TECTONIZED ACTINOLITE—ALBITE ROCKS FROM THE OUTOKUMPU DISTRICT, FINLAND: FIELD AND GEOCHEMICAL EVIDENCE FOR MAFIC EXTRUSIVE ORIGIN

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Field observations and the geochemistry of major and trace elements, including REE, suggest a mafic extrusive origin for the strongly tectonized, actinolite—albite rocks in the Miihkali arch, in the NE part of the Outokumpu district, eastern Finland. These metabasalts occur in close association with massive serpentinites. Compared with the average composition of representative basalts from modern tectonic environments their MgO, Ni and Cr contents are somewhat elevated, and their TiO_2 somewhat low. The REE contents are 5× to 10× chondrites. Their pattern is flat and slightly depleted in LREE. A Proterozoic ocean floor is postulated as the depositional environment.

Key words: actinolite—albite rocks, metabasalts, geochemistry, Proterozoic, Outokumpu-district.

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Introduction

The Outokumpu District lies in the boundary zone between a late Archean basement complex and overlying early to middle Proterozoic rocks (Simonen 1980). The basement complex forms the NE part of the Baltic shield. The lowermost cover sediments, which were deposited until c. 2.0 Ga, include arkoses, conglomerates, quartzites, calc-silicate rocks and black schists, and are associated with basic magmatism. The overlying mica schist is regionally extensive in the Outokumpu District and encloses a serpentinite—carbonate—skarn—quartz rock assemblage that is commonly bounded by black schists and is known as the Outokumpu association (Gaál *et al.* 1975, Huhma 1975). Massive Cu-Co orebodies, including the Outokumpu ore deposit, are closely associated with serpentinites and with a virtually monomineralic quartz rock, that is considered by Huhma and Huhma (1970) to be a metamorphic derivative of colloidal silica precipitates.

In the Miihkali arch area (Fig. 1) the rocks denoted as skarns in regional bedrock mapping at a scale 1 : 100,000 (Huhma 1971) are known to include a considerable amount of strongly foliated chloritic schists and dark coloured amphibolites with possible relict porphyric textures (Koistinen 1981). These rocks are characterized by plagioclase and black to greenish or brownish amphibole with some compositional variation. According to Huhma (1975) the skarns of the Outokumpu association are devoid of feldspars and biotite, and enriched in chromium and nickel; they are particularly noted for their chrome-diopside, chrome-tremolite and other chrome-bearing minerals. Although the actinolite—albite rocks in the Miihkali area are quite different, they must nevertheless be considered to be closely related to the Outokumpu association because of their intimate association with massive serpentinites.

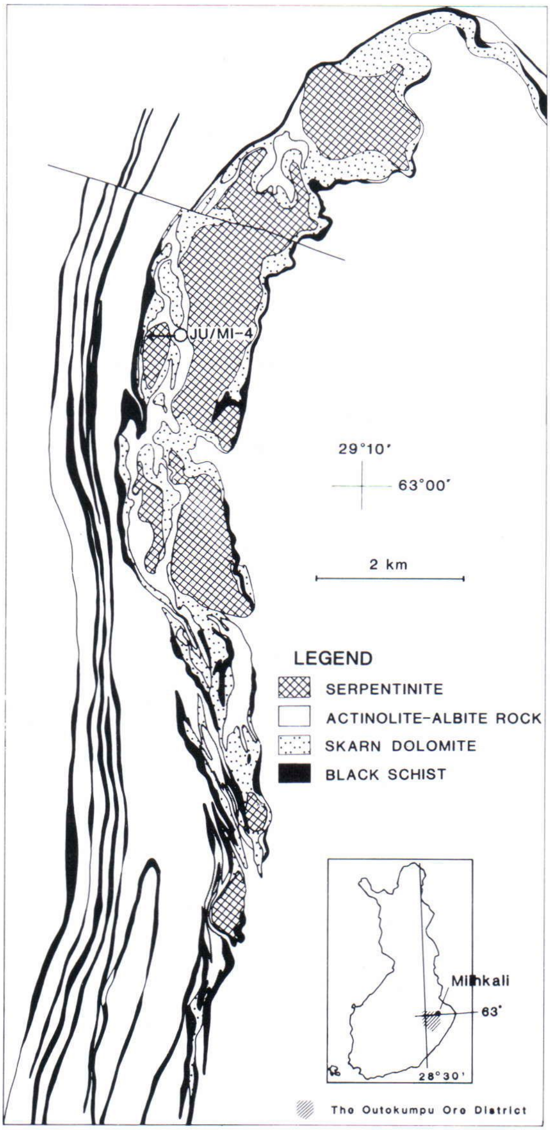

Fig. 1. Geological map of the Miihkali arch in the northeastern part of the Outokumpu District, eastern Finland. Compiled by T. Koistinen. For further information see *e.g.* Huhma (1971, 1975), Koistinen (1981).

The present paper describes the petrography and reports the major, trace and REE chemistry for 15 diamond drill core samples (hole Ju/Mi 4; Fig. 1) representing the continuous intersection of a schistose actinolite—albite rock in close association with large serpentinite masses at Miihkali, in the NE part of the Outokumpu Ore District. For this rock we suggest (1) close relation with the Outokumpu association, (2) extrusive origin and (3) ocean floor depositional environment.

Analytical methods

The major element contents were analysed by X-ray fluorescence at the Geological Survey of Finland, using lithium tetraborate melts and a Philips PW 1420/AHP spectrometer. The coefficients of variation for the XRF data were 1—2 ‰. The FeO contents were determined titrimetrically. Optic emission spectrography was used to analyse the trace metal contents of Cu, Cr, Ni, Co, Zr and Sc. The REE contents were determined in the Reactor Laboratory of the Technical Research Centre of Finland using the instrumental and radiochemical methods described by Rosenberg (1972) and Zilliacus *et al.* (1982). Samples 1, 2, 3, 4 and 10 were analysed by the RNAA method.

Results

The actinolite—albite rocks are strongly schistose, partly blastomylonitic and medium-

Table 1. Major and trace element contents and normative mineral compositions for actinolite-albite rock, diamond drill core JU/MI-4, Miihkali, Outokumpu District.

Major element contents (wt.%)

	depth m	SiO_2	Al_2O_3	FeO	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	P_2O_5
1	99.15	50.99	16.14	5.07	1.52	10.53	10.88	3.03	.20	.14	.36	.04
2	102.00	51.65	16.16	5.49	1.10	10.61	10.98	3.27	.29	.15	.33	.03
3	105.80	50.89	16.13	5.47	1.45	10.22	11.10	3.35	.23	.14	.30	.00
4	108.45	50.11	16.05	5.04	1.71	11.25	10.48	2.93	.30	.14	.39	.00
5	112.34	50.23	15.95	5.75	1.18	10.46	10.55	3.28	.22	.15	.35	.03
6	115.46	49.84	16.09	6.25	1.06	11.21	9.98	3.22	.41	.14	.39	.05
7	118.40	50.22	15.57	5.39	1.33	11.94	10.70	3.07	.32	.14	.38	.06
8	119.00	47.74	14.65	4.65	3.39	14.10	5.49	3.04	.79	.11	.47	.06
9	121.00	51.26	16.70	5.58	1.53	10.68	10.43	3.12	.46	.15	.44	.05
10	122.09	47.46	15.18	5.08	2.19	14.05	6.55	2.94	.47	.13	.34	.04
11	125.45	49.33	15.13	5.77	1.26	12.25	8.55	3.10	.31	.11	.39	.05
12	126.24	45.35	14.19	5.29	3.15	14.92	4.67	3.06	.43	.08	.35	.04
13	129.22	47.25	15.48	6.33	1.82	13.27	10.23	2.57	.20	.13	.47	.07
14	130.98	46.52	15.33	7.32	1.74	13.71	7.32	3.33	.36	.09	.40	.00
15	133.95	47.63	16.03	6.68	1.95	12.54	7.81	3.65	.34	.10	.44	.04

Normative mineral compositions (%).

	or	ab	an	ne	di	hy	ol	c	mt	il
1	1.19	25.92	30.18	0.00	19.28	8.47	11.93	0.00	2.23	0.69
2	1.71	27.65	28.54	0.00	20.60	3.26	15.94	0.00	1.59	0.63
3	1.37	28.55	28.50	0.00	21.62	0.19	17.09	0.00	2.12	0.57
4	1.80	25.36	30.14	0.00	18.09	5.99	15.35	0.00	2.52	0.75
5	1.32	28.27	28.68	0.00	19.62	1.71	17.91	0.00	1.74	0.68
6	2.46	27.35	28.63	0.15	17.05	0.00	21.94	0.00	1.56	0.75
7	1.91	26.20	28.00	0.00	20.08	0.90	20.08	0.00	1.95	0.73
8	4.94	27.22	25.39	0.00	2.38	14.82	18.95	0.00	5.20	0.94
9	2.71	26.29	30.08	0.00	16.92	5.41	15.43	0.00	2.21	0.83
10	2.94	26.34	28.42	0.00	4.54	11.48	22.14	0.00	3.36	0.68
11	1.90	27.25	27.48	0.00	12.99	8.88	18.71	0.00	1.90	0.77
12	2.78	28.29	25.02	0.00	0.00	12.77	25.00	0.32	4.99	0.73
13	1.21	22.05	30.78	0.10	16.48	0.00	25.60	0.00	2.70	0.91
14	2.21	25.64	26.86	1.99	8.75	0.00	31.13	0.00	2.62	0.79
15	2.07	27.59	27.11	2.26	9.99	0.00	27.12	0.00	2.91	0.86

REE contents (ppm).

	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
1	1.26	3.9	1.06	0.92	0.41	0.32	1.27	0.19
2	1.17	3.0	—	0.88	0.27	0.12	1.07	0.26
3	1.27	4.3	1.01	1.04	0.42	0.36	1.67	0.28
4	1.59	4.7	1.45	1.29	0.46	0.38	1.78	0.29
5	1.62	4.0	3.3	1.19	0.48	0.28	1.75	0.21
6	1.41	4.4	3.7	1.33	0.50	0.31	1.99	0.22
7	1.39	3.8	4.1	1.31	0.49	0.34	1.87	0.26
8	2.9	6.1	4.1	1.42	0.47	0.38	2.1	0.24
9	0.98	2.6	3.6	1.43	0.56	0.32	2.2	0.24
10	1.91	4.8	3.1	0.98	0.36	0.39	1.26	0.20
11	1.31	4.3	2.1	1.30	0.41	0.29	1.73	0.21
12	3.6	6.4	4.9	1.60	0.45	0.34	2.1	0.21
13	1.56	5.4	3.8	1.65	0.62	0.37	2.3	0.26
14	1.65	4.8	4.1	1.58	0.51	0.41	2.2	0.25
15	1.42	3.4	3.9	1.46	0.47	0.37	1.89	0.23

Table 1 continued

Trace element contents (ppm).

	Cu	Cr	Ni	Co	Zr	Sc
1	100	370	120	31	40	26
2	110	340	120	34	32	31
3	120	270	120	37	33	37
4	95	430	140	34	39	27
5	95	450	140	37	39	31
6	95	440	140	37	53	26
7	170	710	230	39	49	27
8	80	410	130	36	49	30
9	140	370	120	34	35	30
10	61	630	200	37	44	29
11	71	530	210	41	43	26
12	21	630	210	39	41	25
13	18	590	230	42	43	31
14	38	670	250	59	50	27
15	71	540	160	58	58	30

grained. Two units can be distinguished: the upper unit, which is relatively homogeneous, with actinolite, albite, chlorite and quartz as main minerals, and the lower blastomylonitic unit, which exhibits more variance in grain size and has actinolite, chlorite, hornblende, albite, K-feldspar, quartz and sericite as main minerals. Actinolite porphyroblasts are common in both units and the lower unit also exhibits relict helicitic porphyroclasts of hornblende. Similar, possibly relict minerals have been found in »skarns» from outcrops in the Miihkali area (Koistinen 1981). The structure of the lower unit is characterized by alternating layers of different mineral proportions. The thickness of these layers perpendicular to the S-plane is 2 to 5 mm. The contacts to the serpentinite masses generally appear as thin tremolite seams. The contacts are sharp against related quartz rocks and skarns proper. The mineral paragenesis indicates low grade metamorphism.

The major element abundances are given in Table 1 with calculated normative compositions and trace element characteristics, including REE contents. Comparison with the contents compiled by Ashley *et al.* (1979) for representative basalts from modern tectonic environments reveals that the actinolite—albite rock at Miihkali is high in MgO and low in TiO_2. The average TiO_2 content, 0.39 %, is less than half the TiO_2 content given for the OFB, IAB and MBB representatives. Slight enrichment is observed in Na_2O. The average alkaline contents of 3.1 % Na_2O and 0.4 % K_2O do not give reason to suppose that the bulk composition has changed much in pre-metamorphic or metamorphic alteration (*cf.* Aumento *et al.* 1976, Hughes 1972). The contents of CaO and P_2O_5 are slightly lower than the average given for basalts. Transition metal contents are higher than reported for average ocean ridge and island arc basalts. The means for Cr, Ni and Cu are 492 ppm, 169 ppm and 86 ppm, respectively. The chondrite-normalized REE patterns are rather similar, both being flat with slight LREE depletion (see Fig. 4). Chondrite-normalized La and Yb abundances average 6 and 10, respectively. The normalized La/Sm ratios cluster between the values 0.9 and 0.5.

Discussion

In a plot proposed by Jensen (1976) for classifying subalkalic volcanic rocks, the actinolite- and albite-bearing units form a rather coherent group mainly in the field for high magnesium

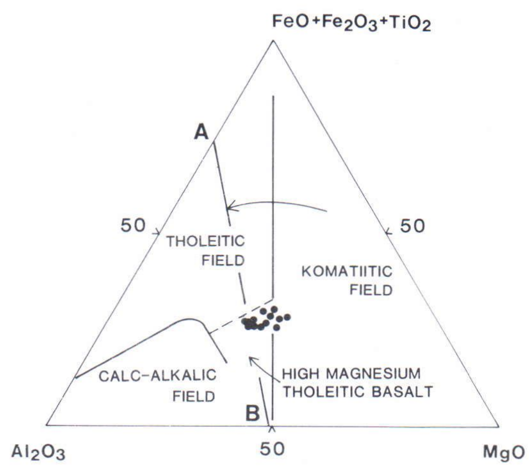

Fig. 2. Jensen cation plot for the actinolite-albite rock (after Jensen 1976), A-B line adopted for Viljoen *et al.* (1982).

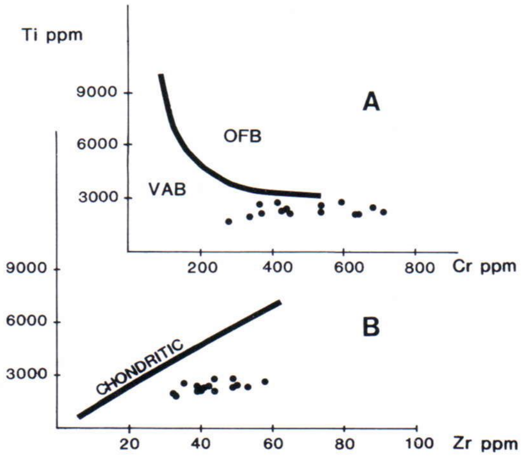

Fig. 3. Ti *vs.* Cr plot (A), fields from Garcia (1978), and Ti *vs.* Zr plot (B) for the actinolite-albite rock.

tholeites but with some samples in the field for basaltic komatiites (Fig. 2). If the komatiitic field is taken as proposed by Viljoen *et al.* (1982) on the basis of data from South African komatiite volcanics, the Miihkali group plots well inside the komatiitic field. Other chemical features indicative of komatiitic origin are high Ni and Cr, and low K_2O, TiO_2 and Zr (Arndt and Nisbet 1982). TiO_2 contents about twice as high as the Zr content are needed to meet the chondritic ratio (see Fig. 3 b).

A gently sloping LREE depleted pattern is also characteristic for basalts of a komatiitic suite (Arndt and Nisbet 1982). In Fig. 4 the pattern of normalized means is compared with a pattern for modern ridge basalts. The low abundances of REE with slight LREE depletion are indicative of a relatively primitive upper mantle source and fractional crystallization. This pattern is consistent with patterns for some Archean komatiitic metavolcanics in eastern Finland (Jahn *et al.* 1980).

Contents of many of the elements analysed and the calculated values of several norm minerals increase or decrease fairly systema-

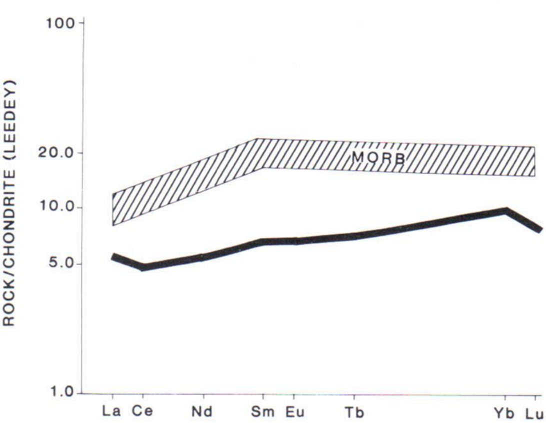

Fig. 4. Chondrite-normalized REE distribution patterns for the means of the actinolite-albite rock. MORB field after Frey *et al.* (1974) and Gill (1976).

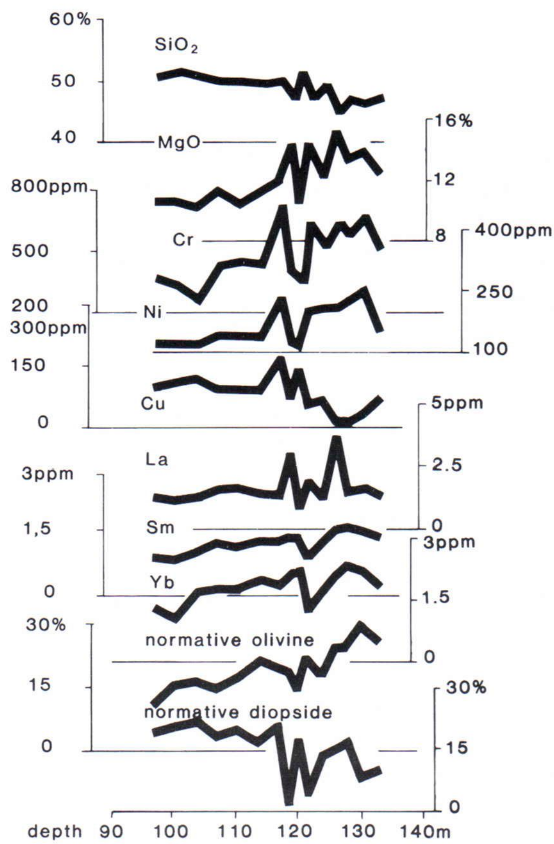

Fig. 5. Transverse distributions of SiO_2, MgO, Cr, Ni, Cu, La, Sm, Yb, normative olivine and normative diopside in the actinolite-albite rock.

tically in the drill core samples (Fig. 5). The trends are comparable to those observed, for instance, in the Munro Township lava flows (Arndt *et al.* 1977). The increase in MgO, Cr, Ni and normative olivine and the decrease in SiO_2, Cu and normative diopside can be attributed to fractionation of the flow. The lower unit may have contained some accumulation or phenocryst enrichment of clinopyroxene or olivine, or both. Clinopyroxene control is implied by the relative increase in HREE in the lower unit (Hanson 1980). The correlations of Ni and Cr to MgO are both 0.7. Ni and Cr are strongly enriched in the early cumulus phases and are therefore sensitive indicators of fractionation (Irvine 1975, Hart and Davis 1978). The relatively uniform Al_2O_3 content in both units is indicative of marked plagioclase crystallization.

An increased variation in element contents is observed from a drill hole depth of 118 m downwards. This variation is probably largely due to metamorphic differentiation. The textures in thin sections indicate stress-induced alternation of layers of varying mineral ratios. The negative correlation between SiO_2 and MgO (Fig. 5) is due to the alternation of quartz-bearing layers with less resistant actinolite-, chlorite- and hornblende-enriched layers in the samples.

Mäkelä (1981) has suggested that the Outokumpu District represents a marginal basin in the early stages of the Svecokarelian orogeny and that serpentinites are former submarine ultramafic lavas extruded through rifts of divergent plate margins. The extrusive origin of the serpentinites is supported by the stratigraphical analysis of folded serpentinite—dominant rock associations based on »grey level» images derived from large-scale aeromagnetic data (Mäkelä 1983). In all probability, the existence of strongly deformed and metamorphosed pillow lavas in the Outokumpu District also indicates a Proterozoic sea floor environment (Park and Bowes 1982). Likewise, application of the discriminant functions calculated by Pearce (1976) points to an ocean floor environment for the actinolite—albite rocks (Fig. 6). To some extent the REE pattern supports this result. Low TiO_2 and Zr contents, however, are suggestive of an island arc environment (Fig. 3 a). The low TiO_2 is probably only indicative of the unusual parental magma composition, and inferences from diagrams based on TiO_2 contents in basalts from modern tectonic environments are probably not therefore justified. Low TiO_2 contents are also found to characterize, among others, basalts of the Cyprus ophiolite complex (Pearce and Gale 1977) and an island arc environment would be consistent with the back-arc

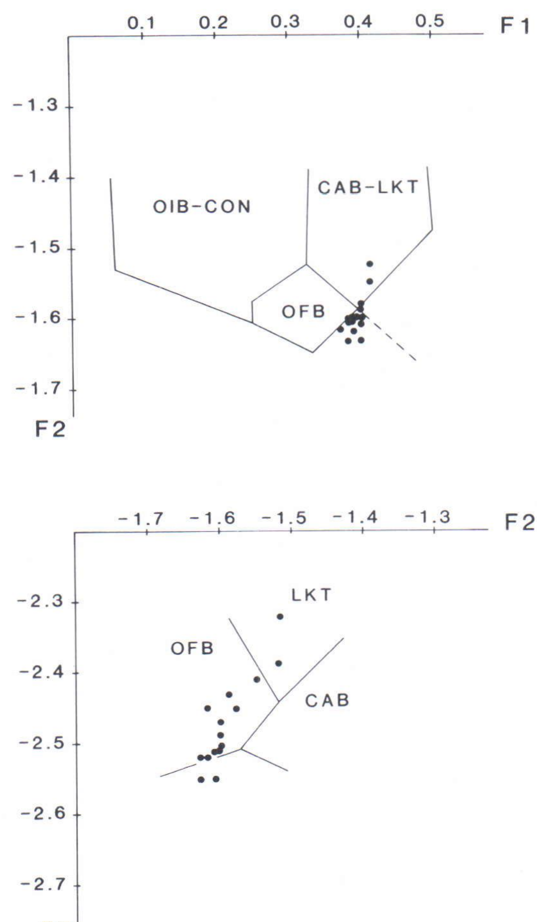

Fig. 6. F1-F2-F3 plots for the actinolite-albite rock (after Pearce 1976).

basin model proposed by Park (1983) for the Proterozoic tectonic setting of the Outokumpu assemblage.

Conclusions

Strongly tectonized actinolite-albite rocks found in close association with massive serpentinites in the Miihkali arch, in the NE part of the Outokumpu District, eastern Finland, have been studied in the field and analysed for major and trace elements, including REE.

Because of its close spatial relation to serpentinites and quartz rocks, we propose that the actinolite-albite rock be regarded as a member of the Outokumpu association. In the Miihkali area the association is enveloped by black schists. The close spatial relation also indicates a relatively short time interval for their appearance. From field evidence, metamorphic mineral assemblages and major and trace element geochemistry, it seems probable that the protolith for the tectonized rock was a high magnesian basalt. A komatiitic rather than tholeitic lineage for the extrusion is suggested mainly on the basis of relatively high MgO, low TiO_2 and Zr, and a flat chondrite-normalized REE pattern. The REE contents of 5X to 10X chondrites and slight LREE depletion are indicative of fractional crystallization and a relatively deep, upper mantle source region. The trends in many element contents and the calculated normative mineral compositions within the studied section indicate low pressure fractional crystallization in the metabasalt (flow). A Proterozoic ocean floor is postulated as the tectonomagmatic environment.

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References

Arndt, N. T. & Nisbet, E. G., 1982. What is a komatiite? 19—27, in Arndt, N. T. and Nisbet, E. G., eds., Komatiites, George Allen and Unwin, London, 526 p.

Arndt, N. T.; Naldrett, A. J. & Pyke, D. R., 1977. Komatiitic lavas of Munro Township: their field, petrographic and chemical characteristics. Jour. Petrol., 18, 319—369.

Ashley, P. M.; Brown, P. F.; Franklin, B. J.; Ray, A. S. & Scheibner, E., 1979. Field and geochemical characteristics of the Coolac ophiolite suite and its possible origin in a marginal sea. Jour. Geol. Soc. Australia, 26, 45—60.

Aumento, F.; Mitchell, W. S. & Fratta, M., 1976. Interaction between sea water and oceanic layer two as a function of time and depth — I. Field evidence. Canadian Mineral., 14, 269—290.

Frey, F. A.; Bryan, W. B. & Thompson, G., 1974. Atlantic Ocean floor: Geochemistry and petrology of basalts from Legs 2 and 3 of the Deep Sea Drilling Project. J. Geophys. Res., 79, 5507—5528.

Gaál, G.; Koistinen, T. & Mattila, E., 1975. Tectonics and stratigraphy of the vicinity of Outokumpu, North Karelia, Finland. Bull. Geol., Surv., Finland, 271, 67p.

Garcia, M. O., 1978. Criteria for the identification of ancient volcanic arcs. Earth Sci. Rev., 14, 147—165.

Gill, J. B., 1976. Composition and age of Lau Basin and Ridge volcanić rocks: Implications for evolution of an inter-arc basin and remnant arc. Bull. Geol. Soc. Am., 87, 1384—1395.

Hanson, G. N., 1980. Rare earth elements in petrogenetic studies of igneous systems. Ann. Rev. Earth Planet. Sci., 8, 371—406.

Hart, S. R. & Davis, K. E., 1978. Nickel partitioning between olivine and silicate melt. Earth Planet. Sci. Lett., 40, 203—219.

Huhma, A., 1971. Geological Map of Finland, Sheet 4311-Sivakkavaara 1 : 100,000. Geological Survey, Espoo.

Huhma, A., 1975. Precambrian rocks of the Outokumpu, Polvijärvi and Sivakkavaara map-sheet areas. Geological Survey, Espoo, 151p.

Huhma, A. & Huhma, M., 1970. Contribution to the geology and geochemistry of the Outokumpu region. Bull. Geol. Soc. Finland, 42, 57—88.

Hughes, C. J., 1972. Spilites, keratophyres, and the igneous spectrum. Geol. Magazine, 109, 513—527.

Jahn, B-M.; Auyray, B.; Blais, S.; Capdevila, R.; Cornichet, J.; Vidal, F. & Hameurt, J., 1980. Trace element geochemistry and petrogenesis of Finnish greenstone belts. Jour. Petrol., 21, 201—244.

Irvine, T. N., 1975. Chromite layers in stratiform intrusions. Yb. Carnegie Instn., Wash., 74, 300—316.

Jensen, L. S., 1976. A new cation plot for classifying subalkalic volcanic rocks. Ontario Div. of Mines, MP 66, 22 p.

Koistinen, T. J., 1981. Structural evolution of an early Proterozoic strata-bound Cu-Co-Zn deposit, Outokumpu, Finland. Trans. Royal Soc. Edinburgh, Earth Sci., 72, 115—158.

Mäkelä, K., 1981. Outokumpu-tyyppisten malmien esiintymismahdollisuuksista Itä- ja Pohjois-Suomessa. — On the potential of finding Outokumpu-type ore deposits in East- and North-Finland. Geologi 33, 17—20.

Mäkelä, M., 1983. Outokumpu-jakso ennen ja nyt — Outokumpu zone before and now. Vuoriteollisuus Bergshanteringen 41, 1, 18—22.

Park, A. F., 1983. Sequential development of metamorphic fabric and structural elements in polyphase deformed serpentinites in the Svecokarelides of eastern Finland. Trans. Royal. Soc. Edinburgh. Earth Sci., 74, 33—60.

Park, A. F. & Bowes, D. R., 1982. Metamorphosed and deformed pillows from Losomäki: evidence of sub-aqueous volcanism in the Outokumpu association, eastern Finland. Bull. Geol. Soc. Finland, 53, 132—145.

Pearce, J. A., 1975. Basalt geochemistry used to investigate past tectonic environments on Cyprus. Tectonophysics, 25, 41—67.

Pearce, J. A., 1976. Statistical analysis of major element patterns in basalts. Jour. Petrol, 17, 14—43.

Pearce, J. A. & Gale, G. H., 1977. Identification of ore-deposition environment from trace-element geochemistry of associated igneous host rocks. 14—24 in Volcanic processes in ore genesis, IMM Special Publ. 7, Geol. Soc. London.

Rosenberg, R. J., 1972. Instrumental activation analysis of lunar samples. Suomen Kemistilehti B 45, 399—404.

Simonen, A., 1980. The Precambrian in Finland. Bull. Geol. Surv. Finland, 304, 1—58.

Viljoen, M. J.; Viljoen, R. P. & Pearton, T. N., 1982. The nature and distribution of Archaean komatiite volcanics in South Africa. pp 53—79 in Arndt, N. T. and Nisbet, E. G., eds., Komatiites, George Allen and Unwin, London, 526 p.

Zilliacus, R.; Kaistila, M. & Rosenberg, R., 1982. Radiochemical neutron activation analysis of small lanthanoid concentrations. Jour. Radioanal. Chem., 71, 1—2, 323—332.