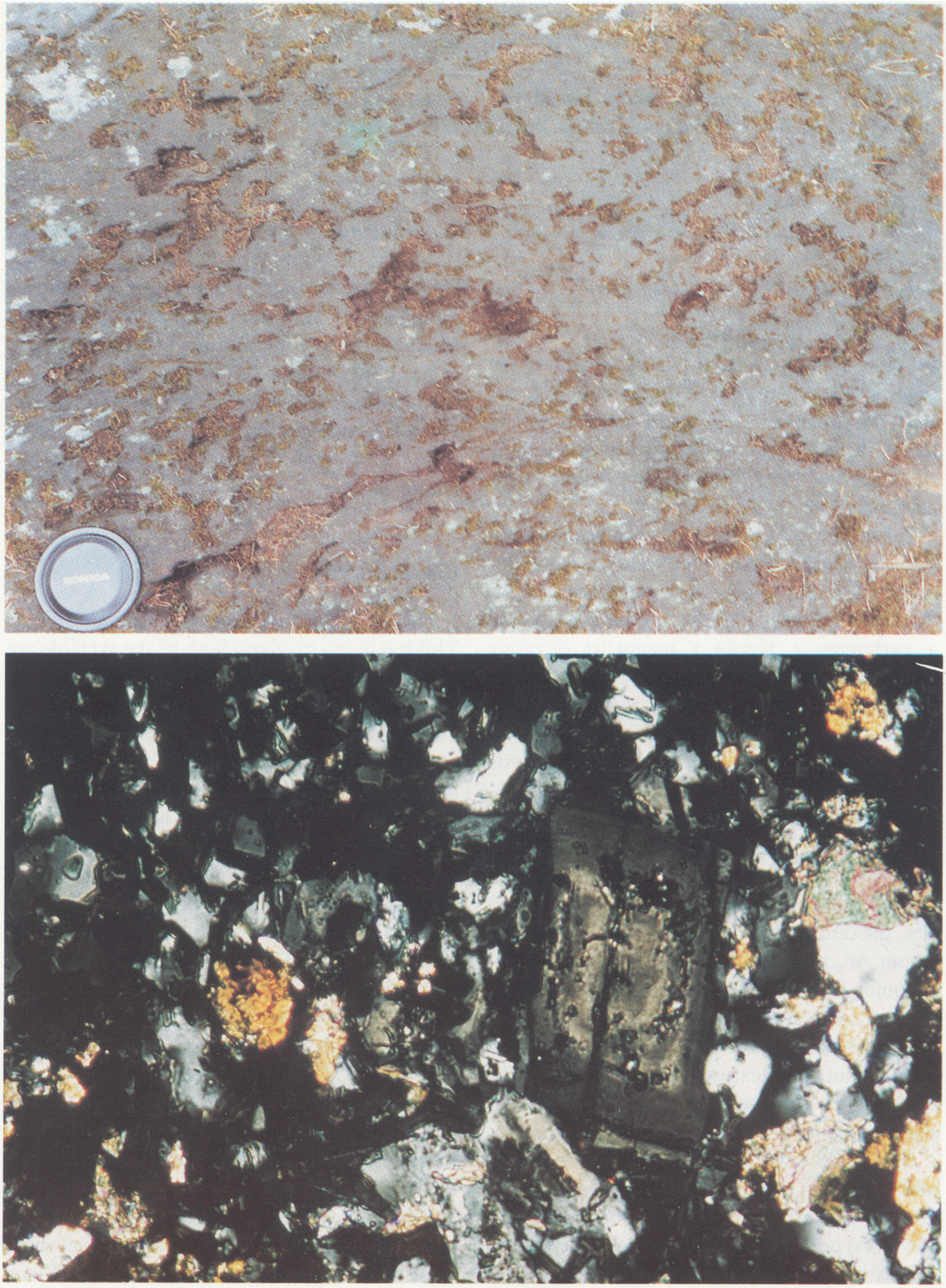
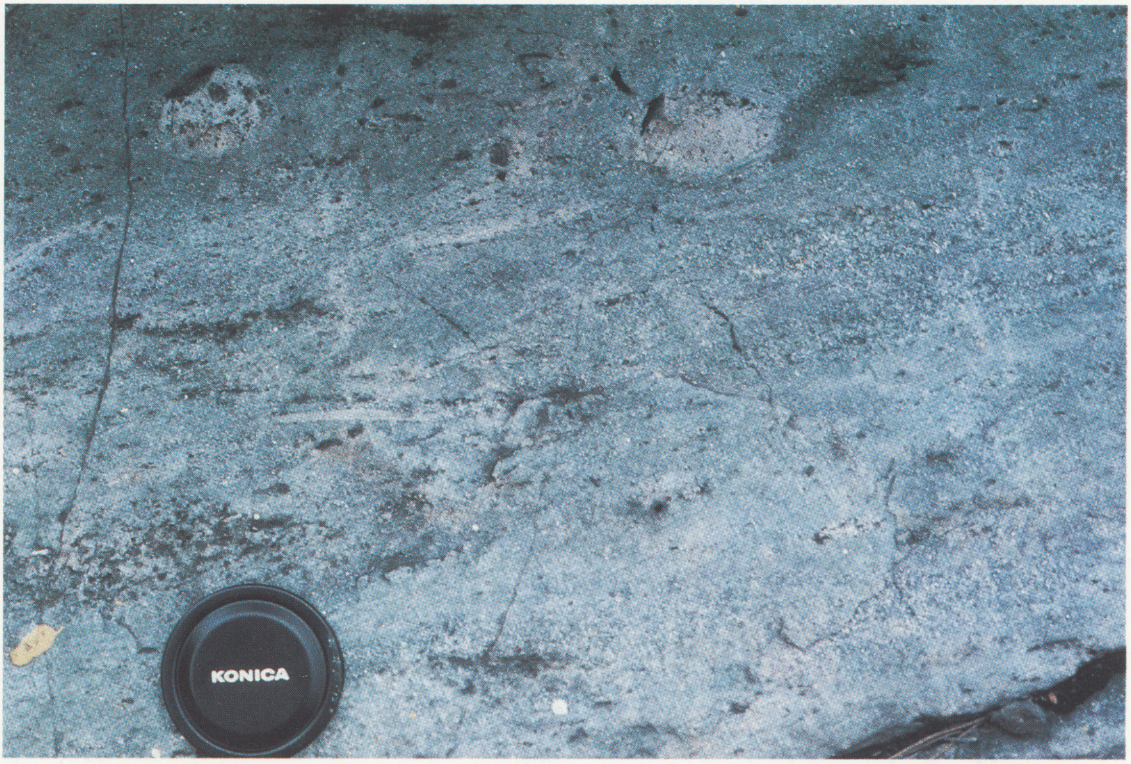


Fig. 38. Structures and textures of the Upper Volcanic Unit at Ylöjärvi. a. Flow-breccia. The area of sample 172, the lens cap is 6 cm in diameter; b. Oscillatory zoning of a microphenocryst of plagioclase. Sample 159, crossed nicols, the field of view is 0.33 mm; c. Polymictic tuff breccia. The area between samples 214 and 215, the lens cap is 6 cm in diameter; d. Rounded pebble in a volcanic conglomerate. The area of sample 276, the scale bar is 10 cm long.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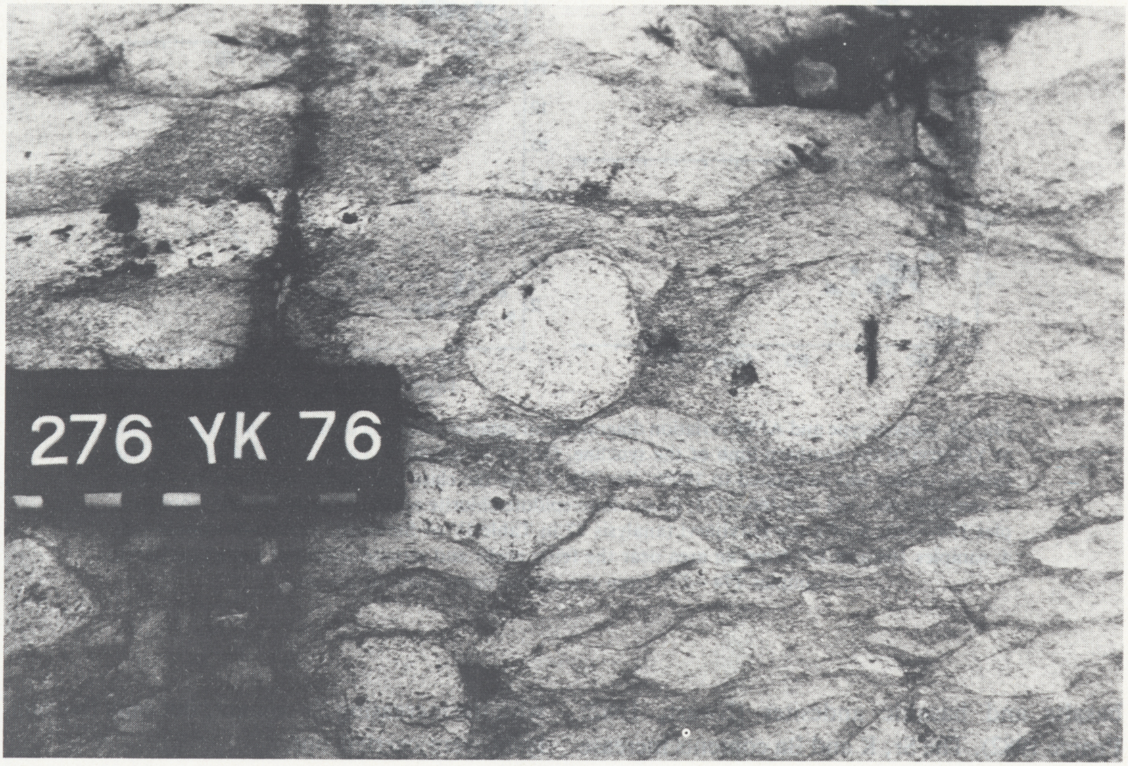
276 YK 76

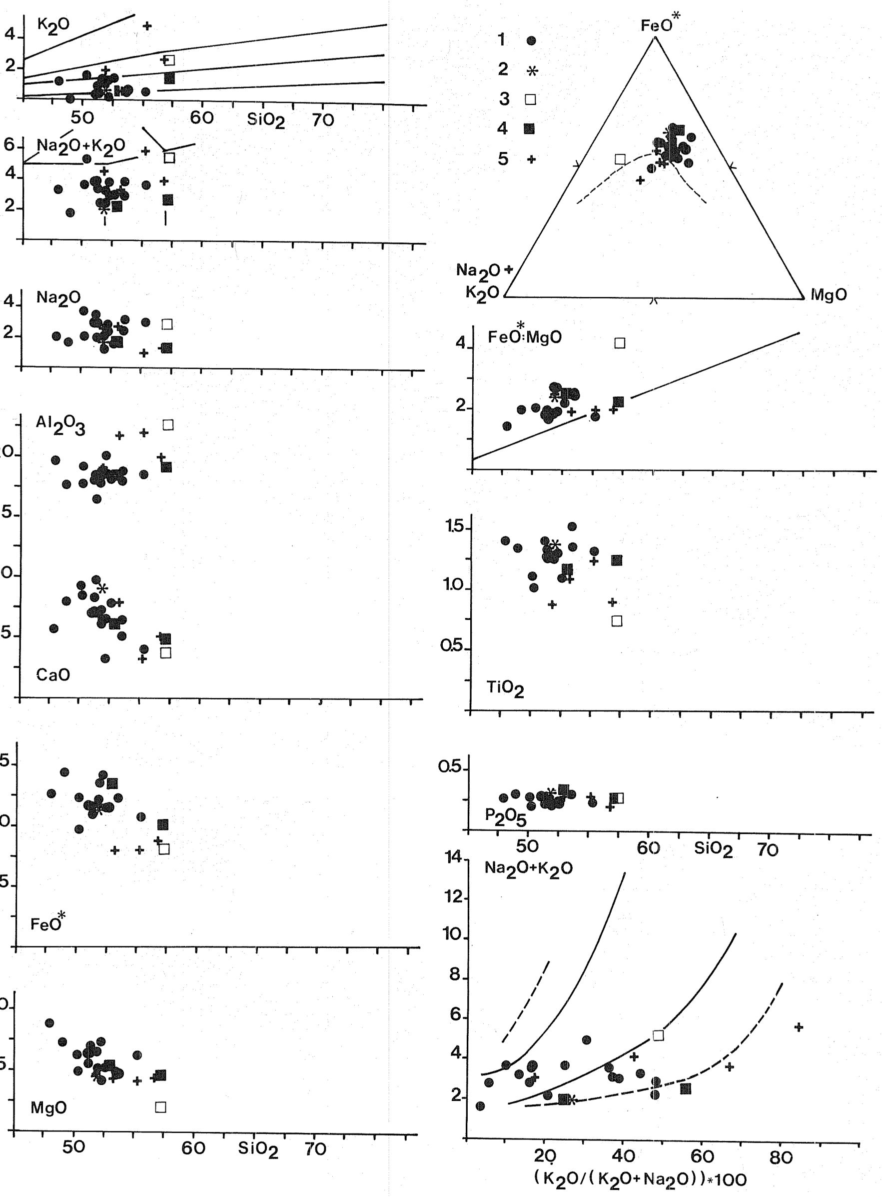

Fig. 39. Harker-type and AFM variation diagrams and igneous spectrum of the Upper Volcanic Unit at Ylöjärvi in the southern limb of the syncline. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 156—163 and 166—173; 2. an albite-epidote-chlorite schist about 400 m NE from samples 158—163, S of Lake Hirvijärvi (analysis 17 in Table IV of Simonen, 1953a); 3. sample 155; 4. samples 164 and 165 from an area near the felsic rocks and sericite schists of Lake Hirvijärvi; 5. samples 174—177 from the northernmost part of the area.

basalts and basaltic andesites (Ewart, 1982; Pearce 1982). The Sr, K and Ba contents increase with the increasing Zr content, but only five analyses were carried out.

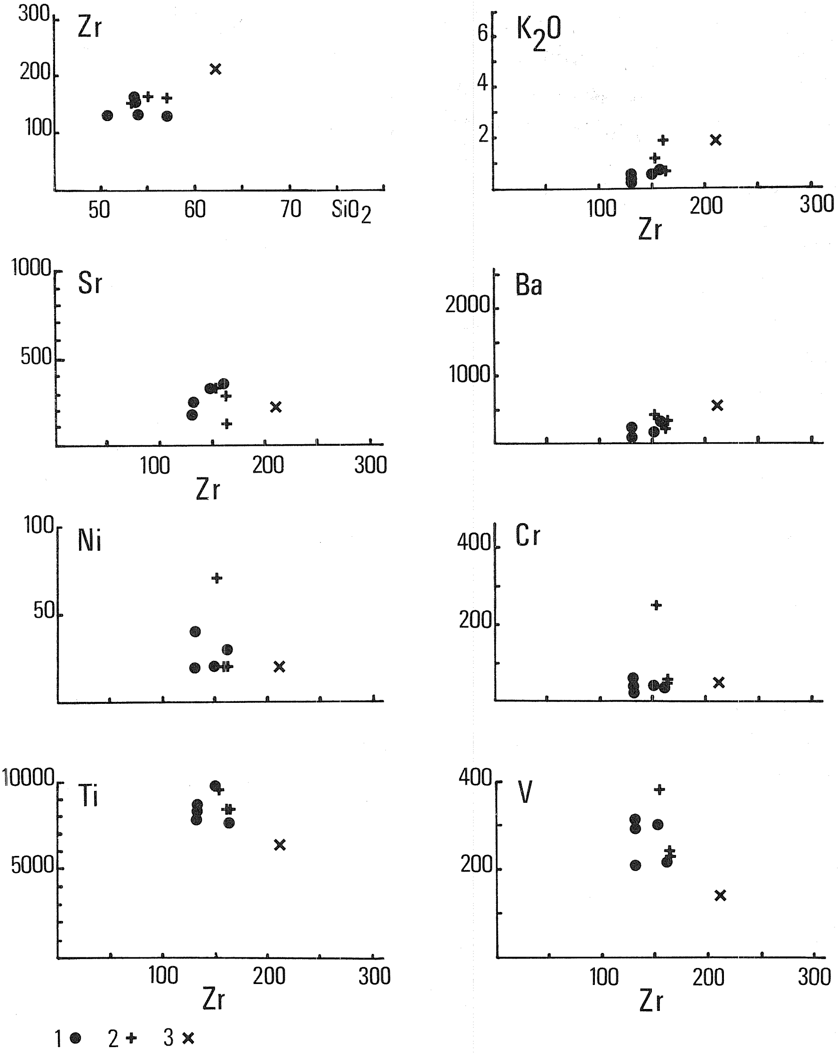

Fig. 40. Zr-SiO$_2$, K$_2$O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Upper Volcanic Unit at Ylöjärvi in the southern and northern limb of the syncline. Data from Table I. SiO$_2$ and K$_2$O in weight%, elements in ppm. Symbols: 1. samples 159, 160, 166, 171 and 172 from the southern limb; 2. samples 213, 215 and 216 from the northern limb; 3. sample 204 from the northern limb.

Simonen's (1953a) sample is similar to the rocks discussed above (Fig. 39). It is a good representative of the Upper Volcanic Unit at Ylöjärvi.

There are some exceptions to the generalizations mentioned above. Sample 155 is a high-K andesite. Its composition is attributed to the abundance of sericite and to the aggregates and veinlets of quartz. Samples 164 and 165 are out of the ordinary because the former is rich in sulphides and the latter is relatively rich in silica. They are associated with the felsic rocks and sericite schists near Lake Hirvijärvi rather than with the typical rocks of the Upper Volcanic Unit.

Samples 174—177 often occur in high-K or even very high-K fields and are partly low in Na. Sample 176, the very high-K rock, contains folded layers rich in muscovite and late-grown biotite (p. 77). This rock and the rocks nearby have been affected by compositional changes. When these samples are ignored there still exists a wide dispersion in K. This is partly attributed to sericitization. For instance, sample 163 (about 50% SiO_2) is a high-K rock and contains a dense network of sericite in the groundmass. On the other hand, the very low K content in sample 166 (Table I) may be a result of leaching of K.

The increase in the Sr content with the increasing Zr content (Fig. 40) might indicate partial melting with Sr and Zr behaving incompatibly. The low Ni and Cr contents could indicate mafic rather than ultramafic sources. Since the rocks are basalts and basaltic andesites, high degrees of fusion were needed (e.g., Marsh, 1982; Brophy & Marsh, 1986). However, because there are only five analyses available, the rising Sr-Zr trend may be mere a chance. Indeed, if samples 213, 215 and 216, also from the Upper Volcanic Unit at Ylöjärvi, are considered, the rising Sr-Zr trend is not pronounced (Fig. 40).

The Upper Volcanic Unit at Ylöjärvi in the northern limb of the major syncline

General description and petrography

The rocks of the Upper Volcanic Unit at Ylöjärvi in the northern limb of the major syncline are dominated by pyroclastic basaltic andesites and andesites. They are mostly agglomerates, tuff breccias and lapilli tuffs but certain strata may be described as volcanic conglomerates (Figs. 38.c,d). The stratum of sample 216 is probably of lava origin. A few rhyolitic tuffites (samples 202, 203) are present. Samples 206 and 211 are sericite schists. In the area near sample 206 metamorphic segregation has caused sericitization (Nironen, in press).

The major minerals in the mafic and intermediate rocks (with the exception of the sericite schists) include plagioclase (mostly albite) + quartz ± chlorite ± carbonate (mostly a minor mineral if present at all) ± muscovite (mostly a minor mineral, abundant in samples 193, 196, 279 and 280 as a fine-grained network), and tourmaline (in sample 193). The rocks contain, particularly in the N and NE parts of the area, plagioclase-phyric fragments (phenocrysts with ø < 1.5 mm amount up to 20 vol.%). Pseudomorphs after phenocrysts of pyroxene are rare but were observed in samples 195 and 216 (about 10 vol.% in each). Some of the pyroxene pseudomorphs in sample 216 contain epidote. Chlorite is of both Fe- and Mg-rich types. In sample 213 the both types precede biotite which has partly altered to Fe-rich chlorite. Biotite occurs mostly as late-crystallized grains which cut chlorite and sericite. Small needles of metamorphic hornblende were observed in sample 216.

Geochemistry and petrology

The volcanic rocks of Upper Volcanic Unit at Ylöjärvi in the northern limb of the major syncline, excluding the samples rich in sericite, are mostly medium-K basaltic andesites and andesites (Fig. 41). They tend to show an increase in the K content with the increasing Si content but the dispersion is wide. In general, the rocks of the N and NE parts are less silicic than those of the other parts. The rocks show tholeiitic affinities but a few occur in the calc-alkaline fields. They are mostly in the modified igneous spectrum. The Al_2O_3 content ranges mostly between 16% and 20%. The Ca, Fe, Mg and Ti contents decrease with the increasing Si content but the dispersions are wide. The TiO_2 content of the basalts and basaltic andesites exceeds 1%. The Cr and Ni contents are low but are high in sample 216 with pseudomorphs after pyroxene phenocrysts (Fig.

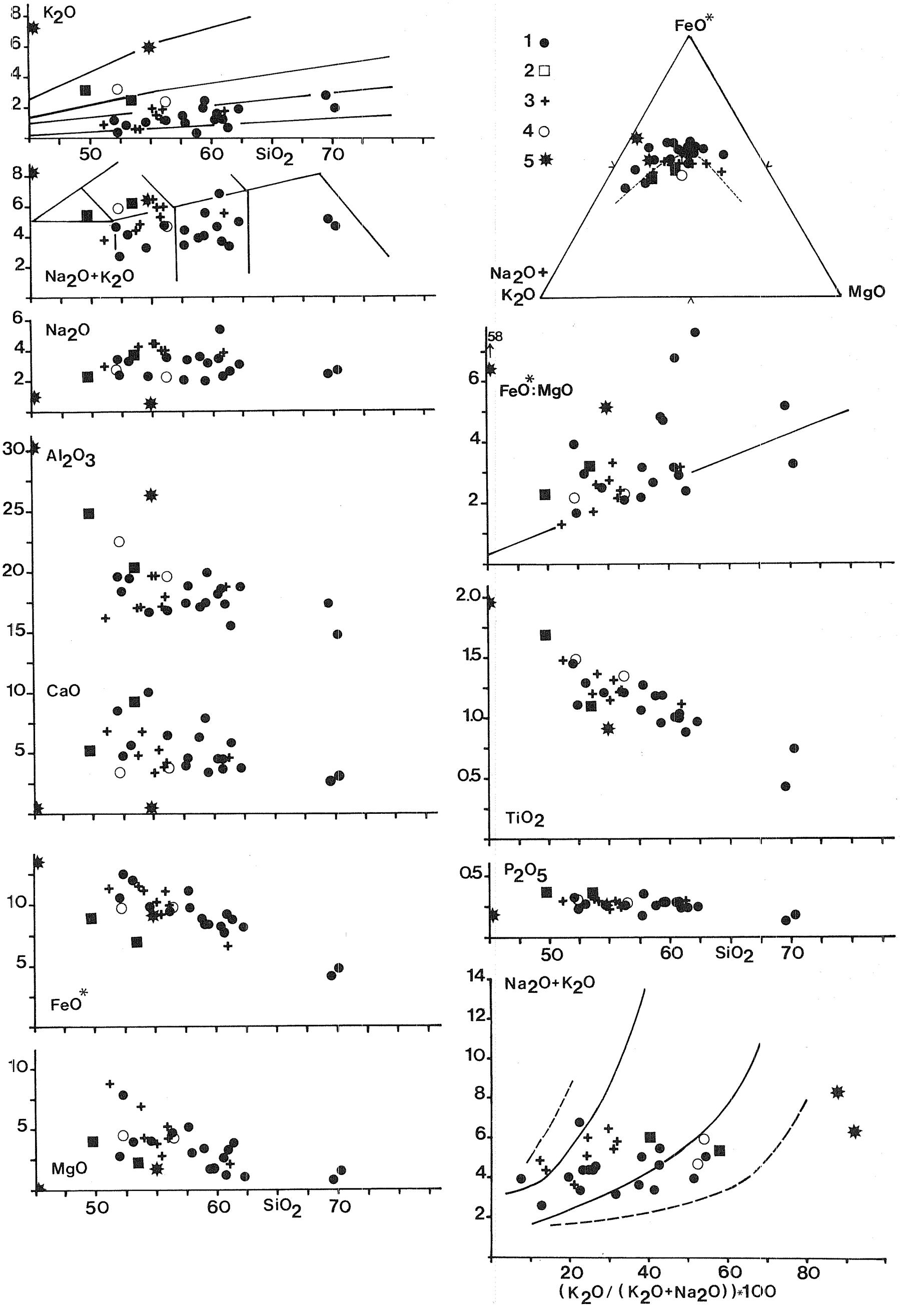

Fig. 41. Harker-type and AFM variation diagrams and igneous spectrum of the Upper Volcanic Unit at Ylöjärvi in the northern limb of the syncline. Oxides in weight%. FeO*: total Fe as FeO. Sum of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 191, 192, 194, 195, 197—205 and 207—210; 2. samples 193 and 196 (altered rocks); 3. samples 212—216 and 276—278; 4. samples 279—280 (altered rocks); 5. samples 206 and 211 (sericite schists).

40; Table I). The basaltic andesites contain 150—160 ppm Zr and the Sr content is below 400 ppm. The Ti content in the andesites, about 1% TiO_2 at 60% SiO_2, tends to be higher than in the andesites of the Lower Volcanic Unit at Ylöjärvi (cf. Figs. 28, 34 and 41).

The rocks of the Upper Volcanic Unit in the northern and southern limb of the major syncline are largely similar in their chemical composition when rocks with equal SiO_2 are compared (Figs. 39 and 41; Table I). When the trace element data from the two areas are considered together, an increase in the Zr content with the increasing Si content, and increases in the K and Ba contents with the increasing Zr content are apparent (Fig. 40). The pooled Sr-Zr pattern is horizontal but dispersed.

The samples rich in sericite deviate from the generalizations presented above. Samples 193, 196, 279 and 280 are relatively high in K and Al. These features are attributed to the abundance of fine-grained muscovite. In addition, a late-stage tourmalinization took place in sample 193.

The two sericite schists, samples 206 and 211, are even more outside the typical ranges. The peculiar compositions (ultra-K, low Na, high Al, low Ca and Mg, high FeO*:MgO ratio) indicate pronounced alteration. The compositional change in sample 206 may have been caused by metamorphic differentiation (p. 82).

When the samples rich in sericite are ignored, many elements still display wide ranges. These dispersions are partly caused by alterations similar to, but less severe than, those described above. A part of the dispersions is primary. For instance, sericite or potassium feldspar are not found in samples 213 and 215. Biotite-bearing domains are found in sample 213 which is higher in K than sample 215 (Table I). Considering the pyroclastic character of these strata (Fig. 38.c), the domains represent pyroclastic fragments. The variation in the K content is here attributed to the heterogeneity of pyroclastic rocks.

Compositional changes, the fragmental structure of the rocks and the scarcity of trace element data restrict petrogenetic discussion. The steeply descending trends in the Cr-Zr and Ni-Zr diagrams, as well as the pseudomorphs after pyroxene phenocrysts in sample 216, suggest that fractional crystallization of mafic phases had a role in controlling the variations in the composition of the basalt and basaltic andesites. However, the dispersions in the K_2O-Zr and Ba-Zr diagrams are so wide that they are difficult to explain by fractional crystallization. Mixing of pyroclastic ejecta is a probable reason for these dispersions. The Cr, Ni and Zr contents in the dacitic sample 204 are so high that this sample cannot be derived from the basaltic andesites with 50—60 ppm Cr and 20 ppm Ni through fractional crystallization with mafic phases in a major role.

The Upper Volcanic Unit at Ylöjärvi in the central parts of the major syncline

General description and petrography

The Upper Volcanic Unit at Ylöjärvi is in the central parts of the major syncline divisible into two parts. Firstly, the area of samples 182—190 is composed of basalts, basaltic andesites and andesites which are often pyroclastic in origin. Secondly, samples 178—180 and 319—322/79 are from a massive plagioclase-phyric andesite-dacite, probably of subvolcanic origin.

Individual strata in the area of samples 182—190 vary from 2 m to 20 m in thickness. The basalts and basaltic andesites with 52—53% SiO_2 (samples 184, 186, 187, 190) are fragmental pyroclastic rocks. Patches of Mg-rich chlorite (ø up to 0.5x4 mm) amount to 10—20 vol.% in samples 184 and 186. The major minerals include andesine/oligoclase + quartz + chlorite + epidote + magnetite ± biotite (a late-grown phase particularly in the chlorite patches).

Two of the basaltic andesites have 55—56% SiO_2. Sample 183 is from a pyroclastic stratum with 20—30 vol.% fragments rich in Fe-chlorite (ø up to 2x20 cm). Sample 185 is from a homogeneous even-grained stratum about 2 m thick. The major minerals in these samples include oligoclase/andesine + quartz + chlorite + biotite (cuts chlorite) ± muscovite (only a minor phase in sample 185).

The andesites with 60—63% SiO_2 derive partly from a homogeneous stratum (sample 182) and partly from fragmental pyroclastic strata (samples 188 and 189). They contain about 10 vol.% phenocrysts of plagioclase (ø <2 mm). The major minerals in sample 182 include oligoclase/albite + quartz + muscovite (as a fine-grained network) + biotite (cuts muscovite).

Plagioclase phenocrysts in the subvolcanic samples 178—180 and 319—322/79 amount to 10—40 vol.%. They are large with ø up to 10 mm. A few aggregates of biotite ± epidote ± opaques are pseudomorphs after phenocrysts of hornblende. The major minerals include plagioclase (mainly oligoclase) + quartz + biotite + epidote ± carbonate. Sample 319/79 contains metamorphic blue-green hornblende.

Geochemistry and petrology

The rocks of the Upper Volcanic Unit at Ylöjärvi in the central parts of the syncline are subalkaline and, when regarded as a group, have tholeiitic affinities in the AFM and FeO*:MgO vs. SiO_2 diagrams (Fig. 42). They range from low-K and medium-K rocks at 52—55% SiO_2 to predominantly high-K rocks at 57—63% SiO_2 (see also Table I). Most samples occur in the igneous spectrum. The P and Zr contents in the samples low in K are higher than those in young low-K arc basaltic andesites but similar to those in medium-K arc basaltic andesites on an average (Ewart, 1982). The Sr contents of below 400 ppm and the Zr contents of 170—310 ppm in the andesites and dacites are more like the averages in medium-K than those in high-K arc andesites and dacites (Ewart, 1979, 1982). The K and Zr contents increase, and the Ti, Mg and Fe contents decrease with the increasing Si content but the dispersions are partly wide (Figs. 42 and 43). The Sr-Zr trend is horizontal. The Ca, Na and Al contents are widely scattered in the samples 182—190 with 52—57% SiO_2. In the massive plagioclase-phyric samples 178—180 and 319—322/79, the Ca and Mg contents display decreases and the Al content an increase with the increasing Si content. Sample 184 is higher in Cr and Ni than the other samples analyzed for trace elements. The andesites and dacites tend to be higher in Ti than most of the andesites and dacites of the Lower Volcanic Unit at Ylöjärvi (cf. Figs. 28, 34 and 42).

The wide dispersions are attributed partly to alteration and partly to the heterogeneity of the rocks. Sample 183 has a high K content, a low Na content, occurs outside the igneous spectrum, and has been sericitized. An increase in the K content is possible also in sample 182 (about 63% SiO_2) because of the presence of the fine-grained network of muscovite. Petrographic investigations indicate that similar changes are less pronounced or not probable in sample 185 and in samples 178—180 and 319—322/79.

The relatively high Cr and Ni contents in sample 184 are petrographically explained by patches of Mg-chlorite, and the composition of this rock is attributed to mixing of pyroclastic ejecta. Sample 183 is not rich in Cr and Ni because its mafic patches consist of Fe-chlorite which has probably a lower Cr and Ni content than Mg-chlorite.

Sample 182, when compared with sample 185, has a higher Zr content but similar Ni and Cr contents. It is not derived from the latter through fractional crystallization with mafic minerals in a major role.

In the massive samples 178—180 and 319—322/79, the decrease in the Fe, Mg and Ti contents with the increasing Si content, and the simultaneous increase in the FeO*:MgO ratio might indicate fractionation of hornblende; par-

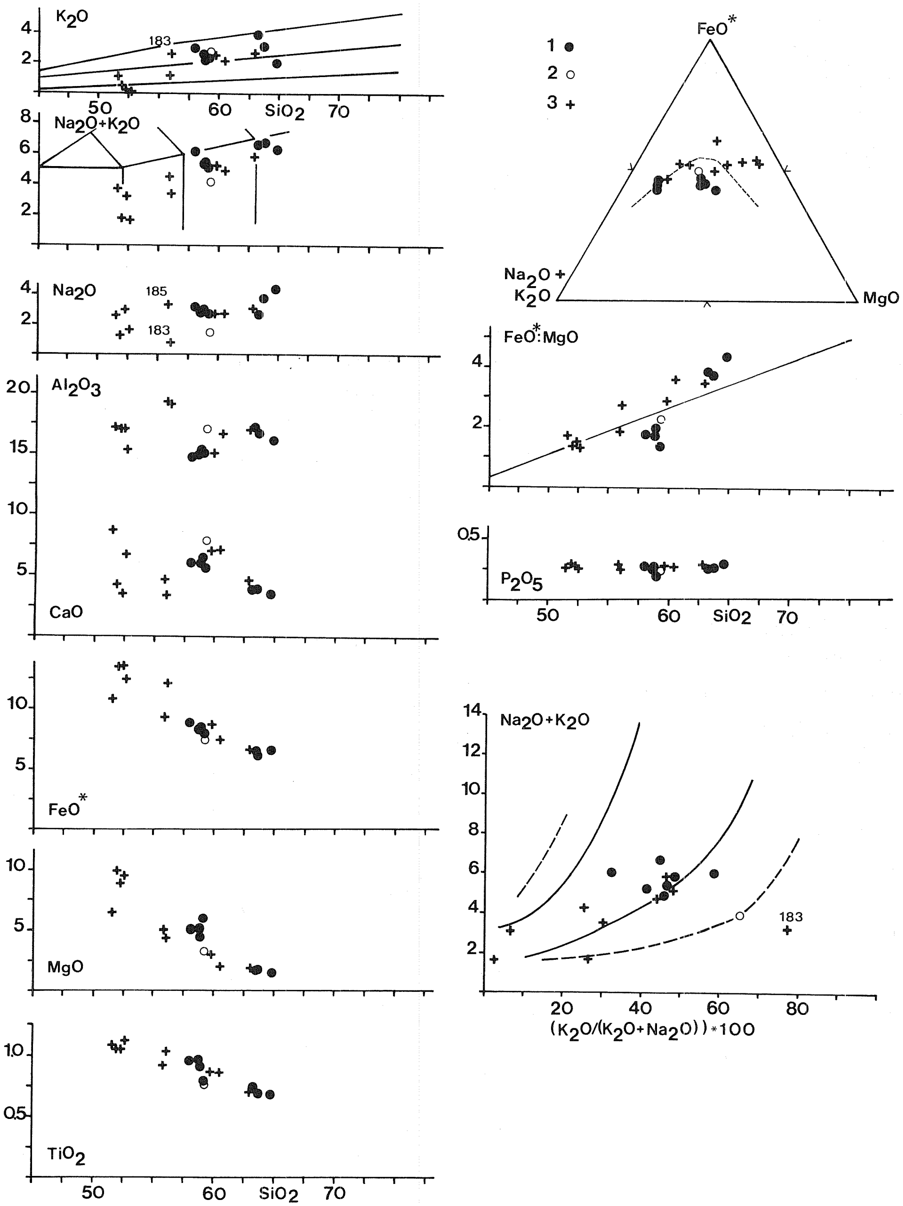

Fig. 42. Harker-type and AFM variation diagrams of and igneous spectrum of the Upper Volcanic Unit at Ylöjärvi in the central parts of the syncline. Oxides in weight%. FeO*: total Fe as FeO. The total of oxides was calculated to 100%. See Fig. 11 for the class boundaries and boundary lines. 1. samples 178—180 and 319—322/79; 2. sample 181; 3. samples 182—190.

ticularly as the rocks contain pseudomorphs after amphibole (p. 85). The phenocrysts of plagioclase are so abundant that plagioclase should also have fractionated. This suggestion is supported by the decrease in the Ca content with the increasing Si content but not, significantly, by the simultaneous increase in the Al content. Furthermore, the increase in the FeO*:MgO ratio is too abrupt to have been caused by fractionation of hornblende which probably has an

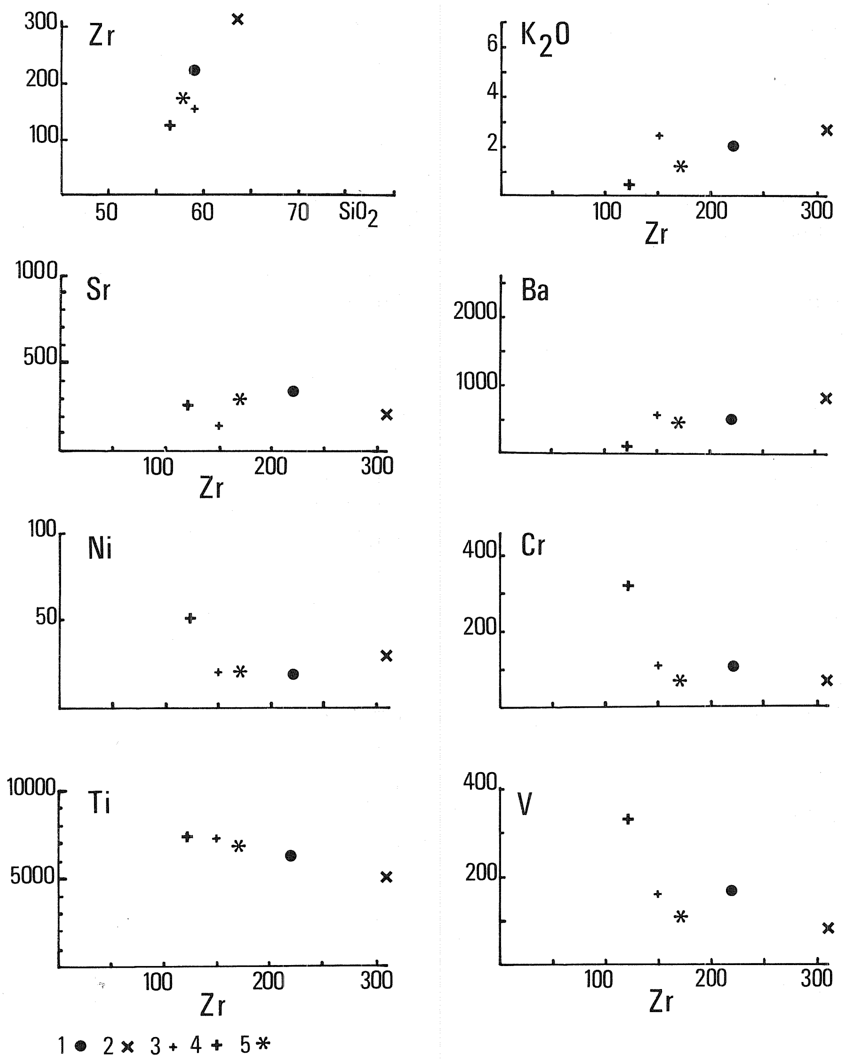

Fig. 43. Zr-SiO_2, K_2O-Zr, Sr-Zr, Ba-Zr, Ni-Zr, Cr-Zr, Ti-Zr and V-Zr diagrams of the rocks of the Upper Volcanic Unit at Ylöjärvi in the central parts of the syncline. Data from Table I. SiO_2 and K_2O in weight%, elements in ppm. Symbols: 1. sample 179; 2. sample 182; 3. sample 183; 4. sample 184; 5. sample 185.

FeO*:MgO ratio close to unity (Gill, 1981). The controversies are, at least partly, attributed to the abundance of phenocrysts. These rocks are not good representatives of melt compositions.

SUMMARY OF GEOCHEMISTRY AND PETROLOGY

The volcanic rocks of the Tampere Schist Belt, when taken as a whole, display wide dispersions in chemical composition. They vary from basalts to rhyolites, from subalkaline types to alkaline types, from low-K rocks to very high-K rocks, and have both calc-alkaline and tholeiitic affinities. Calc-alkaline medium-K and high-K intermediate rocks are the most typical variety. The K_2O:Na_2O ratios in the rhyolitic rocks are mostly close to or in excess of unity. General similarities with volcanic rocks of convergent plate margins are evident.

The dispersion is partly caused by compositional changes, mixing during eruption and redeposition, and accumulation of phenocrysts and clasts. Consequently, the compositions of the rocks do not always adequately represent the composition of the magma.

In spite of alteration and other confusing factors, the volcanic rocks of the Tampere belt may be divided into chemo-stratigraphic units. Each of the units has certain lithological and geochemical properties of its own. The dispersions within the units are smaller than those in the whole of the belt. Most of the deviating compositions are caused by alteration. Low-pressure fractional crystallization can explain a part of the variation trends within some units but other igneous processes must be considered in many instances.

At Orivesi, the Intermediate Unit is about 1 km thick and lies lowermost in the sequence in the northern limb of the major syncline. It is dominated by pyroclastic calc-alkaline high-K dacites, trachydacites and andesites. Compositional changes have caused both increases and decreases in the alkali metal contents. The intermediate rocks display a rising slope in the Sr-Zr diagram. This feature is not caused by alteration. It can be explained by variations in the degree of partial melting or fractional crystallization at depths where plagioclase was not stable, but mixing and liquid-state differentiation can yield a similar trend. The rhyolites vary from very high-K rocks to medium-K rocks. Fractionation of plagioclase played a major role in the genesis of certain rhyolites. The few mafic rocks are mostly metamorphosed alkaline dykes near highway 9 but near Lake Teerijärvi the unit contains subalkaline mafic rocks in two horizons.

In the shear zone between the Intermediate Unit and the Subalkaline Basaltic to Rhyolitic Unit, alkali metals and silica have been mobilized. According to their present composition the rocks are calc-alkaline high-K and very high-K dacites and rhyolites. Primarily they were intermediate and felsic volcanic rocks.

The Subalkaline Basaltic to Rhyolitic Unit at Orivesi overlies the Intermediate Unit and is about 150 m thick in the profile studied. It consists mainly of distal pyroclastic and other volcaniclastic rocks not necessarily derived from a single vent. Certain parts of the unit are bimodal because of the repeated variation of mafic and felsic strata. In all, however, andesites and dacites are also frequent. The rocks are characterized by subalkaline medium-K and high-K compositions and they have calc-alkaline affinities. The andesites tend to be lower in K than the basalts but the data are not sufficient to determine whether this is a primary feature or caused by alteration. Redeposition has affected the composition of many of the felsic strata.

The Shoshonitic Unit at Orivesi overlies the former and is up to 130 m thick in the profile investigated. It is characterized by very high-K basaltic trachyandesites and trachyandesites. The K_2O:Na_2O ratios are near unity. The FeO^*:MgO ratios are constant and low. The Cr, Ni and Zr contents are relatively high and dispersed. The K_2O and Zr contents decrease with the increasing SiO_2 content and the K_2O content increases with the increasing Zr content. These features are not caused by alteration or fractional crystallization. They can be explained by mixing of very high-K trachybasalts or basaltic trachyandesites with high-K intermediate magmas, or by assimilation of slightly older crust low enough in K and Zr by trachybasalts.

The overlying Trachytic Unit at Orivesi is up to 100 m thick and may be traced for about 10 km in the E-W direction. It is dominated by pyroclastic very high-K trachytes which have K_2O:Na_2O ratios near unity. The FeO^*:MgO ratios are widely dispersed and high. Some scattering in the K, Ca and Si content is caused by secondary changes. Dry melting of mafic rocks is thought to explain the high FeO*:MgO ratios and trachytic composition. Similar rocks are found at several stratigraphic levels in the Tampere Schist Belt.

The overlying conglomerates-pelites were partly derived from sources resembling the Trachytic Unit, but the samples analyzed have intermediate volcanic provenances which differ from the two underlying alkaline units.

The Shoshonitic Unit and the Trachytic Unit are also exposed in the southern limb of the major syncline at Orivesi. The underlying sequence in the southern limb contains both volcanic and sedimentary rocks. The analyzed rocks are from the uppermost parts of the succession. They vary form basaltic andesites and basaltic trachyandesites to rhyolites and from medium-K types to very high-K types. Two very high-K basaltic trachyandesites are similar to the rocks of the Shoshonitic Unit.

The Vaavujärvi sill lies in the southern limb of the major syncline. It is up to 400 m thick and 6 km long. The rocks are mostly high-K trachyandesites. The major parts of the sill have higher Si, Zr, Sr, Mg and Cr contents and lower Na, Al, Fe, Ti and P contents than the contact zones. The peculiar features are explained by albitization in the contact zones and accumulation and silicification in the major parts.

The Kämmenniemi area comprises an anticline in the northern limb of the major syncline. It is characterized by volcanic rocks but there are also redeposited strata. The rocks are mostly calc-alkaline high-K dacites and trachydacites. The variation trends are coherent for most elements. The few mafic rocks, occurring typically as tuffitic strata, are mostly high-K basaltic andesites. Because of the low P_2O_5 content of about 0.2% the high-K feature of these mafic rocks is not regarded as primary but is attributed to mixing and alteration.

In the profile investigated, the Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline is only 100 m thick. Here the unit is characterized by massive andesites and dacites which straddle the low-K/medium-K boundary. The low K content is probably primary because the Sr, Zr and P contents are relatively low. The intermediate rocks display Fe-enrichment but the decrease in the Ti content with the increasing SiO_2 content is also pronounced. The Sr-Zr tend is horizontal and the Cr, Ni, Ti and V contents decrease steeply with the increasing Si and Zr contents. These features might indicate fractional crystallization of assemblage plagioclase + clinopyroxene + hornblende, but the horizontal K_2O-SiO_2, K_2O-Zr and Ba-Zr trends are controversial. The rhyolites resemble the andesites and dacites in showing K_2O:Na_2O ratios well below unity, but deviate from them in having calc-alkaline affinities and relatively high Cr and Ni contents. Mixing with pelites is probable.

The overlying sedimentary rocks and Simonen's (1953a) data show that the Lower Volcanic Unit at Ylöjärvi contains in the southern limb of the major syncline also medium-K and high-K basalts and basaltic andesites with variable Ni, Cr and Mg contents, as well as very high-K basaltic trachyandesites and trachyandesites rich in Ni and Cr. The latter resemble the rocks of the Shoshonitic Unit at Orivesi. High-K/medium-K andesites and dacites and low-K/medium-K dacites were also present in the source areas. The overlying succession also contains medium-K basaltic andesites as sills and as a fragmental lava. These volcanic rocks are lower in Al and P than the typical basaltic andesites of the Upper Volcanic Unit at Ylöjärvi. There are also intermediate and rhyolitic volcanic rocks and a calc-alkaline low-K subvolcanic dacite.

The Lower Volcanic Unit at Ylöjärvi is about 1 km thick across the strike in the northern limb of the major syncline. It is composed mainly of pyroclastic medium-K and high-K basaltic andesites, andesites and dacites with calc-alkaline affinities. The rocks display wide compositional dispersions. This is caused partly by compositional changes which are most pronounced in and on the margins of fault zones. Another reason is that the unit might be divided into smaller parts. For instance, the northernmost (and lowermost) part is composed of intermediate rocks, while the rocks of the area immediately to the south vary from basalts to rhyolites. The uppermost strata of this unit are characterized by stratified intermediate rocks. The Cr content in the andesites and dacites is relatively high. In the uppermost part this is caused by mixing during redeposition but in the lowermost part it is a primary feature of magmas.

The felsic and intermediate rocks between the Lower Volcanic Unit and the Upper Volcanic Unit in the northern limb of the major syncline show signs of alteration and deformation. The K_2O, Na_2O and Al_2O_3 contents and the FeO*:MgO ratios are highly variable. These features are attributed to weathering, decomposition or deformation. Mixing during sedimentation has also contributed to the compositions. A few strata have escaped these processes.

The Upper Volcanic Unit at Ylöjärvi is characterized by medium-K basalts, basaltic andesites and andesites which have tholeiitic affinities. Basalts and basaltic andesites are most abundant in the southern limb but are also frequent near the NE-boundary of the unit. The Cr and Ni contents are mostly low. Sericitization has caused an increase in the K content in several samples. Another reason for the variations is mixing of pyroclastic ejecta. The basalts and basaltic andesites tend to have higher Ti and Zr contents than most of the mafic rocks of the Lower Volcanic Unit at Ylöjärvi. The andesites and dacites are mostly higher in Ti than the andesites and dacites of the Lower Volcanic Unit at Ylöjärvi. In the central parts of the unit there occurs a massive plagioclase-phyric high-K andesite-dacite which is probably of subvolcanic origin.

COMPARISONS

Comparisons with Archaean greenstone belts

The Tampere Schist Belt is merely a part of the Svecofennian terrain. Comparison of an individual belt with Archaean greenstone belts formed during a period of about 1 Ga might be questionable. In spite of this, some similarities and differences are evident.

The Tampere Schist Belt and Archaean greenstone belts are similar in that turbidites dominate among the sedimentary rocks and low-Ti rocks are common among mafic volcanic rocks (cf. Goodwin, 1977, 1981; Condie, 1981, 1985). A short time span of igneous evolution is also a common feature although volcanic activity in some Archaean belts lasted for 0.3 Ga (cf. Condie, 1981; Ayres & Thurston, 1985). Structures are similar in that isoclinal folds with subvertical axial planes characterize most Archaen greenstone belts. The depositional basement of Archaean successions is often unknown but in places the supracrustal rocks were deposited on older sialic rocks. In some areas with unknown basement there is evidence of the existence of older sialic crust nearby (Goodwin, 1981; Ayres & Thurston, 1985; Kröner, 1985). A sialic basement of the Tampere succession is not known although a preceding early Proterozoic volcanic and crustal evolution is possible (see Ojakangas, 1986; Huhma, 1987; Kähkönen, 1987). The Tampere Schist Belt is a Proterozoic greenstone belt.

There also exist differences. Komatiites, pillow lavas and iron formations are either absent or rare at Tampere, while they are frequent in Archaean greenstone belts (cf. Condie, 1981). The average composition of the volcanic rocks at

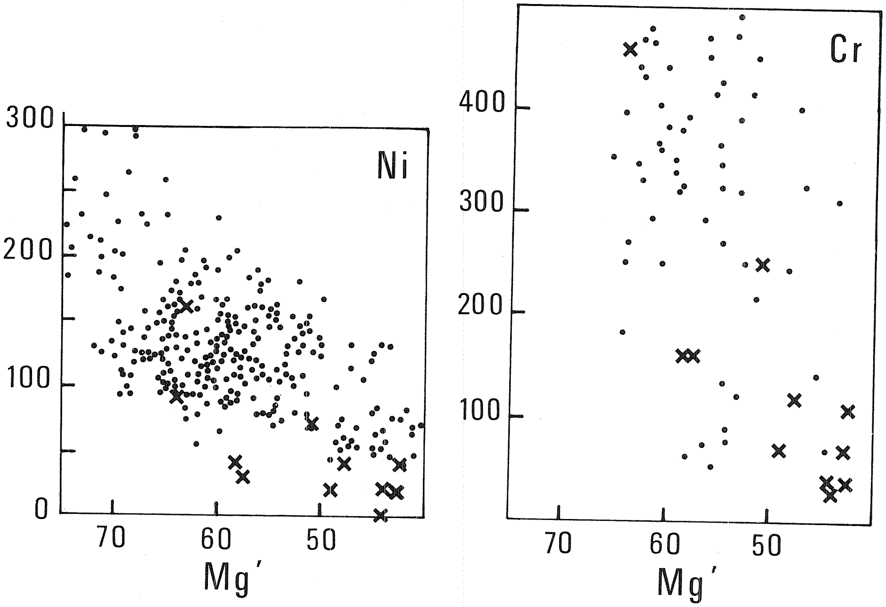

Fig. 44. Ni-Mg' and Cr-Mg' diagrams of mafic volcanic rocks of the Tampere Schist Belt and Archaean greenstone belts. Mg' = Mg/(Fe^{2+} + Mg), Fe_2O_3:FeO was set at 0.15. The crosses represent the mafic rocks of this study (SiO_2 < 54 %; data from Table I) and the dots represent Archaean greenstone belt basalts (Cr: Gill, 1979; Ni: Condie, 1985).

Tampere is less mafic than that in typical Archaean successions (cf. Goodwin, 1977, 1981; Condie, 1981; Thurston *et al.*, 1985). Calc-alkaline medium-K and high-K intermediate volcanic rocks, as well as shoshonites and trachytes are more frequent at Tampere than in Archaean belts. Cyclicity of volcanism, typical of many Archaean greenstone belts, is not a pronounced feature at Tampere. The Archaean trend such that intermediate and felsic volcanic rocks and sedimentary rocks are proportionally more abundant higher in the sequence than lower in the sequence is not evident in the study areas at Tampere.

When compared with younger basalts with equal Mg' values, the Archaean basalts are higher in Ni and Cr (Gill, 1979; Condie, 1985). This concerns also the Ni contents in the mafic rocks of the Tampere Schist Belt, but the difference is not pronounced for Cr (Fig. 44).

Comparisons with early Proterozoic successions

Condie (1982c) divided the early to middle Proterozoic supracrustal successions into three major categories: (I) quartzite-carbonate-shale successions of stable continental margins or intracratonic basins, (II) bimodal volcanics-quartzite-arkose successions of continental rifts, and (III) continuous (tholeiitic and calc-alkaline) volcanics-greywacke successions of cratonic rifts or convergent plate margins. Certain successions have characteristics of more than one category. The Svecofennian successions in Finland and Sweden are one of the examples of assemblage

(III) and they contain also rocks not typical of this assemblage. The Tampere Schist Belt is, however, a good representative of assemblage (III).

The Svecofennian supracrustal rocks vary from well-preserved greenschist or amphibolite facies rocks to higher-grade gneisses and migmatites. The well-preserved belts are synclines with subvertical axial planes and gently plunging fold axes (Latvalahti, 1979; Vivallo & Rickard, 1984; Claesson, 1985; Lagerblad & Gorbatschev, 1985; Colley & Westra, 1987; Nironen, in press; this study). The gneisses and migmatites, as well as some belts with well-preserved primary structures show signs of an early recumbent folding (Campbell, 1980; van Staal & Williams, 1983; Bleeker & Westra, 1987; Colley & Westra, 1987).

The northern and southern Svecofennian provinces are dominated by volcanic rocks (Gaál & Gorbatschev, 1987). Certain volcanic successions in the southern Svecofennian province are interbeds in thick sedimentary sequences (Ehlers *et al.*, 1986; Lundström, 1987). On the other hand, some successions of the central Svecofennian province are rich in volcanic rocks. The Haukkamaa succession at Kuru, about 60 km north of Tampere, is dominated by volcanic rocks (Tiainen & Kähkönen, in prep.). The proportion of volcanic rocks to sedimentary rocks in the Tampere Schist Belt is about 1:1 (Figs. 2 and 4).

The interpretation of Svecofennian stratigraphic successions varies from belt to belt and also from author to author. The basement of deposition is generally not known but at Pyhäsalmi, near the Archaean craton in central Finland, the lowermost supracrustal rocks are underlain by tonalitic gneiss about 1.93 Ga old (Helovuori, 1979). Felsic volcanic rocks comprise the lowermost unit at Bergslagen in south central Sweden, at Skellefte in northern Sweden and at Orijärvi in southwestern Finland (Latvalahti, 1979; Oen *et al.*, 1982; Claesson, 1985; Lagerblad & Gorbatschev, 1985; Lundström, 1987; Vivallo & Claesson, 1987). They are overlain by sedimentary rocks and felsic, intermediate and mafic volcanic rocks. According to Colley and Westra (1987), basalts are the lowermost supracrustal rocks at Orijärvi. At Uppsala—Nyköping, 100—200 km east of Bergslagen, the volcanic rocks are underlain and overlain by greywackes-pelites (Lundström, 1987). The lowermost strata at Pellinge in southern Finland comprise sedimentogenic felsic schists with minor conglomerates and limestones (Laitala, 1973). They are overlain by mafic and intermediate volcanic rocks. At Tampere, the Aitoniemi greywackes-mudstones represent the lowermost unit according to the conventional stratigraphic scheme, but volcanism was common during or shortly before their deposition. The basalts of the Haveri Formation may be older. The Upper Volcanic Unit at Ylöjärvi comprises the youngest volcanic unit at Tampere and it is rich in mafic rocks. Shoshonitic and trachytic rocks, relatively common at Tampere, have not been observed in other Svecofennian belts.

The successions of the southern Svecofennian province contain more carbonate sedimentary rocks and iron formations than the Tampere belt. Conglomerates are more frequent at Tampere than in most other Svecofennian belts. There are a few occurrences of quartz arenites in southern Finland and south central and central Sweden (Simonen, 1980a; Lundqvist, 1987). At Tampere, quartz arenites are known only as clasts in sedimentary rocks (Ojakangas, 1986; observations by the author).

Several Svecofennian volcanic successions display a bimodal frequency distribution of silica (Marttila, 1976; Oen *et al.*, 1982; Vivallo & Rickard, 1984; Claesson, 1985; Lagerblad & Gorbatschev, 1985; Mäki, 1986; Colley & Westra, 1987; Vivallo & Claesson, 1987). Bimodality is less pronounced or absent in other successions (Latvalahti, 1979; Kähkönen, 1987; Lundström, 1987; Tiainen & Kähkönen, in prep). The Svecofennian bimodal successions are mostly interpreted to indicate rifting at convergent plate margins (e.g., Vivallo & Rickard, 1984; Claesson, 1985; Colley & Westra, 1987; but see also

Oen *et al.*, 1982). Some of the Svecofennian volcanic successions occurring as interbeds among sedimentary strata are rich in mafic rocks (Ehlers *et al.*, 1986; Lahti *et al.*, in prep.; Vaarma & Kähkönen, in prep.). A few Svecofennian successions contain ultramafic and boninitic volcanic rocks (Claesson, 1985; Ehlers *et al.*, 1986; Schreurs *et al.*, 1987).

Most Svecofennian mafic volcanic rocks have arc affinities in that they are low in Ti (Salli, 1964; Laitala, 1973; Koljonen & Rosenberg, 1975; Helovuori, 1979; Huhtala, 1979; Latvalahti, 1979; Löfgren, 1979; Vivallo & Rickard, 1984; Claesson, 1985; Mäki, 1986; Colley & Westra, 1987; Kähkönen, 1987; Vivallo & Claesson, 1987; Lahti *et al.*, in prep.). Certain Svecofennian mafic volcanic rocks tend to be higher in Ti than typical arc basalts (Pharaoh & Pearce, 1984; Ehlers *et al.*, 1986; Lahti *et al.*, in prep.; Vaarma & Kähkönen, in prep.). A few of these high-Ti mafic rocks do not show the Ta-Nb depletion typical of arc and marginal basin basalts. The mafic units near Tampere are mostly low in Ti but some of them are relatively rich in Ti (Mäkelä, 1980; Kähkönen, 1987).

The U-Pb zircon ages of the Svecofennian volcanic rocks cover a time span of about 1.91—1.86 Ga and mostly exceed 1.88 Ga (Aho, 1979; Hopgood *et al.*, 1983; Åberg *et al.*, 1984; Skiöld & Cliff, 1984; Patchett & Kouvo, 1986; Welin, 1987; Skiöld, 1987; Vaasjoki & Sakko, 1988; Kähkönen *et al.*, in press; Lahti *et al.*, in prep). The Tampere volcanic rocks with ages of 1.904—1.889 Ga almost cover the typical time span. The Svecofennian plutonic rocks have similar or slightly younger ages (Patchett *et al.*, 1981; Wilson *et al.*, 1985; Huhma, 1986; Patchett & Kouvo, 1986; Skiöld, 1988).

Outside the Svecofennian terrain, the Trans-Hudsonian successions of North America resemble the Tampere Schist Belt and some other Svecofennian belts in age and lithological properties (cf. Stauffer *et al.*, 1975; Moore, 1977; Lewry *et al.*, 1985, 1987; Chauvel *et al.*, 1987; Van Schmus *et al.*, 1987). The Trans-Hudsonian volcanic rocks have mostly arc affinities but in places they have features not typical of arc volcanics (Gaskarth & Parslow, 1987; Watters & Pearce, 1987). The Trans-Hudsonian successions contain abundant pillow lavas and they are rich in subalkaline basalts, basaltic andesites and andesites. They are more primitive than most of the volcanic successions near Tampere and in the Svecofennian terrain.

The volcanic-sedimentary belts of the northern Guayana Shield comprise another group which resembles the Tampere belt and other Svecofennian belts (Gibbs, 1987; Renner & Gibbs, 1987). U-Pb zircon ages of the volcanic rocks are not available but zircons from the greywackes yield ages of 2.25 Ga. This figure is close to the zircons 2.3 Ga old in the greywackes at Tampere. The volcanic rocks of the Guayana Shield are dominated by mafic rocks and the population has bimodal affinity. The rocks show mutually contradictory tectonomagmatic affinities.

DISCUSSION

The units identified

In general, the units identified are thinner than the tholeiitic chemo-stratigraphic units of Archaean greenstone belts (Gélinas *et al.*, 1977; Condie, 1981; Ayres & Thurston, 1985). They resemble in size the members of the Archaean Favourable Lake complex (Ayres, 1977) which are mostly composed of pyroclastic and sedimentary rocks.

The boundaries between the units are shown by abrupt changes in composition or by indications of a period of quiescense in volcanic activity. At Orivesi, the fine-grained strata between the Subalkaline Basaltic to Rhyolitic Unit and the Shoshonitic Unit form a proper boundary. The sedimentary strata between the Lower and the Upper Volcanic Unit at Ylöjärvi may also indicate a quiet period in volcanic activity, although the sedimentary rocks in the southern and northern limb do not necessarily represent exactly the same horizon. In some instances the unit boundaries consist of areas of intensive deformation. At Orivesi, the shear zone between the Intermediate Unit and the Subalkaline Basaltic to Rhyolitic Unit causes problems when the mutual relations between the two units are discussed. The observations on top of strata indicate, however, that the Intermediate Unit and the Subalkaline Unit lie probably in the same limb of the major syncline.

The units vary widely in dimensions. The Intermediate Unit at Orivesi is about 1 km thick while the Trachytic Unit at Orivesi is no more than 10 m thick in the southern limb of the syncline. Variations both along and across the strike are also observed in individual units. At Orivesi, the Shoshonitic Unit and the Trachytic Unit are thicker in the northern limb of the syncline than in the southern limb. At Ylöjärvi, shoshonitic rocks are known near Lake Mastosjärvi but in the profile studied they were observed only as redeposited strata. Rocks resembling the Trachytic Unit were not identified at Ylöjärvi. In volcanic environments, abrupt lateral changes in the dimensions of strata are natural and more realistic than ''layer cake'' models (Ayres, 1977; Fisher & Schmincke, 1984; Ayres & Thurston, 1985).

Some units show considerable variation in geochemical and lithological properties. They may, therefore, be disassembled into smaller units. In the profile studied, the rocks of the Lower Volcanic Unit at Ylöjärvi in the northern limb of the syncline are different from those in the southern limb. In this unit, the lowermost strata in the northern limb are different from those higher in the sequence. In the southern limb at Ylöjärvi, the Lower Volcanic Unit contains near Lake Mastosjärvi rocks not present in the profile studied. Pooling all these rocks into a single unit is a simplification, but a reasonable one, with the data available.

Lateral extensions of some units are unknown. The Subalkaline Basaltic to Rhyolitic Unit at Orivesi is largely composed of distal rocks. Identification of the proximal facies of these strata is not possible without extensive field studies.

The compositions of the units are not necessarily confined to a single stratigraphic horizon as is evidenced by the composition typical of the Trachytic Unit. Sample 86 is from a stratum within the Shoshonitic Unit, and rocks resembling those of the Trachytic Unit are present on several levels in the sequence near Lake Näsijärvi.

Volcanic-sedimentary evolution of the Tampere Schist Belt

Final conclusions on the volcanic-sedimentary evolution of the Tampere belt are hampered by insufficient data on some study areas. The relation of the Haveri Formation to the volcanic rocks at Orivesi—Ylöjärvi is not known with certainty. At Orivesi—Ylöjärvi, the relationship of the predominantly volcanic rocks in the northern limb of the major syncline to the predominantly sedimentary rocks in the southern limb is open. For instance, the relationship of the Aitoniemi greywackes-mudstones to the Intermediate Unit at Orivesi, and the age of the volcanic rocks interlayered with the Aitoniemi greywackes are not known. The relationship of the Mauri arkose to the other supracrustal rocks of the belt is also unknown.

In spite of the problems just considered, some points can be speculated. Using the geochemistry of volcanic rocks and the character of the sedimentary rocks, much of the volcanic and sedimentary evolution of the Tampere Schist Belt was found to occur in environments resembling those of present-day convergent plate margins. The scarcity of pillow lavas and the abundance of pyroclastic calc-alkaline intermediate rocks indicate that most of the volcanic rocks now observed represent evolved stages rather than immature stages. In spite of this, a significant part of the evolution occurred in subaqueous environments.

The Haveri Formation probably represents the oldest supracrustal unit in the Tampere Schist Belt. The tectonomagmatic affinities of the Haveri basalts are not known well. They are higher in Ti than typical arc basalts and show LREE enrichment not typical of MORB or island arc tholeiites (Kähkönen *et al.*, 1981). The Haveri basalts may have been formed during initial stages of arc evolution (Mäkelä, 1980), but they may also represent E-type MORB or marginal basin basalts.

The greywackes overlying the Haveri Formation resemble certain greywackes at Aitoniemi (observations by the author) which belong to the lowermost strata near Lake Näsijärvi. The Ahvenlammi conglomerate about 15 km east of Aitoniemi (Fig. 4) is probably a channel deposit of the Aitoniemi turbidites (observations by the author). The Aitoniemi greywackes and the Ahvenlammi conglomerate were largely derived from volcanic and granitoid provenances. They also contain quartzites (Ojakangas, 1986; observations by the author) and fairly old clastic zircon (Kouvo & Tilton, 1966). According to Sm-Nd studies, the provenances were dominated by recently formed crust, and only a minor input from Archaean sources is possible (Huhma, 1987). The Archaean imprint does not necessitate a nearby Archaean continent. For instance, the Java trench off the Indonesian arc is partly filled with continent-derived turbidites of Bengal fan (p. 388 in Miall, 1984). The volcanic clasts in the Aitoniemi greywackes are dominated by felsic and intermediate rocks but there are also remnants of mafic volcanic rocks. Felsic and intermediate volcanic rocks form, more probably than basaltic rocks, easily weathered pyroclastic cones or erupt as pyroclastic flows which may, in subaqueous environments, transform to turbiditic flows. Thus the scarcity of mafic clasts in the greywackes does not necessarily indicate scarcity of basaltic volcanism at the time of formation of the greywacke provenances.

The Aitoniemi turbidites contain volcanic interbeds and volcanic rocks get more common up the sequence. The sedimentary rocks higher in the succession comprise conglomerates and associated finer-grained sedimentary rocks. Their palaeocurrents were predominantly from the east and southeast (Rautio, 1987). In general, these rocks are more mafic than the Aitoniemi greywackes (observations by the author). They were derived from provenances different from those of the Aitoniemi greywackes although the two groups have westerly palaeocurrents. The sedimentary rocks high in the sequence are mostly inner-fan and channel deposits of a submarine fan (Ojakangas, 1986; Rautio, 1987) but, according to a tentative interpretation of J. Leveinen, a part of these strata may be fluvial. Considering also the abundance of volcanic rocks, these parts of the sequence may resemble delta-fan complexes of growing volcanic islands.

At Orivesi the volcanic strata just below the conglomerates comprise shoshonites and trachytes. At Ylöjärvi, the strata below the conglomerates in the southern limb comprise shoshonites but similar rocks were not found in the northern limb. Although the shoshonites are found relatively high in the sequence, their occurrence is rather spatially controlled. Also the trachytes seem to be spatially controlled; they are found at several stratigraphic horizons at Orivesi and in the southern limb near Lake Näsijärvi but they are not known in the northern limb near Lake Näsijärvi and in the profile studied at

Ylöjärvi. The Upper Volcanic Unit at Ylöjärvi indicates that the shoshonites and trachytes do not represent the final stages of volcanic evolution at Tampere.

Svecofennian supracrustal belts and crustal evolution

The Svecofennian events were preceded by rifting of Archaean craton and by formation of oceanic crust (p. 7). Most Svecofennian volcanic and plutonic rocks resemble subduction-related igneous rocks. The Svecofennian evolution occurred in environments which somehow resembled convergent plate margins. There also exist differences. Subduction-related igneous activity in young convergent plate margins lasts more than 0.1 Ga and Recent volcanic arcs are typically not more than 100—200 km wide (Gill, 1981; Thorpe, 1982). Some arcs are wider but they comprise significant proportions of old crust. The spatially extensive but practically simultaneous Svecofennian evolution differs in these respects from that in young convergent plate margins.

Park *et al.* (1984) and Park (1985) suggested that the Svecofennian terrain evolved through accretion of diachronous volcanic arcs. This model could explain some of the variation shown by the Svecofennian supracrustal successions but the presently available U-Pb zircon ages indicate simultaneous rather than diachronous evolution 1.91—1.86 Ga ago (p. 93). This contrasts with the Cordilleran terranes which range in age from middle Proterozoic to Cenozoic (Coney *et al.*, 1980).

The pronounced bimodality shown by certain Svecofennian belts, as well as the occurrence of high-Ti mafic units indicate that extensional regimes dominated at some periods in some areas. The units high in Ti are found both within and outside the Bothnian Basin. Some of them do not have the Ta-Nb depletion typical of marginal basin basalts (p. 93). These rocks may represent rifting-spreading events not necessarily related to subduction. The thick sedimentary strata in the southern Svecofennian province indicate the presence of significant sedimentary basins outside the Bothnian Basin. On the other hand, there are volcanic rocks with arc affinities within the proposed area of the Bothnian Basin. It seems that there existed several extensional basins between arc-like areas.

The Svecofennian sedimentary rocks are mostly turbiditic greywackes-pelites but they vary in lithological properties. Calcareous sedimentary rocks are common in some areas. They are not typical sedimentary rocks of volcanic arcs. In certain Svecofennian belts they are related to rifting episodes (e.g., Oen *et al.*, 1982). Carbonate sediments may, however, occur at volcanic arcs as reefs fringing the volcanic islands (e.g., Brown *et al.*, 1977; Fisher & Schmincke, 1984, pp. 400—405). In any case, shallow-water environments are evident at some periods in some areas. The fluvial and deltaic sandstones indicate that the evolution occurred partly in subaerial environments.

The lowermost parts of several Svecofennian volcanic successions are dominated by felsic volcanic rocks. This indicates, in the absence of Archaean crust, that they represent evolved stages. This evolution probably occurred before 1.91 Ga because the 1.904 Ga old Intermediate Unit at Orivesi is dominated by calc-alkaline high-K dacites-andesites. U-Pb zircon evidence for the preceding evolution is rare. Near the Archaean craton in central Finland, the 1.92—1.93 Ga old tonalites (Helovuori, 1979; Korsman *et al.*, 1984) might represent this event. In SW Finland, the Uusikaupunki trondhjemites are probably 1.90 Ga or older (Patchett & Kouvo, 1986). The abundance of felsic and intermediate volcanic rocks at Bergslagen, Skellefte, Orijärvi and Tampere indicates that the pre-1.91 Ga evolution occurred in a wide area.

The Svecofennian evolution involved practically simultaneous spreading and subduction events in a wide and complex region. Subduction directions were probably not constant all over the terrain. It is also possible that subduction polarities changed with time. In these respects the area might resemble the Indonesian region (Hamilton, 1979). A difference is that Archaean crust is absent in the Svecofennian terrain, while there occur several Palaeozoic or Precambrian microplates in the Indonesian region. The Svecofennian crustal formation was more rapid than that at present-day convergent plate margins (Kähkönen *et al.*, in press; see also Patchett & Arndt, 1986 and Schubert & Reymer, 1986).

CONCLUSIONS

The wide dispersion in the chemical composition of the volcanic rocks of the Tampere Schist Belt is partly attributed to compositional changes. These processes are presently visible as sericitization, albitization, potassium-feldspathization, silicification, carbonatization, tourmalinization and prehnitization. They are partly indications of synvolcanic alteration but partly they are associated with later events. Furthermore, sedimentary reworking and cumulation of phenocrysts and clasts had an affect so that the rock compositions do not always adequately represent magma compositions.

In spite of the compositional changes, the volcanic rocks of the Tampere Schist Belt can be divided into chemo-stratigraphic units. Stratigraphy has, therefore, a significant role in considering the compositional variations of the volcanic rocks. The units identified vary from tholeiitic units straddling the low-K/medium-K boundary to shoshonitic and trachytic units. Those dominated by calc-alkaline medium-K and high-K intermediate rocks are most frequent. The 1.904 Ga old Intermediate Unit at Orivesi is the oldest unit under present discussion. It is characterized by calc-alkaline high-K pyroclastic dacites, trachydacites and andesites. Outside the area now studied, the basalt-rich Haveri Formation may be older. The 1.889 Ga old Upper Volcanic Unit at Ylöjärvi is the youngest unit. It is characterized by medium-K basalts, basaltic andesites and andesites with tholeiitic affinities.

The rhyolitic rocks have K_2O:Na_2O ratios mostly close to or in excess of unity. The Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline comprises felsic rocks which have K_2O:Na_2O ratios well below unity.

The size of the units varies both along and across the strike. The units may be repeated in the different limbs of the folds but there are also instances where a unit, or its part, was identified in one limb only. In future studies, some units may be disassembled into smaller units.

Compositional changes, heterogeneity of pyroclastic rocks, mixing during redeposition, accumulation of phenocrysts, and scarcity of trace element data prevent a thorough petrogenetic discussion in several units. Low-pressure fractional crystallization may have caused a part of the compositional variations but in many cases this process did not play the major role. Many features of the variation trends of the andesites and dacites of the Lower Volcanic Unit at Ylöjärvi in the southern limb of the major syncline could be explained by low-pressure fractional crystallization, but the horizontal K_2O-SiO_2 and K_2O-Zr trends are controversial. The rising Sr-Zr trend of the Intermediate Unit at Orivesi is not a result of low-pressure fractional crystallization. The trend can be explained by variation in the degree of partial melting or fractional crystallization at high pressure but some other possibilities can also be considered. The descending K_2O-SiO_2 and Zr-SiO_2 trends in the Shoshonitic Unit at Orivesi cannot be explained either by fractional crystallization or by partial melting, and mixing is more plausible. Many of the variation trends which deviate from the generalized crystallization trends can be explained by igneous processes other than fractional crystallization, and they do not necessarily indicate alteration.

The basaltic rocks of the Tampere Schist Belt are fairly evolved in that their Cr and Ni contents tend to be low and their FeO*:MgO ratios exceed unity. They do not represent primary mantle melts but have experienced fractionation of olivine ± Cr-spinel ± pyroxene.

When compared with typical volcanic rocks in Archaean greenstone belts, the volcanic rocks of the Tampere Schist Belt are more silicic and higher in K. The mafic rocks at Tampere tend to be lower in Ni than the Archaean basalts with equal Mg' value.

By and large, the volcanic rocks of the Tampere Schist Belt resemble those of Recent convergent plate margins at mature island arcs or active continental margins. Some mafic units high in Ti may indicate extensional environments at some periods in some areas. The Svecofennian crustal formation was more rapid than that at modern convergent plate margins.

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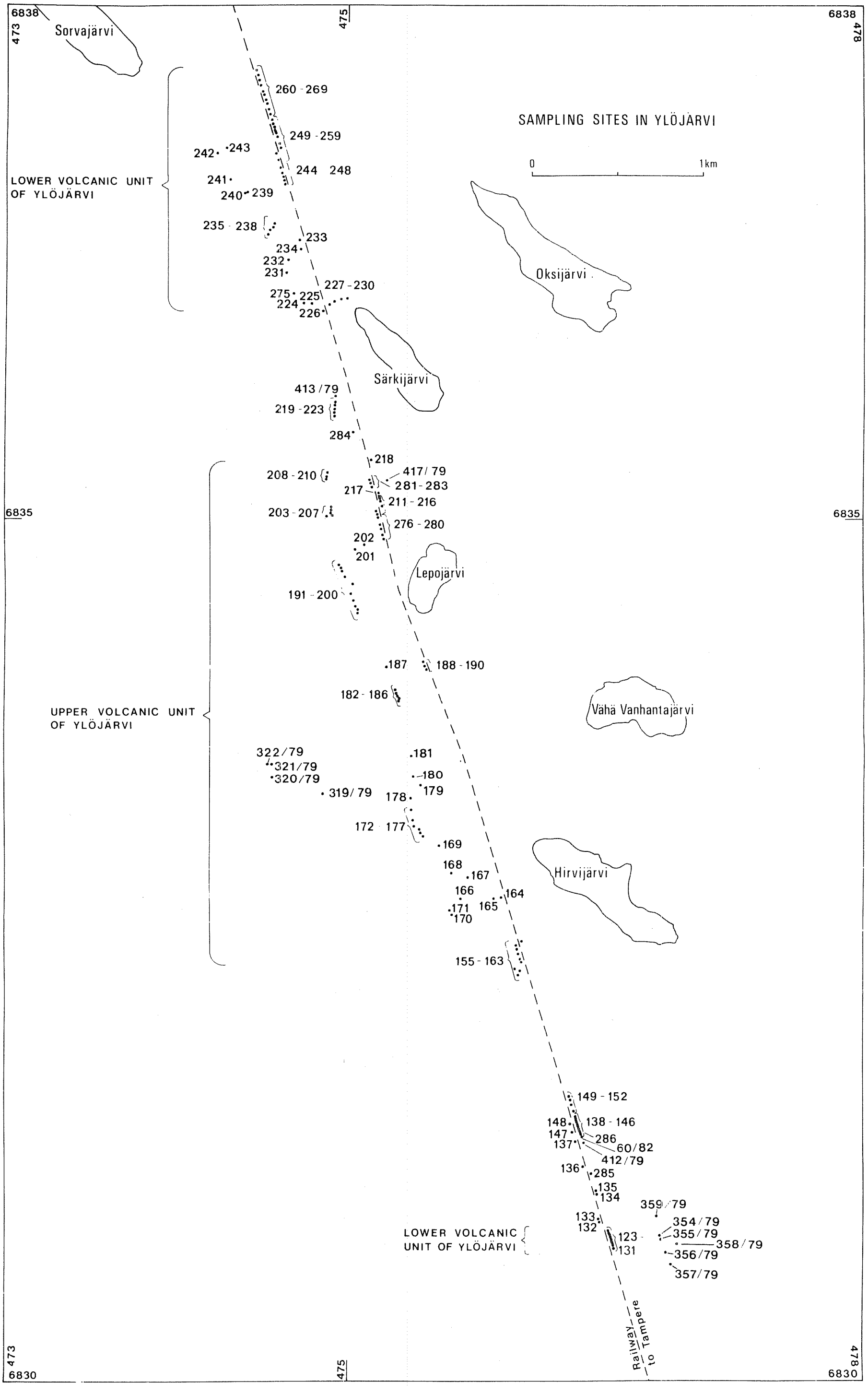
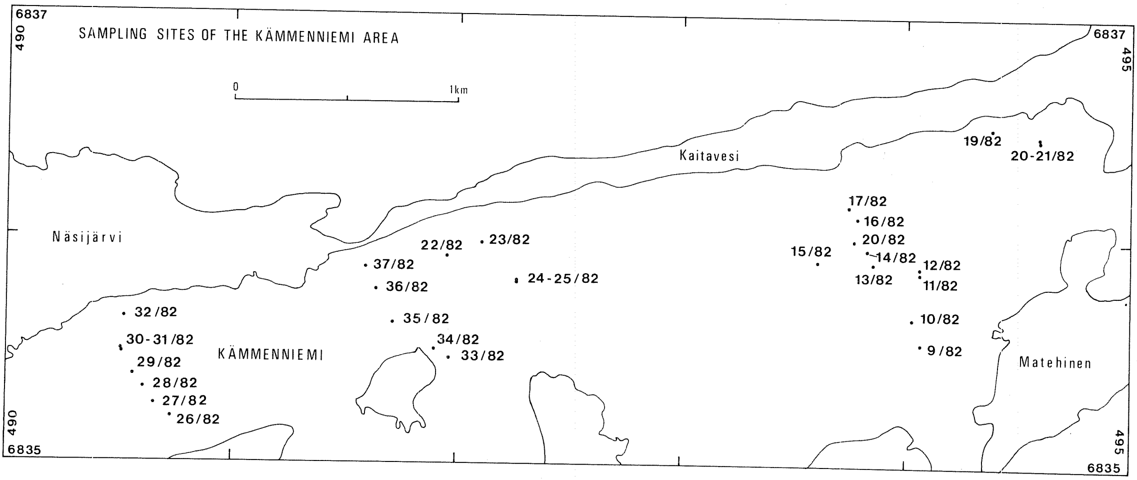
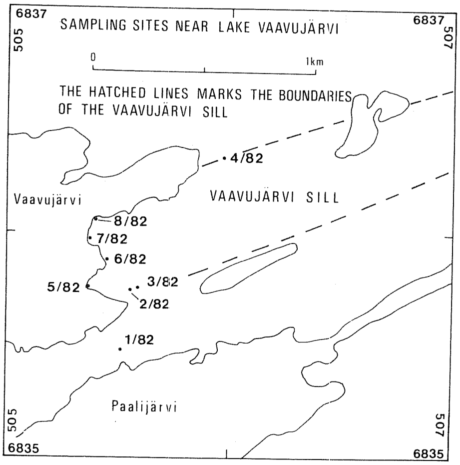
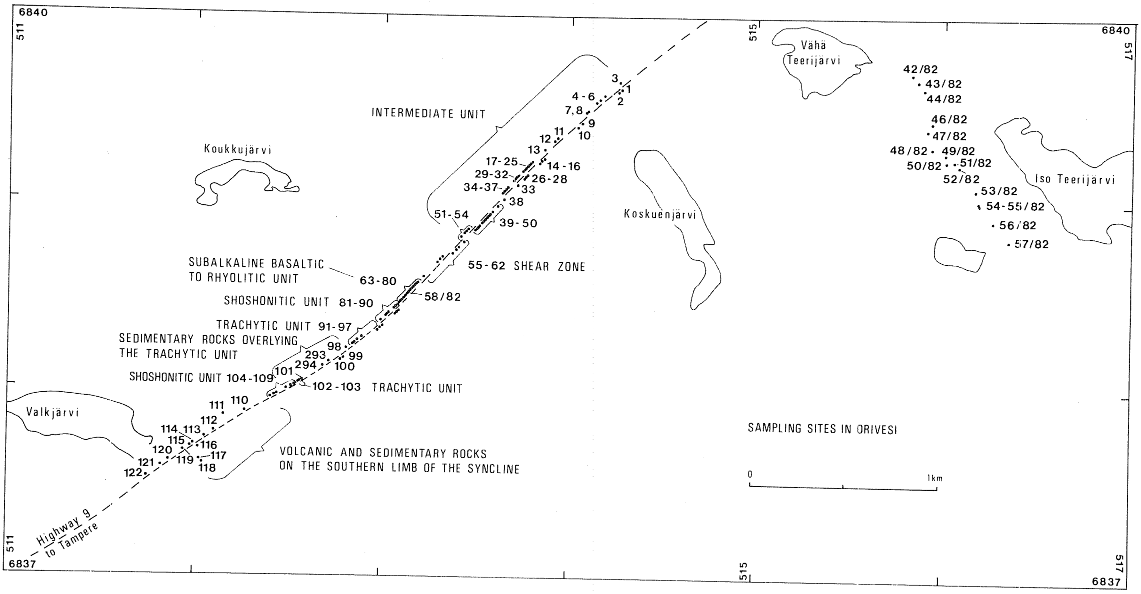
Appendix: Sampling sites at Ylöjärvi, Kämmenniemi, Vaavujärvi and Orivesi.




SAMPLING SITES OF THE KÄMMENNIEMI AREA
0
1km
6837
490
6837
495
6835
490
6835
495
Näsijärvi
Kaitavesi
KÄMMENNIEMI
Matehinen
19/82
20-21/82
17/82
16/82
20/82
15/82
14/82
12/82
13/82
11/82
10/82
9/82
22/82
23/82
37/82
36/82
24-25/82
35/82
34/82
33/82
32/82
30-31/82
29/82
28/82
27/82
26/82


SAMPLING SITES NEAR LAKE VAAVUJÄRVI
0
1km
THE HATCHED LINES MARKS THE BOUNDARIES
OF THE VAAVUJÄRVI SILL
6837
505
6837
507
6835
505
6835
507
Vaavujärvi
VAAVUJÄRVI SILL
Paalijärvi
4/82
8/82
7/82
6/82
5/82
3/82
2/82
1/82


SAMPLING SITES IN ORIVESI
0
1km
6840
511
6840
517
515
6837
511
6837
517
515
Vähä Teerijärvi
Iso Teerijärvi
Koukkujärvi
Koskuenjärvi
Valkjärvi
Highway 9 to Tampere
INTERMEDIATE UNIT
SUBALKALINE BASALTIC TO RHYOLITIC UNIT 63-80
SHOSHONITIC UNIT 81-90
TRACHYTIC UNIT 91-97
SEDIMENTARY ROCKS OVERLYING THE TRACHYTIC UNIT
SHOSHONITIC UNIT 104-109
102-103 TRACHYTIC UNIT
55-62 SHEAR ZONE
58/82
VOLCANIC AND SEDIMENTARY ROCKS ON THE SOUTHERN LIMB OF THE SYNCLINE
3
1
2
4-6
7,8
9
10
11
12
13
17-25
14-16
29-32
26-28
34-37
33
38
51-54
39-50
98
293
99
294
100
101
110
111
112
114
113
115
116
120
119
117
121
118
122
42/82
43/82
44/82
46/82
47/82
48/82
49/82
50/82
51/82
52/82
53/82
54-55/82
56/82
57/82