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TWO EARLY PROTEROZOIC THOLEIITIC DIABASE DYKE SWARMS IN THE KOLI—KALTIMO AREA, EASTERN FINLAND — THEIR GEOLOGICAL SIGNIFICANCE

by

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The Koli-Kaltimo area is part of the Early Proterozoic North Karelia Schist Belt bordering upon the Archaean granitoids in the east and north. Mafic sills and dykes, occurring predominantly in the NW direction, are common in the Proterozoic metasediment cover in North Karelia. These are divided into three groups; low-Al tholeiitic or karjalitic sills described in earlier papers, Fe-tholeiitic (T1) and tholeiitic (T2) dykes, with ages of about 2.2 Ga, 2.1 Ga and 1.97 Ga, respectively. New data presented here focus on the geochemistry and petrology of the T1 and T2 tholeiitic diabases.

The T1 dykes are the most common, occurring in swarms throughout the area, whereas the T2 dykes have been found only in connection with Proterozoic quartzites. The primary mineralogy and texture of the T1 dykes have generally been destroyed, while the T2 dykes are only slightly altered containing primary olivine, pyroxenes and plagioclase and having an ophitic texture.

Zircons from the T2 dykes provide an age of 1965 ± 10 Ma, which is supported by the Sm-Nd mineral age of 1985 ± 80 Ma. The initial $\varepsilon_{Nd} = +1.8 \pm 0.6$ suggests that the mantle source had time-integrated LREE depleted characteeristics.

The T1 diabase dykes are quartz-normative, while the T2 dykes are olivine- and quartz-normative. The T1 and T2 tholeiitic suites are distinct in both their major-element and trace-element geochemistry. The T1 dykes are enriched in Fe, P, Ti, Zr and Y and depleted in Mg, Cr and Ni as compared with the T2 dykes, which have slightly evolved Mg* values (71 — 49) and slightly enriched LREE patterns, ranging from 5 to 28 times chondrites ($[La/Yb]_N = 1.6$ to 2.6). The T1 dykes with evolved Mg* values (49 — 36) have high total REE abundances from 30 to 70 times chondrites ($[La/Yb]_N = 2.8$ to 4.1). Petrophysically both T1 and T2 diabases are nearly paramagnetic and are distinguished from each other only with respect to their NRM intensities. The T2 dykes may have been generated by 20 — 30 % partial melting of a LREE-enriched mantle peridotite and the T1 dykes from a mantle source with 10 — 20% melting.

On the basis of their geochemistry, the T1 diabases must have originated in a continental setting, whereas the T2 diabases bear similarities to island arc tholeiites and were connected with a subduction.

Key words: (GeoRef Thesaurus, AGI): diabase, dike swarms, tholeiitic composition, geochemistry, electron probe data, rare earths, petrophysics, genesis, absolute age, Proterozoic, Koli, Kaltimo, Finland

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INTRODUCTION

Thousands of dykes intersect the Archaean basement and most of its Proterozoic cover in the north-eastern part of the Fennoscandian shield, i.e. in eastern and northern Finland, as indicated by the geological and geophysical maps of the area (Aro and Laitakari, 1987). Despite the fact that their occurrence is evidently fairly well known on the basis of these maps, their geological significance is rather indeterminate. It can be assumed, however, that the tholeiitic dykes are connected with some of the significant igneous events recognized in the Proterozoic cover, which are characterized by layered intrusions (2.44 Ga; Piirainen et al., 1974; Alapieti, 1982), differentiated low-Al tholeiitic or karjalitic sills (~2.2 Ga; Hanski, 1986; Vuollo and Piirainen, 1992), large amounts of Fe-tholeiitic lavas (~2.1 Ga; Pekkarinen, 1979; Huhma, 1986; Huhma et al., 1990, Pekkarinen et al. 1991) and ophiolites (1.97 Ga; Kontinen, 1987; Vuollo and Piirainen, 1989c).

The majority of the dykes are oriented roughly from NW to SE and from WNW to ESE in swarms, but N-S and transverse NE trends may occur subordinately. The dykes are predominantly tholeiitic in composition (Gorbatschev et al., 1987).

The Koli-Kaltimo area has always played an important role in investigations into the Proterozoic cover (Tigerstedt, 1892; Frosterus, 1902; Frosterus and Wilkman, 1920; Väyrynen, 1933, 1937; etc.). The dykes are visible here in an interesting manner and several types are found (Piirainen, 1969) which illustrate the outlines of the geological evolution of the Proterozoic cover. The current investigations into mafic magmatism in the area have been going on since 1985, and the oldest dykes (c. 2.2 Ga), composed of low-Al tholeiite, or karjalite as it is called, have already been described (Hanski, 1986; Vuollo and Piirainen, 1989a,b,1992), so that the tholeiitic types which intersect these karjalites, and extensive parts of the Archaean basement and the Proterozoic formations, can be examined next.

GEOLOGICAL SETTING

The Koli-Kaltimo area is situated on the north-eastern edge of the early Proterozoic North Karelia Schist Belt (Fig. 1). The Archaean terrain with granitoids, 2.6 — 2.9 Ga in age (Kouvo and Tilton, 1966), and greenstones extends to the north and north-east, while Proterozoic formations cover most of the Archaean basement towards the south-west. The Proterozoic formations are intersected by granitoids of age about 1.8 — 1.9 Ga some distance away to the south-west (Huhma, 1986).

The major stratigraphic units of the Proterozoic belt in the north-eastern part of the Fennoscandian shield are Sumi, Sariola, Jatuli and Kaleva. The Sumian volcanics and layered intrusions (2.44 Ga) are absent in the Koli-Kaltimo area, while the Sariolan formations (Marmo et al., 1988) are visible in places and the Jatulian and

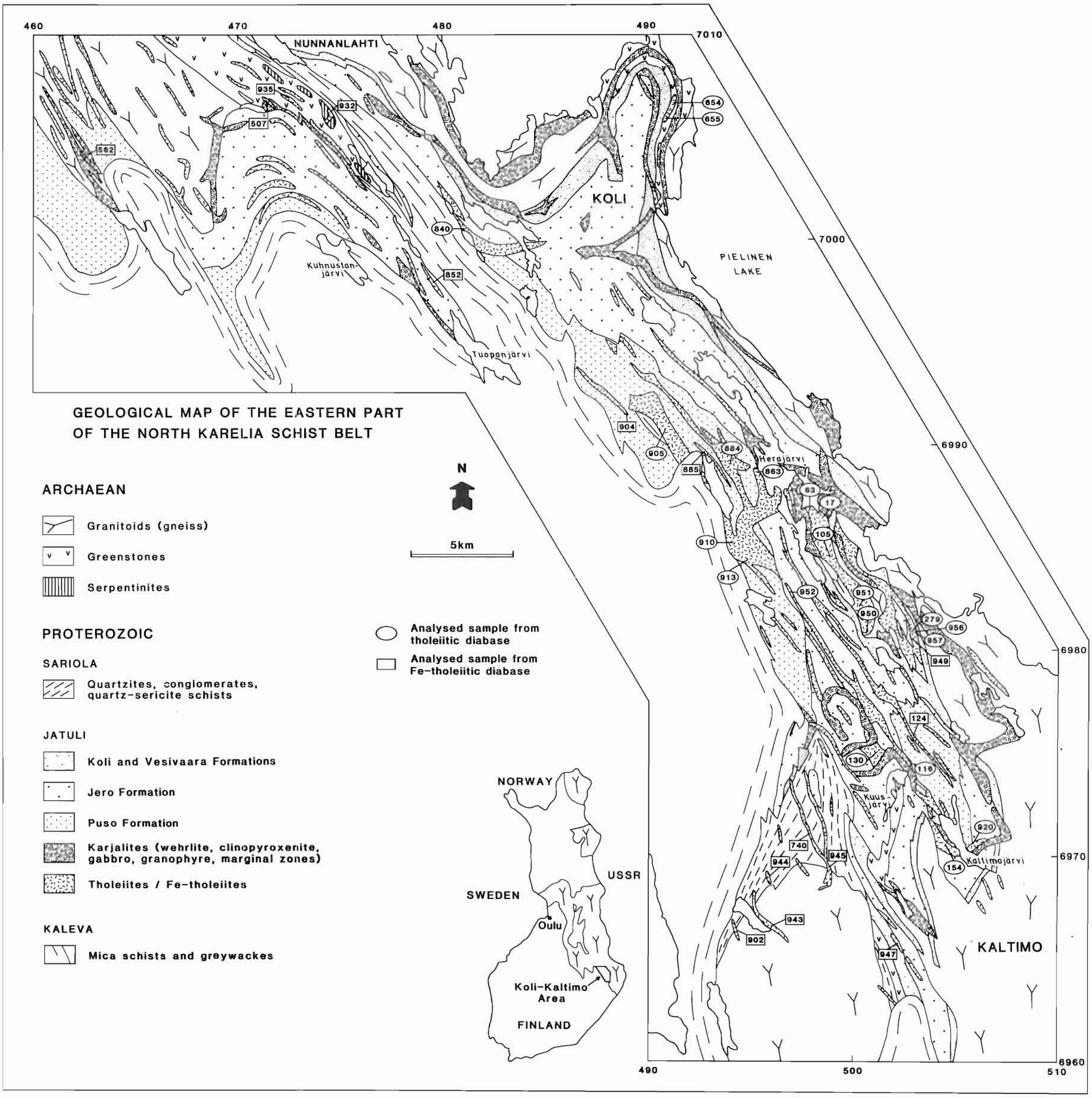

Fig. 1. Geological map of the eastern part of the North Karelia Schist Belt and the research area with locations of the sampling sites.

Kalevian formations are present over wide areas.

The Jatulian sequence (Fig. 2) begins with a thick palaeoregolith which changes through a quartz pebble conglomerate to orthoquartzite (Koli Fm), including a U-bearing horizon (Piirainen, 1968). The orthoquartzitic Koli Formation is overlain by the arkose quartzitic Jero Formation. The Koli Formation is only 100 — 200 m

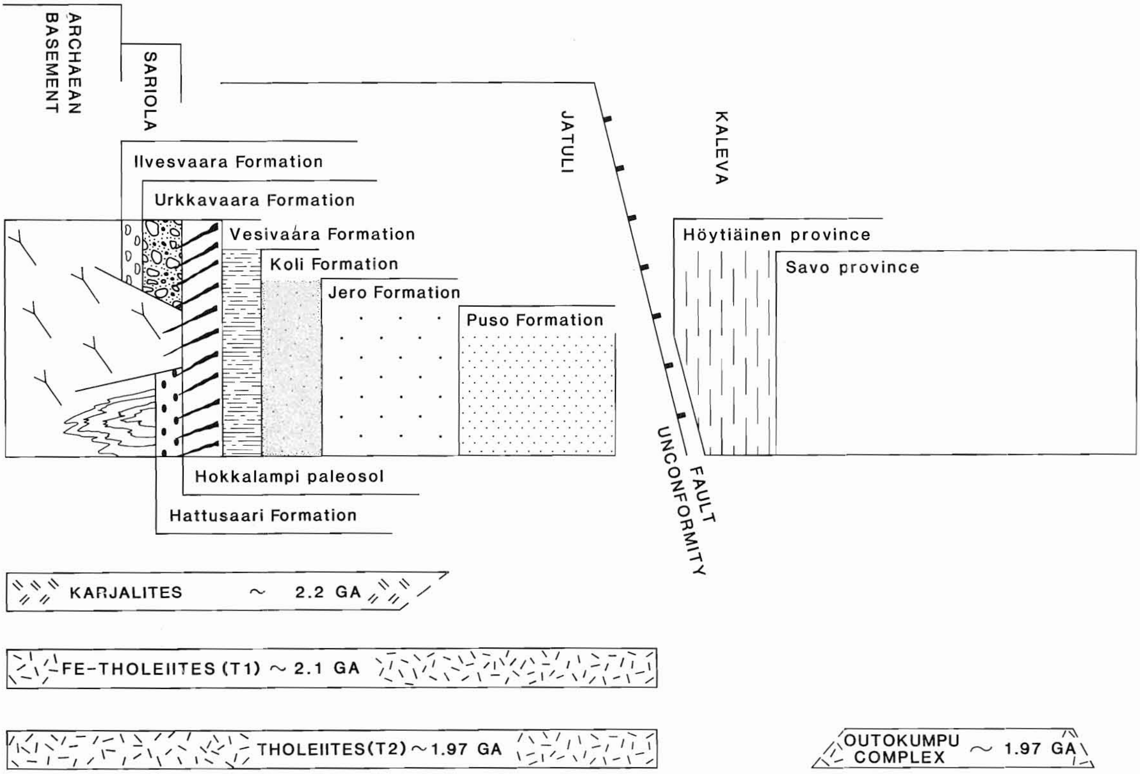

Fig. 2. Stratigraphy of the Koli-Kaltimo area, modified after Ward (1987) and Kohonen et al. (1990).

thick, while the Jero Formation is more than 1000 m thick. The Jatulian metasedimentary sequence terminates in an orthoquartzitic unit, the Puso Formation (Marmo et al., 1988).

The sedimentation of the Jatulian sequence was accompanied by igneous events. As mentioned above, the low-Al tholeiitic or karjalitic magmas first intruded through the basement about 2.2 Ga ago (Hanski, 1986; Vuollo and Piirainen, 1992), reaching the level of the Jero Formation (Figs. 1 and 2), and most of the karjalites occur as sills, while the tholeiites, which intruded later forming dykes, intersect the whole Jatulian sequence.

The Jatulian sequence with karjalitic sills and tholeiitic dykes (T1 and T2) is overlain by the turbiditic Kalevian mica schists. The Jatulian and Kalevian units are separated from each other by an unconformity with conglomerates, and the contact is tectonic due to overthrusting of the Kalevian schists (Kohonen et al., 1990). The Kalevian mica schists continue some distance to the south-west from the contact and are entangled with the Outokumpu ophiolite complex (Koistinen, 1981; Vuollo and Piirainen, 1989c) dated at 1.97 Ga (Huhma, 1986).

All early Proterozoic units were deformed and metamorphosed at several stages within the Svecofennian orogeny about 1.8 — 1.9 Ga ago and many granitoids were intruded not in the Koli-Kaltimo area, but far away to the south-west.

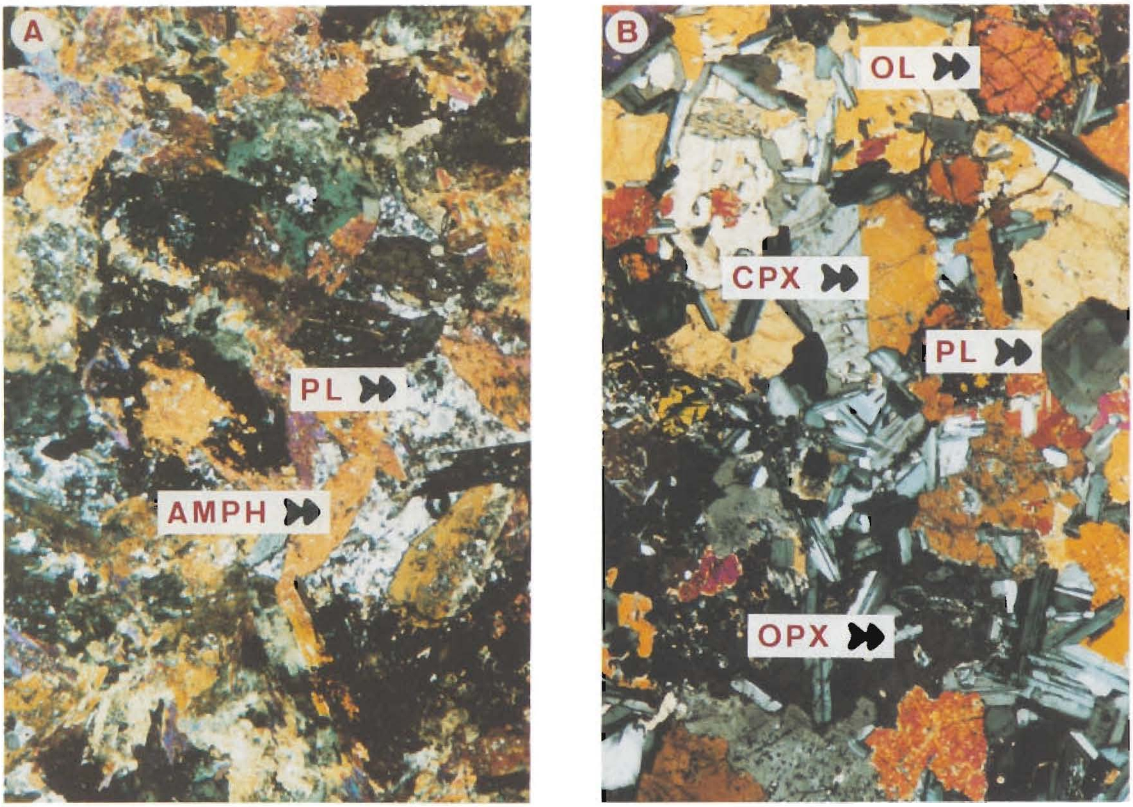

Fig. 3. Petrographic photographs of A) Fe-tholeiitic (Sample 945-JIV-89) and B) tholeiitic diabase dykes (Sample 279-JIV-86). from the Koli-Kaltimo area. Crossed nicols, photo length 4.5 mm. PL = plagioclase, AMPH = sec. amphibole, OL = olivine, CPX = clinopyroxene, OPX = orthopyroxene.

PETROGRAPHY AND MINERALOGY OF THE T1 AND T2 DIABASES

The tholeiitic diabase dykes of the Koli-Kaltimo area can be divided petrographically into two groups. The dykes of the older group (T1) are highly altered metadiabases, while the younger ones consist of almost unaltered diabases (T2). The dykes differ in their geochemical properties (T1 Fe-tholeiites and T2 tholeiites) and in age, and also represent entirely different stages in the geological evolution of the area.

Fe-tholeiitic diabases (T1)

Fe-tholeiitic diabases (T1) T1 diabases occur all over the area, both in the Archaean basement and among the Sariola and Jatuli formations, their dykes being much narrower (10 — 100 m) than those of the T2 diabases (Fig. 1). They continue for some distance into the area of Archaean

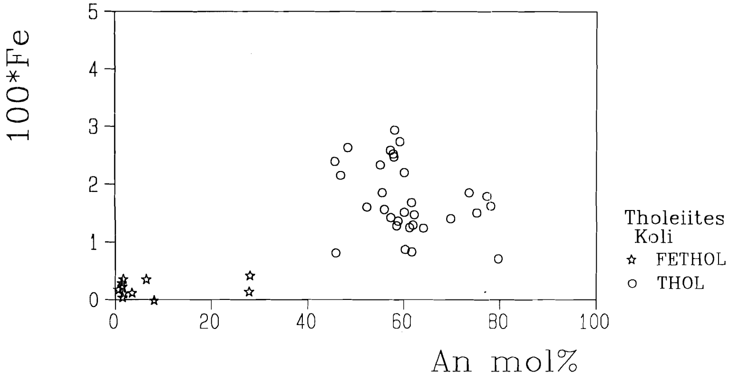

Fig. 4. Iron vs. anorthite content in analyses of plagioclase from diabases in the Koli-Kaltimo area. Iron content refers to total iron in a mole fraction based on a plagioclase of eight oxygens.

bedrock and are part of a dyke swarm intersecting the vast Archaean basement (Tuukki et al., 1987), whereas the T2 diabases occur only in the Jatuli formations in the schist belt.

The primary mineralogy and structure have almost entirely disappeared from the T1 diabases, which are markedly recrystallized (Fig. 3a). They vary from small to medium in grain size and from nematoblastic to granoblastic in structure, or sometimes blasto-subophitic, consisting mainly of amphibole (50 — 70%) and plagioclase (30 — 40%). Accessory minerals include sericite, biotite, quartz, epidote, carbonate, chlorite, titanite and ilmenite.

Figure 4, which presents the An content of plagioclase in the diabases versus Fe, shows the plagioclases of the T1 diabases to be markedly poorer in An than those of the T2 diabases and to have a distinctly lower Fe content. The plagioclase of the T1 diabases, which occur inside the Jatuli sediments consists of albite (Table 1, anal. 11), whereas that in the Sariola sediments in the southern parts (Table 1, anal. 12) and inside the Archaean basement complex (Table 1, anal. 13) is oligoclase. The albitic plagioclase in the T1 diabases always includes large amounts of epidote, but the amounts diminish as the composition becomes richer in An. On the basis of this we can claim that the plagioclase in the T1 diabases is not primary, but has changed into either albite or oligoclase due to metamorphism. The amphibole consists mainly of bluish-green ferroan hornblende (Table 1, anal. 15) or lighter ferroan pargasitic hornblende (Table 1, anal. 14). The only oxide ore mineral is ilmenite, but pseudomorphs of the original ilmenomagnetite are found in places.

Tholeiitic diabases (T2)

T2 tholeiitic dykes are found only in the Jatuli formations, occurring in places in fairly thick (max. 1 km), relatively homogeneous dykes which usually run in the NW — SE direction.The primary ophitic — subophitic structure has been retained in most samples, of which the best example is given in Figure 3b. Some samples have also retained almost entirely their original minerals, i.e. plagioclase, clinopyroxene, orthopyroxene and ilmenomagnetite and olivine at the high-magnesian end of the spectrum and minor interstitial quartz at the low-magnesian end. But the majority of the dykes are now composed predominantly of altered pyroxenes, mainly actinolite/actinolitic hornblende (60 — 75% by mode) and often also primary plagioclase (25 —

40% by mode), the accessories being chlorite, sericite, epidote and sphene. However, the low level of alteration in the rocks is indicated by the fact that the plagioclase is fresh in most dykes (i.e. calcic and normally zoned).

Table 1 presents some analyses of the primary minerals in the T2 diabases (Table 1, anal. 1—10). According to analyses 7 and 8, the An content is 79.7% in the core of the zonal plagioclases and approx. 60% on the rim. Figure 4 shows that the Fe and An concentrations of the plagioclases in the T2 diabases are higher

Table 1. Microprobe analyses of the main minerals of tholeiitic (T1 and T2) diabases from the Koli-Kaltimo area.

	Olivine		Ca-pyroxene		Ca-poor pyroxene		Plagioclase			
	1	2	3	4	5	6	7(m)	8(c)	9	10
SiO_2 (wt%)	36.0	36.6	51.6	51.1	52.8	52.0	53.6	47.9	51.7	51.2
TiO_2	0.04	0.06	0.63	0.31	0.57	0.38				
Al_2O_3			2.26	2.27	1.33	0.87	29.2	32.9	30.3	29.4
Cr_2O_3	0.00	0.03	0.14	0.13	0.03	0.04				
FeO^{tot}	34.1	33.9	9.0	6.5	19.4	24.0	0.38	0.19	0.33	0.38
MnO	0.47	0.33	0.22	0.16	0.38	0.39				
MgO	29.5	29.5	14.8	16.7	23.1	19.9				
CaO	0.06	0.07	20.4	19.8	2.52	1.87	12.1	16.1	13.1	12.6
Na_2O			0.33	0.22	0.05	0.02	4.91	2.23	4.02	4.44
K_2O							0.07	0.05	0.03	0.08
NiO	0.13	0.13	0.04	0.03						
Sum	100.3	100.8	99.5	97.3	100.2	99.6	100.4	99.5	99.6	98.3
X	60.61	60.84	74.5	82.2	68.0	59.7	57.3	79.7	64.1	60.8
Y							42.3	19.9	35.7	39.2
Z							0.4	0.4	0.2	0.7

	Plagioclase			Sec.amphibole		
	11	12	13	14	15	16
SiO_2 (wt%)	66.7	60.2	61.3	41.8	41.9	51.8
TiO_2				0.44	0.27	0.06
Al_2O_3	20.5	24.2	23.8	13.9	12.5	2.80
Cr_2O_3				0.00	0.03	0.18
FeO^{tot}	0.10	0.04	0.08	17.9	21.8	13.6
MnO				0.25	0.24	0.26
MgO				7.96	5.44	14.4
CaO	1.38	5.88	5.23	11.5	10.9	12.1
Na_2O	11.0	8.4	8.9	1.42	1.29	0.24
K_2O	0.06	0.06	0.08	0.51	0.45	0.09
Sum	99.8	98.9	99.5	95.8	95.0	95.6
X	6.5	27.9	24.3	44.2	30.8	65.3
Y	93.2	71.8	75.2			
Z	0.3	0.3	0.5			

Notes: (1) 279-JIV-86 , (2,3,5,9) 259-JIV-85, (4) 22-JIV-85, (6) 303-JIV-86, (7,8) 193-JIV-85, (10) 255-JIV-85, (16) 950-JIV-89, analyses from T2 diabases, (11) 885-JIV-88, (12) 943-JIV-89, (13,14) 935-JIV-89, (15) 953-JIV-89, analyses from T1 diabases. X = Fo in olivine, An in plagioclase and $100 \times Mg/(Mg + Fe^{2+})$ in Ca-pyroxene, Ca-poor pyroxene and amphibole, Y = Ab in plagioclase, Z = Or in plagioclase. c = core of a grain, m = margin of agrain.

(An: min. 40%) than those in the T1 diabases. The pyroxenes are most typically replaced with uralitic amphibole (actinolite; anal. 16, NB. high Cr_2O_3 content), but both orthopyroxene and clinopyroxene are found in some samples. When plotted on the discrimination diagrams of Laterrier et al. (1982), all the clinopyroxenes fall within the sub-alkaline field and have the orogenic character of an island arc tholeiite (Fig. 5). The oxides are lamellar to granular intergrowths of ilmenite and magnetite, but are altered in places so that only the ilmenite is left.

The grade of metamorphism most likely corresponds to greenschist facies, but the mineral proportions are different from those in a normal regionally metamorphosed assemblage. The proportion of chlorite is small (0 — 2% by mode) and that of epidote practically non-existent in many samples. Although the changes are clearly more marked in places, such a composition may be caused by metamorphism of actinolite facies (Elthon and Stern, 1978; Elthon, 1981) under conditions of very low water/rock ratios (Mottl, 1983).

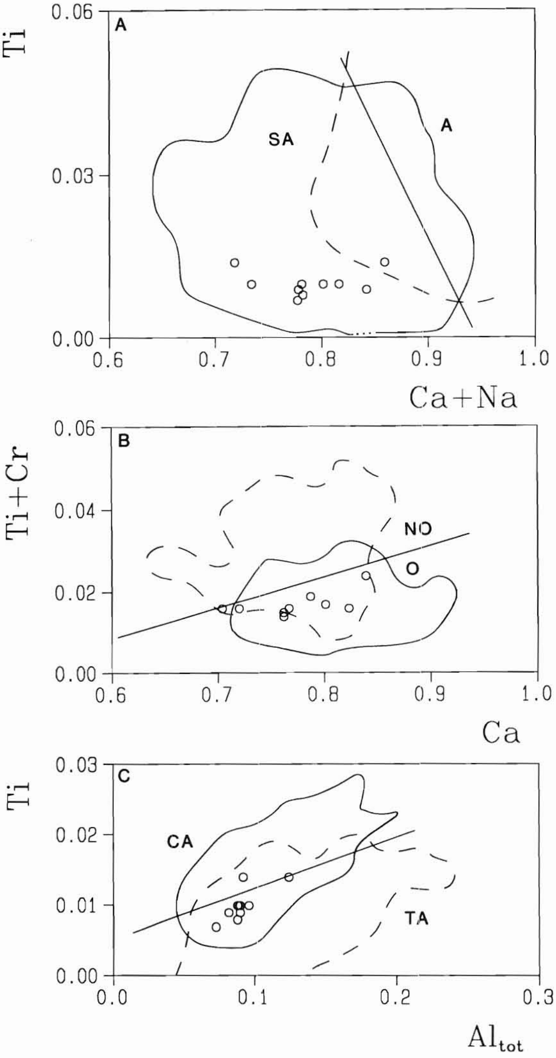

Fig. 5. Clinopyroxene compositions of tholeiitic diabases (T2) plotted on the discrimination diagrams of Leterrier et al. (1982). A, alkaline; SA, subalkaline; O, orogenic, NO, non-orogenic; TA, arc tholeiites; CA, calc-alkaline.

GEOCHEMISTRY

Sampling and analytical methods

The aim when collecting the samples from the Koli-Kaltimo area was to acquire as representative a set as possible (Fig. 1) and equal amounts from both diabase types (Table 2). On both petrographical and geochemical (Fig. 6) grounds 36 analyses from the best preserved samples were selected for the diagrams and analyses of the average values. The samples were taken from the mid-parts of the dykes wherever the exposure conditions allowed this.

The analyses were performed at the laboratories of X-Ray Assay Ltd. in Canada. The major-elements and Rb, Zr, Ba and Nb were determined by conventional X-ray fluorescence analysis

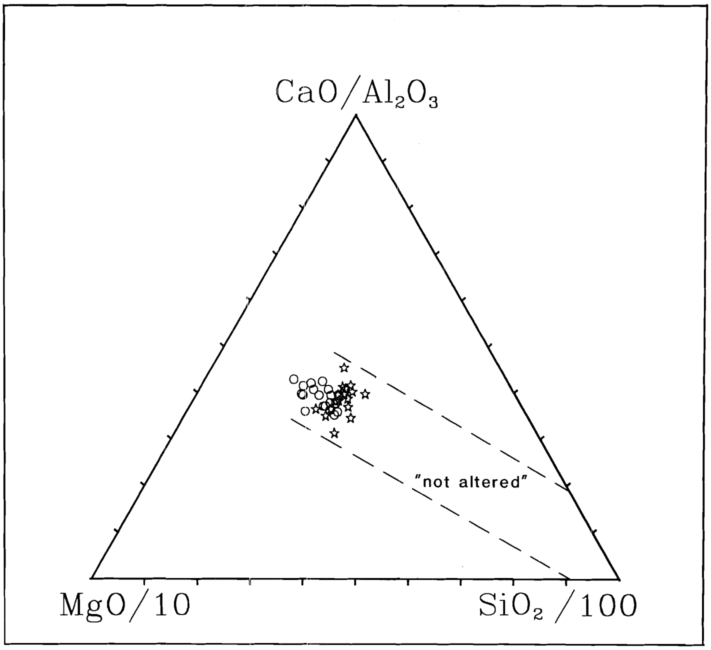

Fig. 6. Locations of the T1 and T2 diabases on a $MgO/10$ — CaO/Al_2O_3 — SiO_2 diagram illustrating alteration (Davis et al. 1979). Symbols as in Fig. 4.

(XRF) and concentrations of the trace-elements Ni, Cu, Zn, Sc, Sr and Y by ICP, REE by ICPMS, Cr, Th and U by INAA and V by DCP. Centerville diabase W-2 (USGS) was used as an analytical standard.

Mineral phases were analysed using a JEOL JCXA 733 electron microprobe, following the method described by Alapieti and Sivonen (1983), at the Institute of Electron Optics, University of Oulu.

The isotopic analyses were made at the Geological Survey of Finland, and for the most samples the methods were similar with those described by Huhma (1986). The chemical separation of Sm and Nd for most recent analyses followed methods described by Richard et al. (1976).

Results

The mean compositions of both major- and trace-elements of the T1 and T2 diabases in the area are presented in Table 2. The T1 and T2 diabases are distinctive in both their major- and trace-element geochemistry. 15 of the T2 diabase samples were quartz-normative and 6 olivine-normative, whereas the majority of T1 samples were from quartz-normative (14) to marginally olivine-normative (1). None of the samples analysed was nepheline-normative. The mean of Mg* value (mol. $Mg/(Mg+0.9Fe_{tot})$ in the T2 diabases, 56.7 (range 50 — 71, Fig. 7), was markedly higher than that in T1 diabases, 42.3 (36 — 50, Fig. 7). The Mg* values of both groups were lower than those of basalts thought to have been in equilibrium with a peridotitic mantle, which ranged from 79 to 70 (Basaltic Volcanism Study Project (BVSP), 1981; Fig. 4, p. 568). Thus both tholeiitic suites have undergone fractionation and the lower Mg* value of the T1 diabases indicates a more advanced fractionation. The T2 group has moderately low TiO_2 (av. 1.01 wt%), Fe_2O_{3tot} (av. 12.78 wt%), K_2O (av. 0.51 wt%) and P_2O_5 (av. 0.09 wt%) content, while the T1 group has distinctly higher TiO_2 (av. 1.98 wt%), Fe_2O_{3tot} (av. 16.43 wt%), K_2O (av. 0.79 wt%) and P_2O_5 (av. 0.21 wt%) content.

Table 2. Average chemical compositions of Fe-tholeiitic (T1) and tholeiitic (T2) mafic dykes of Koli-Kaltimo area.

Dykes	T1		T2	
N	15		21	
	Mean.	S.D.	Mean.	S.D.
SiO_2 (wt%)	49.18	1.58	49.51	1.35
TiO_2	1.98	0.26	1.01	0.21
Al_2O_3	13.35	0.66	13.46	1.31
Fe_2O_{3tot}	16.43	1.45	12.78	1.33
MnO	0.25	0.04	0.21	0.02
MgO	5.50	0.72	7.80	1.59
CaO	8.82	0.95	10.82	1.74
Na_2O	2.21	0.30	1.84	0.62
K_2O	0.79	0.32	0.51	0.40
P_2O_5	0.21	0.03	0.09	0.02
Mg^*	42.32	3.74	56.87	6.24
V (ppm)	447	68	332	51
Cr	69	25	170	147
Ni	66	15	98	43
Cu	167	112	131	144
Zn	158	28	119	27
Sc	41	4	42	4
Rb	45	18	28	20
Sr	189	60	157	33
Y	33	6	18	4
Zr	138	35	59	19
Nb	11	5	6	6
Ba	171	115	90	58
La (ppm)	16.0	4.08	5.4	1.48
Ce	36.4	8.40	14.0	5.55
Nd	20.9	3.83	8.5	2.10
Sm	4.8	0.94	2.3	0.60
Eu	1.7	0.39	0.8	0.17
Tb	0.9	0.20	0.5	0.11
Yb	3.2	0.42	1.8	0.42
Lu	0.4	0.06	0.2	0.06
Hf	4.5	0.67	2.0	0.53
Th(N = 15,6)	1.63	0.53	0.58	0.13
U(N = 12,11)	0.89	0.66	0.43	0.32
Petrography	Hbd,plag,biot,quartz,op recrystallized		Cpx,opx,plag,oliv,op ophitic-subophitic	
Rock	Fe-tholeiite		Tholeiite	
Sm-Nd and U-Pb age(Ma)	estim. 2100		1985 ± 80 1965 ± 10	

Total Fe as Fe_2O_3, Mg^* = molar $[Mg/(Mg+Fe^{2+})]x100$, assuming $Fe^{2+} = 0.9\ Fe^{tot}$ (Brooks, 1976), N = number of samples

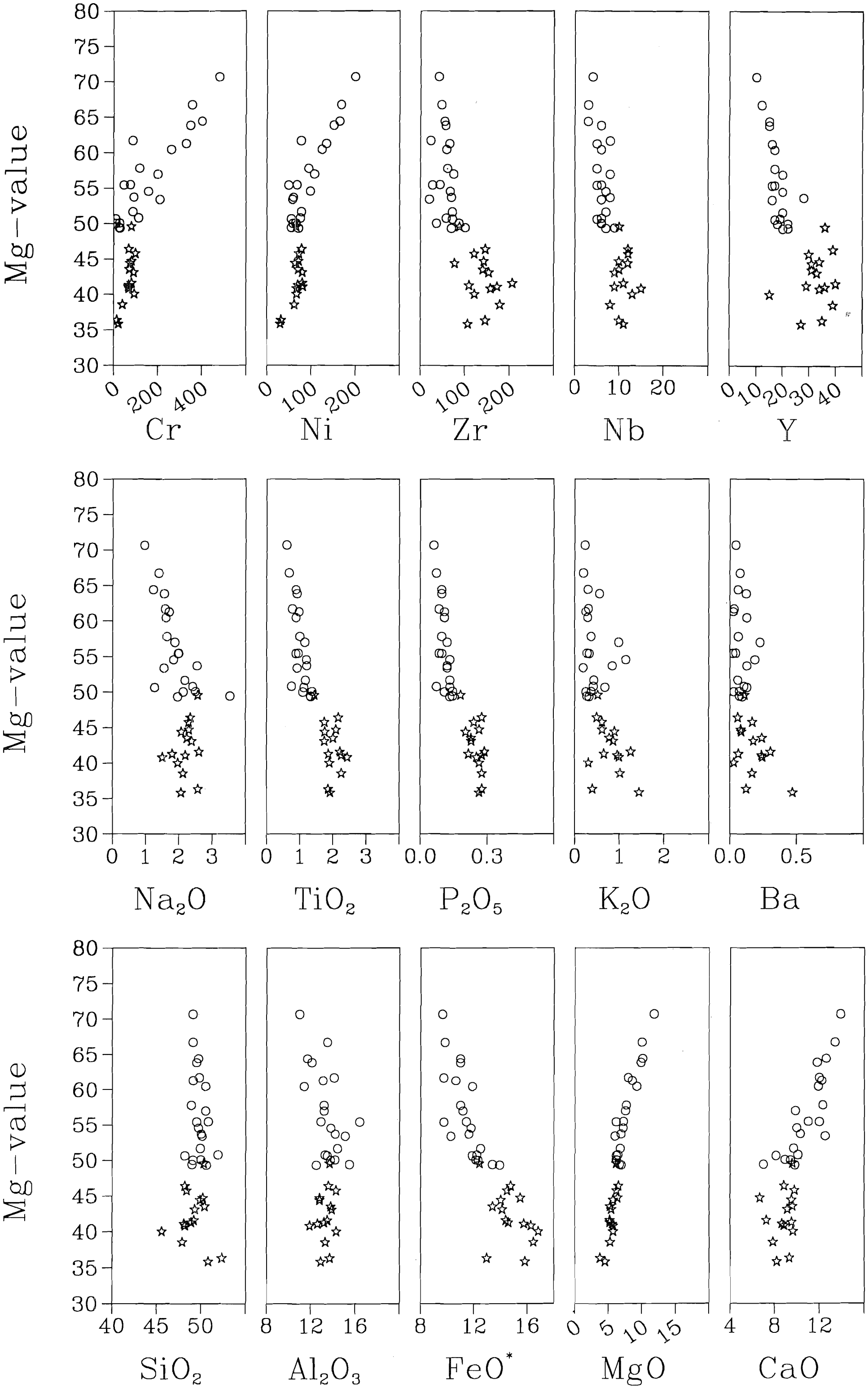

Fig. 7. Mg* value variation diagrams. Symbols as in Fig. 4.

Mg* value vs. trace-element diagrams also show a division into two groups in the case of some trace elements (Fig. 7), in that the T2 diabases have higher Cr (av. 170 ppm) and Ni (av. 98 ppm) values and lower Zr (av. 59 ppm) and Y (av. 18 ppm) values, while the corresponding values for the T1 diabases are 70, 65, 137 and 32, respectively.

All the samples analysed are located in the basalt field in the total alkali-silica diagram (Fig. 8a) and are subalkaline in nature (Irvine and Baragar, 1971). Both of the diabase groups lie

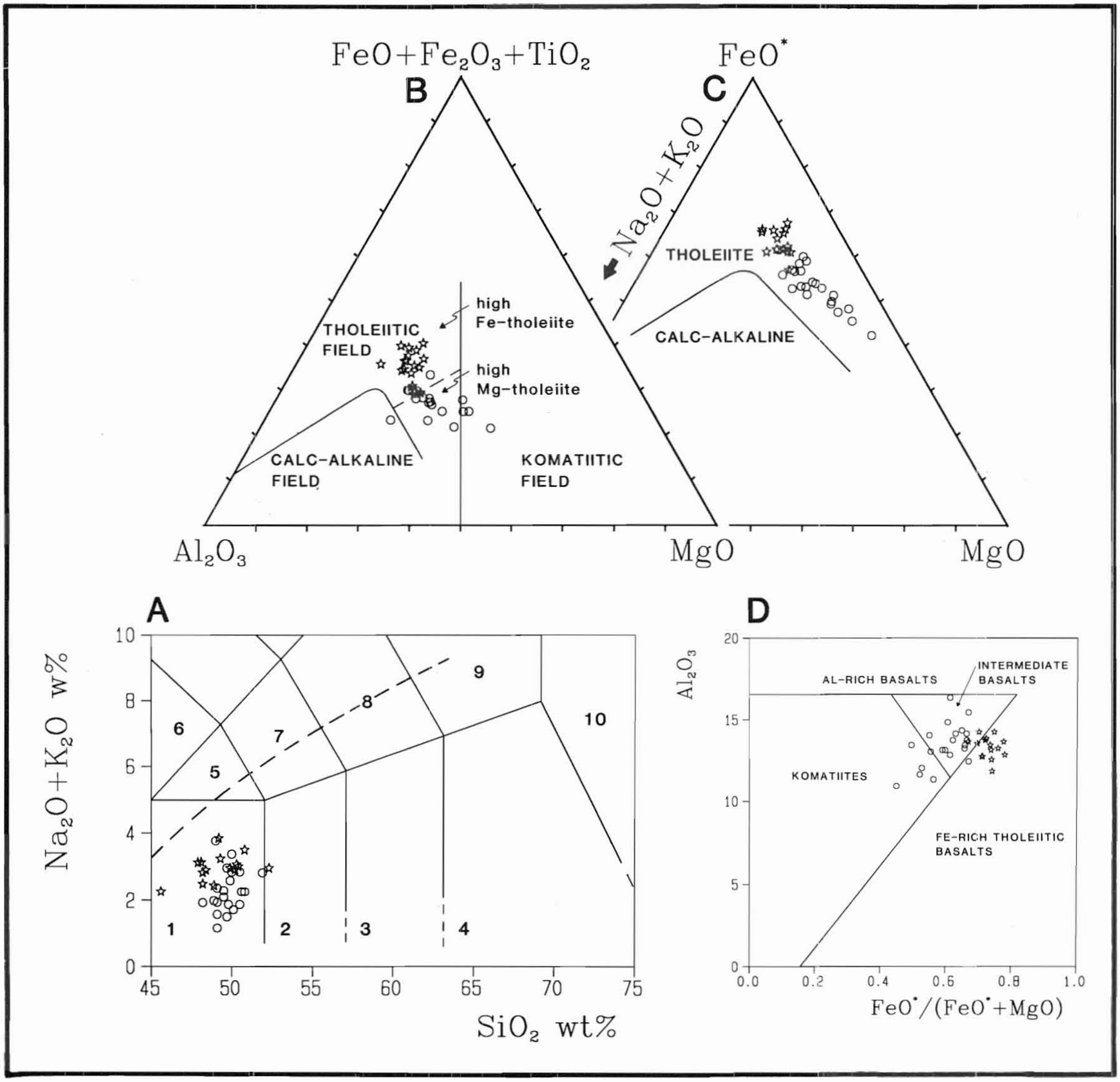

Fig. 8. Compositions of the Fe-tholeiitic (T1) and tholeiitic (T2) diabase dykes of the Koli-Kaltimo area. A) $Na_2O + K_2O$-SiO_2 diagram showing the IUGS classification fields (Le Bas et al. 1986): 1. basalt, 2. basaltic andesite. The broken line separates subalkaline and alkaline compositions (Irvine and Baragar 1971. B) Cation diagram of Jensen (1976) for tholeiitic diabases. C) AFM diagram showing fields of tholeiitic and calc-alkaline rocks after Irvine et al. 1971. D) $FeO^*/(FeO^* + MgO)$ vs. Al_2O_3 diagram after Naldrett et al. 1976. Symbols as in Fig. 4.

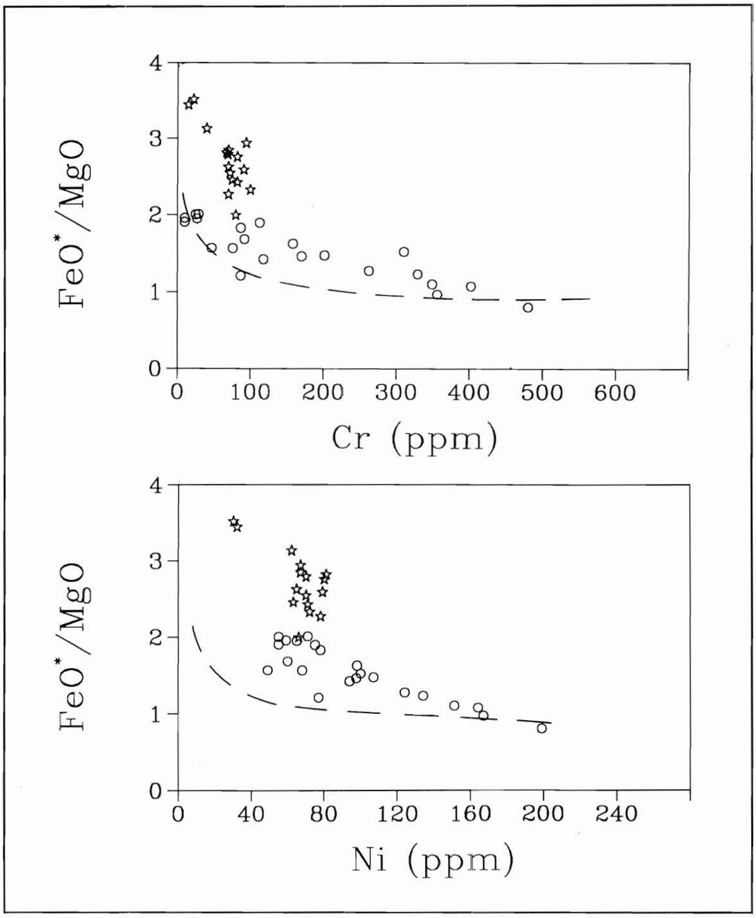

Fig. 9. FeO*/MgO vs. Cr (ppm) and Ni (ppm) plots. The lines show the expected evolutionary trends for Ni and Cr and FeO*/MgO ratios in closed magmatic systems dominated by simple Raleigh crystal fractionation. Symbols as in Fig. 4.

almost entirely in the tholeiite field in the various geochemical diagrams (Fig 8b and c), the purpose of which is to distinguish between tholeiitic basalts, and calc-alkaline and alkaline basalts (Jensen, 1976; Irvine and Baragar, 1971). In addition, Jensen's cation ratio diagram (Fig. 8c) indicates well the division of the diabases into Fe- and Mg-tholeiites. Some of the T2 diabases richest in Mg are within the komatiite field. The same division in composition can also be seen in the Al_2O_3 vs. FeO*/(FeO* + MgO) diagram (Naldrett and Arndt, 1976), in which the diabase dykes are divided into two groups, Fe-rich tholeiitic basalts and intermediate basalts, of which some Mg-rich occur in the komatiite field (Fig. 8d).

The data for Ni and Cr in both diabase groups are plotted versus FeO*/MgO, the index of the compositional evolution of the magma, in Figure 9. The dashed lines on these two plots show the expected evolutionary trends for Ni and Cr and FeO*/MgO ratios in closed magmatic systems dominated by simple Rayleigh crystal fractionation. The majority of the T2 diabase samples lie along or close to these fractionation lines, which indicates that they have crystallized in a relatively closed system, whereas the Fe-rich T1 diabases lie above the curves implying highly advanced fractionation of their parent magma at an early stage before intrusion.

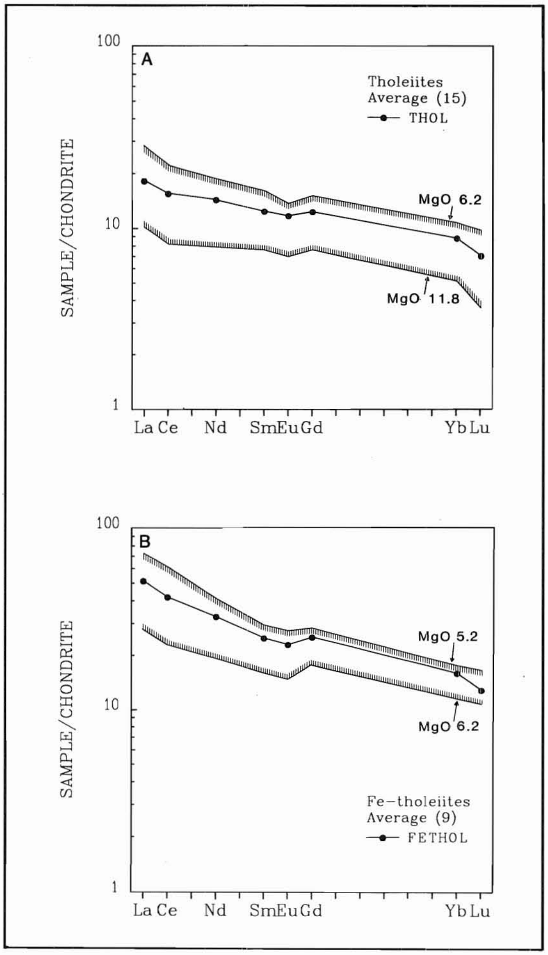

Fig. 10. Rare-earth element (REE) variation and average analyses for the A) tholeiitic (T2) and B) Fe-tholeiitic (T1) diabase dykes in the Koli-Kaltimo area.

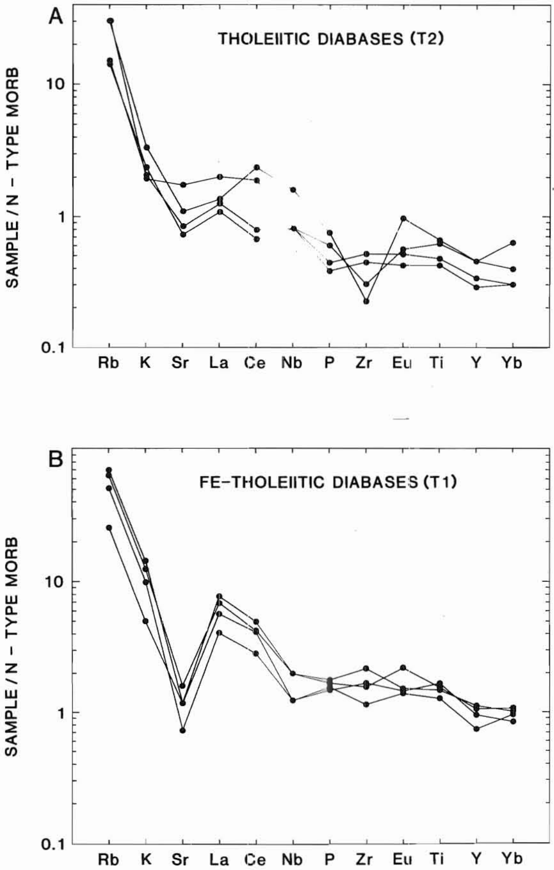

Fig. 11. Spider diagrams for the A) tholeiitic (T2) B) Fe-tholeiitic (T1) diabase dykes in the Koli-Kaltimo area, normalized to N-type MORB (Saunders and Tarney 1984).

The T2 diabases feature chondrite-normalized REE patterns which vary from flat to slightly enriched at the LREE end ($[La/Yb]_N = 1.6$ to 2.6), the total REE content varying from 5 to 30 times chondrites (Fig. 10a). The T2 samples are clearly enriched in large-ion lithophile elements (LILE) Rb and K and slightly enriched in Sr, La and Ce compared with the N-type mid-ocean ridge basalt (MORB), but contain less of the high field strength elements (HFSE) Nb, P, Zr, Eu, Ti, Y and Yb (Fig. 11a). T1 diabases are consistently enriched in LILE and HFSE, and Y and Yb overlap the N-type MORB (Fig. 11b), apart from which T1 is markedly enriched in LREE ($[La/Yb]_N = 2.8$ to 4.1) with total REE from 15 to 70 times chondrites (Fig. 10b). Both suites have a slight negative Eu anomaly (Figs. 10 a and b).

ISOTOPIC STUDIES

Small amounts of zircon were found in T2 diabase A1144 from Paukkajanvaara (sample 279-JIV-86). Zircon occurs as transparent broken fragments and original morphology can not be seen. Zircon from an other sample A1175 (202-JIV-85) is also mostly transparent but partly turbid. Due to small amounts of zircon only one analysis is available on both samples (Table 3). Analysis for A1144 is concordant at 1963 ± 8 Ma, whereas A1175 is slightly discordant with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1972 ± 5 Ma. For common lead correction the lead isotopic ratios measured from the Outokumpu ore has been used (Vaasjoki, 1981). This is supported by the Pb isotopic composition measured for the whole rock A1144 ($^{206}\text{Pb}/^{204}\text{Pb} = 16.95$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.27$), which implies a relatively low initial $^{207}\text{Pb}/^{206}\text{Pb}$ ratio. Based on these data the age of crystallization of the T2 diabase is estimated to be 1965 ± 10 Ma (Fig. 12a).

Well-preserved magmatic minerals together with whole rock from sample A1144 were used for Sm-Nd analyses. These data provide an age of 1985 ± 80 Ma with an initial $\varepsilon_{Nd} = +1.8 \pm 0.6$ (Table 4, Fig. 12b).

Due to alteration and lack of zircon no Sm-Nd or U-Pb mineral analyses have been made on the Fe-tholeiitic diabases (T1). Based on field observations these diabases are considered to be older than ca. 1.97 Ga old T2 diabases, but younger than the differentiated low-Al tholeiites (karjalites), which elsewhere in Finland have yielded U-Pb zircon and baddeleyite ages of about 2.2 Ga (Sakko, 1971; Perttunen, 1991; Silvennoinen, 1991). Some of the diabases in eastern Finland have provided U-Pb zircon ages of about 2.1 Ga

Table 3. U-Pb data on zircon from the tholeiitic (T2) diabases.

Sample	weight		Measured					Age (Ma)
		^{238}U (ppm)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$ 1)	$^{208}\text{Pb}/^{206}\text{Pb}$ 1)	$^{206}\text{Pb}/^{238}\text{U}$ 2)	$^{207}\text{Pb}/^{235}\text{U}$ 2)	$^{207}\text{Pb}/^{206}\text{Pb}$ 2)
A1144A	0.5 mg	578	1452	0.1274	0.4807	0.3548	5.893	1963 ± 8
A1175A	2.1 mg	329	423	0.1511	0.3981	0.3327	5.554	1972 ± 5

1) Corrected for blank (0.5 ng).
2) Corrected for blank and initial common lead ($^{206}\text{Pb}/^{204}\text{Pb} = 14.73$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.02$, $^{208}\text{Pb}/^{204}\text{Pb} = 34.48$)

Table 4. Sm-Nd data for the tholeiitic (T2) diabases.

Sample		Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}^{*}$	$^{143}\text{Nd}/^{144}\text{Nd}+$	Initial $\varepsilon_{Nd}(1970)$
A1144	wr	1.64	5.21	0.1902	0.512645 ± 43	+ 1.7
A1144 #2	wr	1.56	4.92	0.1921	0.512672 ± 31	+ 1.8
A1144	plag	0.22	1.24	0.1074	0.511552 ± 20	+ 1.2
A1144	cpx	2.22	6.35	0.2111	0.512907 ± 35	+ 1.6
A1144	apatite	103.00	455.00	0.1366	0.511971 ± 14	+ 2.1
A1175	wr	2.82	9.60	0.1779	0.512447 ± 10	+ 0.9
885-JIV-88	wr	2.00	6.75	0.1787	0.512519 ± 10	+ 2.2

*: error is 0.5%. The concentration were determined from liquid aliquots.
+: ratios normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Reported errors are δ 2 m.

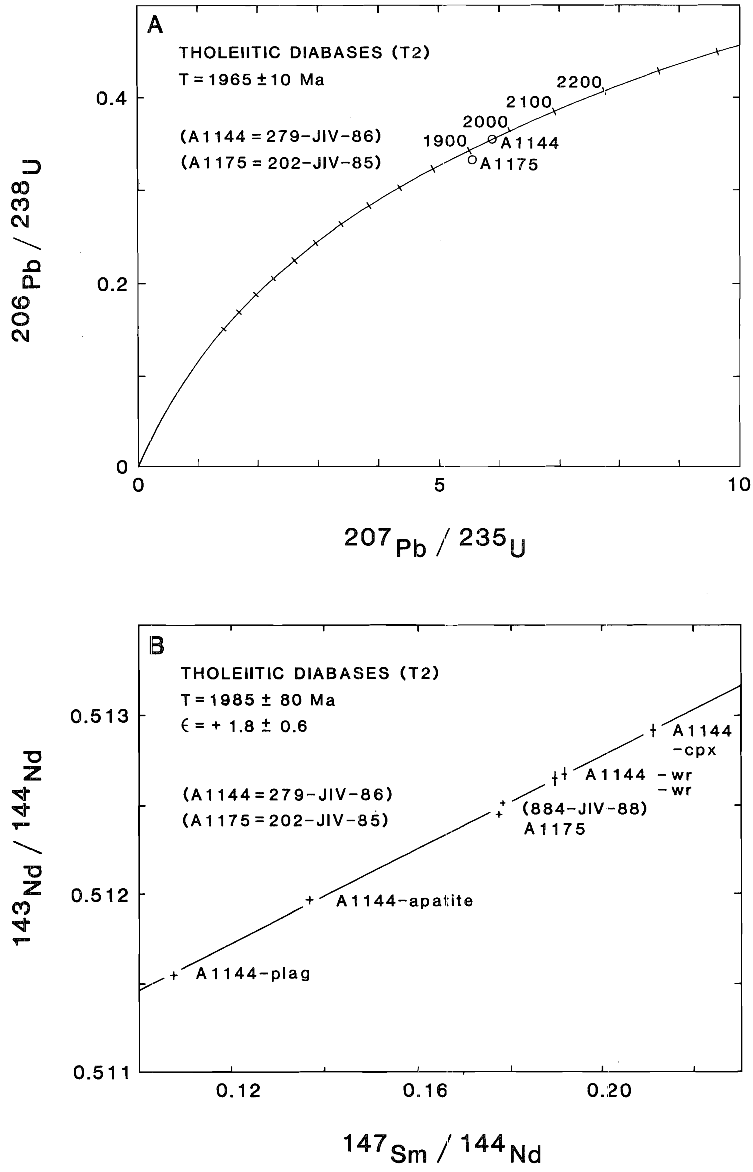

Fig. 12. A) Concordia plot of U-Pb zircon data on two T2 diabase samples, B) Sm-Nd diagram for mineral fractions and whole rocks (wr) from the T2 diabases.

(Huhma, 1986; Pekkarinen and Lukkarinen, 1991), and these bear similarities with Fe-tholeiites (T1) described in this study. Whether Fe-tholeiitic diabases represent one magmatic phase or several temporally distinct stages of intrusion remains, however, an open question.

PETROPHYSICAL STUDIES

Approx. 200 samples were collected from the area for petrophysical measurements, from which 88 relatively unaltered samples were selected on petrological and geochemical grounds. The measurements were carried out by the Geological Survey of Finland in Rovaniemi, and included density, magnetic susceptibility and intensity of the natural remanent magnetization, and calculation of the relation between remanence and susceptibility (Q-ratio). The results of the measurements concerning the physical properties of the two diabase dyke swarms are summarized in Table 5.

The densities of the 53 T2 diabase samples ranged from 2670 kg/m^3 (altered) to 3122 kg/m^3 (fresh), the mean and standard deviation of the individual values being 2933 ± 96 kg/m^3, while the densities of the 35 T1 diabase samples ranged from 2744 kg/m^3 to 3186 kg/m^3, the mean and standard deviation being 3002 ± 90 kg/m^3. The wide range of densities results from the variable mineralogy of the diabases, but it is obvious that the samples with a smaller density are more altered containing carbonate, chlorite and biotite.

The histograms depicting density, natural remanent magnetization (NRM) intensity, susceptibility and Koenigsberger (Q) ratio are lognormally distributed, and the T1 and T2 diabases are almost the same in their magnetic susceptibility (Fig. 13a). Some T2 diabases have a slightly increased magnetic susceptibility, however, in which case petrographic observations indicate that they have a slightly higher number of ilmenomagnetite grains. The clearest variation is seen in NRM intensity, which is a slightly higher for the less altered T2 diabases (approx. 0.2 Am^{-1}) but very low for the highly altered, recrystallized T1 diabases (approx. 0.03 Am^{-1}). The Q-ratio values change considerably from typically less than one (av. 0.78) in the T1 dykes, to mostly greater than one (av. 3.39) in the T2 dykes. Such clear differences in the Q-ratio and NRM intensity can be explained in mineralogical terms, in that the T1 diabases do not contain any magnetite, the only remaining oxidic mineral being ilmenite, whereas small amounts of ilmenomagnetite are found in the T2 diabases, and magnetite occurs in small grains, causing a higher NRM intensity.

Table 5. Petrophysical properties of T1 and T2 diabases of Koli-Kaltimo area.

Property	n	Arith. Mean	S.D.
	Fe-tholeiites (T1)		
Bulk density/kg m^{-3}	35	3002	90
NRM intensity/Am^{-1}	35	0.03	0.03
Susceptibility /x10^{-3}S.J.Units	35	0.98	0.18
Koenigsberger (Q) ratio	35	0.78	0.71
	Tholeiites (T2)		
Bulk density/kg m^{-3}	53	2933	96
NRM intensity/Am^{-1}	53	0.16	0.22
Susceptibility /x10^{-3}S.J.Units	53	0.97	0.45
Koenigsberger (Q) ratio	53	3.39	3.28

n: number of samples, Arith. Mean: arithmetic mean, S.D.: standard deviation of individual values

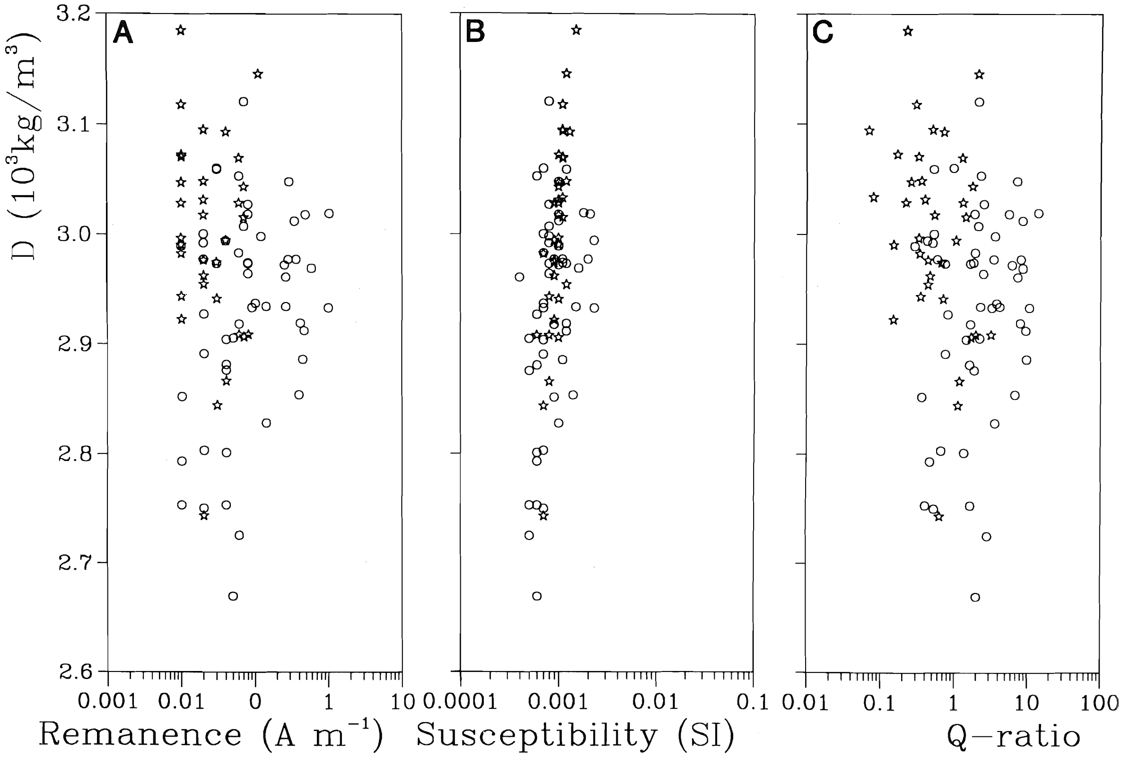

Fig. 13. A) NMR intensity vs. density, B) magnetic susceptibility vs. density, and C) Koenigsberger ratio vs. density for diabases in the Koli-Kaltimo area. Symbols as in Fig. 4.

DISCUSSION

Petrogenesis

The considerable variations in Mg* value (mol[MgO/(MgO + 0.9xFeO$_{tot}$]), Ni and Cr (Fig. 7) show that the diabases of the Koli-Kaltimo area underwent variable but high degrees of fractionation. The clear positive correlation between Mg, Ni and Cr and the Mg* value indicates the fractionation of mafic minerals. The decrease in Sc as SiO$_2$ increases may be connected with the fractionation of clinopyroxene in the T1 diabases, while this is not found in the T2 diabases, which nevertheless show an increase in Ti and V as differentiation proceeds, indicating that no significant amounts of Fe-Ti oxides have fractionated from them. On the other hand, this enrichment is not so clear in the T1 diabases, i.e. small amounts of Fe-Ti oxides have probably fractionated from the magma. Minimal fractionation of the plagioclase in both groups is indicated by a small Eu anomaly (Fig. 10) and Al, Ca and Sr variation (Fig. 7).

Experimental results indicate that tholeiites can be formed when the upper mantle peridotites melt to an extent of approx. 15 — 30% (Green and Ringwood, 1968; Green, 1973; Jacques and Green, 1980). Both REE and other trace-elements and their distributions have often been used for the examination of petrogenesis.

Rajamani et al. (1985) and Condie et al. (1987) have used Zr and Ni to examine the petrogenesis of komatiites and tholeiites. Zr should be an almost incompatible element during melting, while Ni should be one of the most compatible ones. Furthermore these elements are among the least mobile ones in connection with both alteration and metamorphism, and therefore they are highly suitable for the assessment of the petrogenesis of metamorphic mafic rocks.

The Zr and Ni concentrations in the diabases of the Koli-Kaltimo area are plotted in Figure 14a for the paths of melting of a mantle with 2000 ppm Ni and 11 ppm Zr at 1500°C and 1 atm. This diagram suggests that the T2 diabases in the area were produced as a result of an average of over 20% batch melting of a lherzolitic source followed by an up to 50% fractional crystallization of olivine. The wide variation in Ni content of the T2 diabases points to various stages of fractionation of olivine (from 40 to 60 %), while the variation in Zr refers to changes in the stages of melting (up to over 30 %). The Ni content of the T1 diabases is very stable and indicates a 50 % fractionation of olivine, while the Zr content varies considerably, which probably reflects varying degrees of melting from about 5 to 20% (average point approx. 10% batch melting).

The Cr and Y pair is commonly used to examine the petrogenesis of mafic rocks. Figure 14b shows analyses plotted on a Cr/Y diagram as

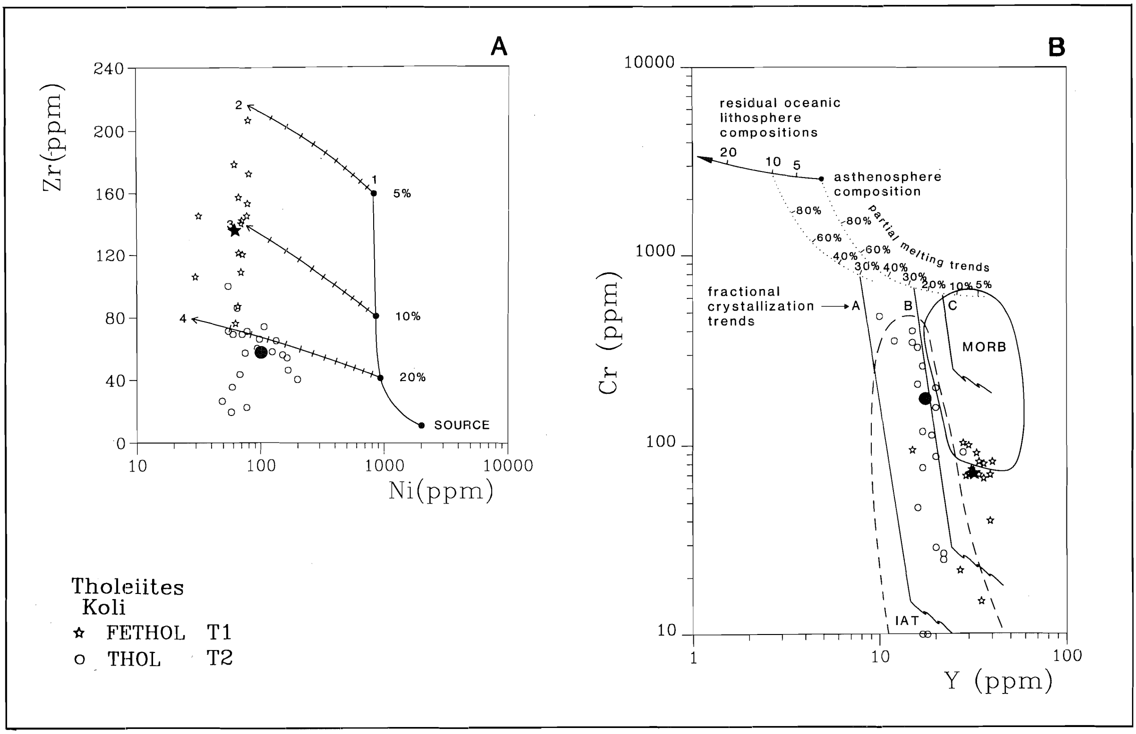

Fig. 14. A) Zr-Ni diagram for the tholeiitic (T1 and T2) diabases (after Rajamani et al. 1985 and Condie et al. 1987). Curve 1 represents batch melting at 1500°C (1 atm) with degrees of melting indicated in percentages. Curves 2, 3 and 4 represent olivine fractionation with percentages of olivine removed indicated in 5% increments. B) Cr and Y values for tholeiitic diabases, plotted on a diagram after Pearce et al. (1984). MORB = mid-ocean ridge basalts, IAT = island arc tholeiites. The solid circle and star represent mean analysis values. Symbols as in Fig. 4.

used by Pearce et al. (1984), who maintain that a Cr/Y diagram can be used since neither element appears to be significantly affected by processes causing heterogenity in the convecting upper mantle. The compositions of the melts which evolved from this mantle can be presented as partial melt trends modelled according to the degree of partial melting, and fractional crystallization can be represented by crystallization vectors. The lines A, B and C in the figure depict the petrogenetic pathways of various basalts, of which A represents a typical boninitic suite, B a typical island arc tholeiite (IAT) and C a typical MORB.

The Cr/Y diagram shows the relationship of the T2 diabases in the Koli-Kaltimo area to the IAT field and of the T1 diabases to the MORB field of Pearce et al. (1984) or WPB; Fig. 16 d (Pearce, 1982). The plot of the analyses from the T2 diabases on a fractional crystallization vector runs parallel to pathway B (Fig. 14b), suggesting that the source magma is almost an island arc tholeiite, while the corresponding T1 plot is located below the fractional crystallization pathway C, indicating marked fractionation of this magma. About 30 % partial melting of the mantle material seems to be a reasonable estimate for the T2 diabases, whereas the T1 diabases seem to represent a lower degree of melting, i.e. 10 — 20%.

Together with the distribution of the main components, these two petrogenetic diagrams provide similar results for the petrogenesis of the Koli-Kaltimo diabases. In summary, it may be said that the source magma of the T2 diabases suggests approximately a 30% batch melting, that only olivine has fractionated from it to a significant extent and that the magma is of the island arc tholeiite type. In addition, the initial $\varepsilon_{Nd} = +1.8$ for T2 diabases suggest that their source has been depleted in LREE for some time during it's history. The T1 diabases originate from a magma formed through an approximately 10 — 20% partial melting of the mantle which was of the highly fractionated (olivine, clinopyroxene, Fe-Ti oxide and plagioclase).

Tectonic setting

The major- and trace-element signatures of the diabase dykes in the Koli-Kaltimo area facilitate definition of their tectonic setting, since they seem to have been preserved in a geochemically fairly unchanged state (Fig. 6). Although most tectono-magmatic diagrams have been drawn up for volcanites (Pearce and Cann, 1973; Pearce et al., 1977; Pearce, 1982; Mullen, 1983; Holm, 1985), they are also widely used for discriminating diabases in connection with volcanites (Harnois and Morency, 1989; Condie et al., 1987; Höy 1989).

Almost all of the T1 diabases fall into the continental basalt field in the FeO — Al_2O_3 — MgO diagram (Fig. 15a). The T2 diabases form a more diverse group, being located on both sides of the limit between the continental basalt field and oceanic-island basalt field. In the second main component FeO^*/MgO vs. TiO_2 diagram (Fig. 15b) the T1 diabases are Fe-rich either in the upper parts of the IAT or MORB fields or above them, while the T2 diabases are located in the IAT field. As was the case with the above diagrams, the T2 diabases lie in the IAT field and the T1 diabases in the MORB field in the $MnO \times 10$-TiO_2-$P_2O_5 \times 10$ diagram (Fig. 16a) presented by Mullen (1983).

The hygromagmaphile elements (the H elements Th, Ta, Nb, Zr, Ti, Y and V) are characterized by a low $K_d << 1$ in all mineral phases which exist in the source rock or crystallize in the course of magmatic differentiation. Therefore, although the absolute concentrations change, the proportions of the H elements will not change

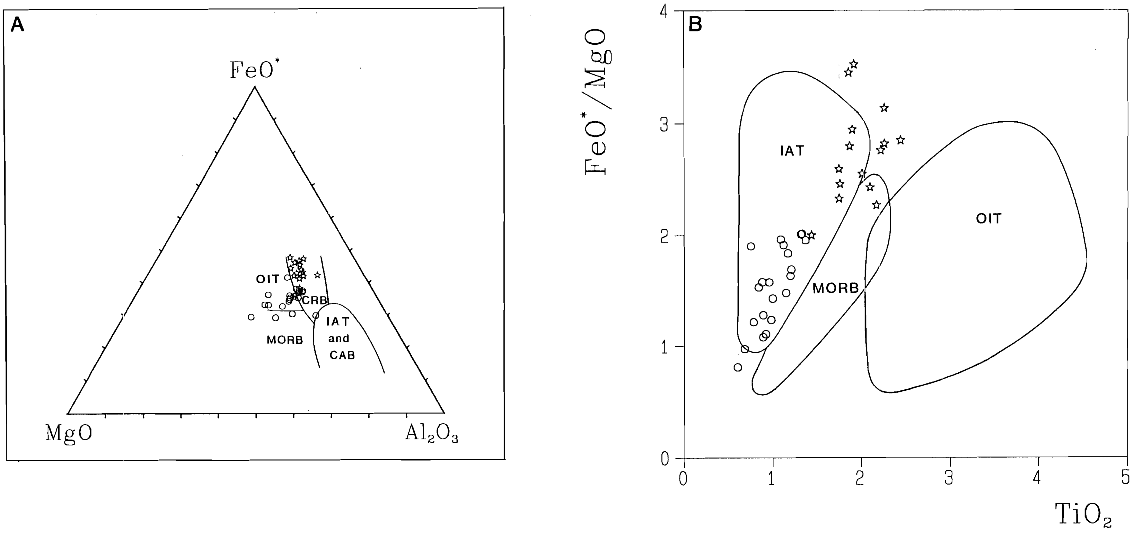

Fig. 15. A) FeO- Al_2O_3- MgO diagram after Pearce et al. 1977. B) FeO*/MgO vs. TiO_2 diagram after Jelinek et al. 1980. FIELDS: CRB, continental rift basalt; OIT, ocean-island tholeiites ; MORB, mid-ocean ridge basalts; IAT, island arc tholeiites; CAB, calc-alkaline basalts. Symbols as in Fig. 4.

either during the melting process or crystal fractionation. Instead these elements reflect the heterogeneity of the source material and therefore also their tectonic environment.

The T1 and T2 diabases of the Koli-Kaltimo area are plotted on discrimination diagrams for several relatively immobile trace elements (Fig. 16) in order to characterize their tectonic setting. The T2 diabases are located in the IAT field in the Ti-Zr-Y × 3 diagram (Fig. 16c) while the T1 diabases are transitional from a within-plate setting to an ocean-floor setting, and the T2 diabases in the Ti-Zr-Sr/2 diagram (Fig. 16b) are either in the IAT field or in the ocean floor field, while the T1 diabases are entirely in the ocean floor field.

Plotting of the diabase analyses on a log diagram of Ti vs. Zr (Pearce, 1982) shows that the two diabase types fall into separate groups (Fig. 16e), the data points for the TiO_2-rich T1 diabases falling into the within-plate basalt (WPB) field and the TiO_2-poor T2 diabases into the IAT basalt field within and outside the MORB. According to these data, the T2 diabases have a close association with an island arc assemblage and the T1 diabases with a within-plate assemblage.

The same features can perhaps be seen even better from the following log diagrams, e.g. Y vs. Cr (Pearce, 1982) and Zr vs. Zr/Y (Fig. 16d and f). The T2 diabases again lie within the IAT field and the T1 diabases in the WPB field in the former diagram (Fig. 16d), and a comparable distribution can be seen in the latter (Fig. 16f) even though the data points are not located in the same manner.

The T2 diabases are very similar to the island arc low-K tholeiite from above the Benioff zone in their general characteristics, but differ from oceanic/continental back-arc tholeiite (Holm, 1985). Compared with the N-type MORB, the tholeiites of the arc environment usually have higher LILE (Rb, K, Sr, La, and Ce) and lower HFSE (Nb, P, Zr, Eu, Ti, Y, and Yb). Reference samples of both island arc tholeiites and back-arc tholeiites (Holm, 1985) are presented in Figure 17a, which indicates that both are enriched in with LILE, but the back-arc type is less deplet-

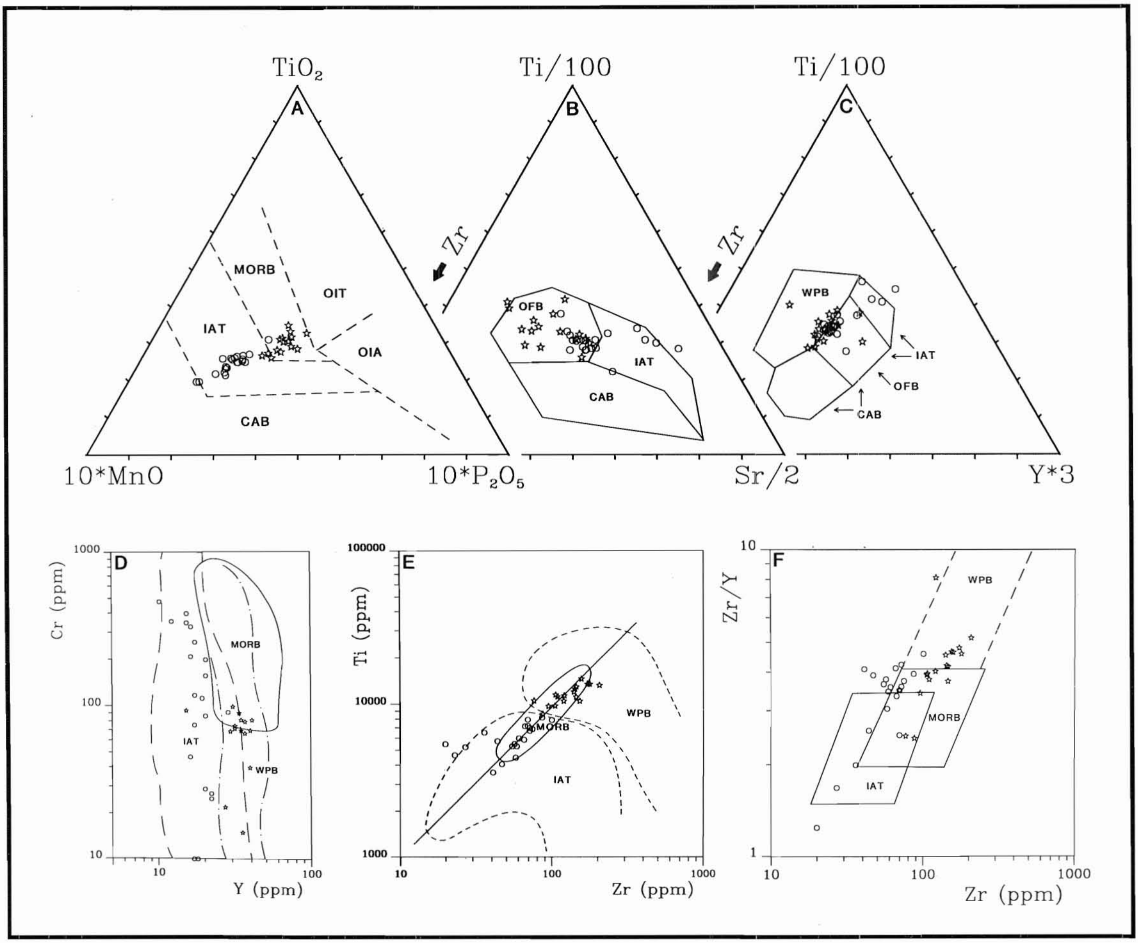

Fig. 16. Plot of selected elements and elemental ratios in the tholeiitic (T1 and T2) diabase dykes of the Koli-Kaltimo area. A) TiO_2-MnO(x10) — P_2O_5(x10) diagram of Mullen (1983) for basaltic rocks. B) Ti/100-Zr-Sr/2 and C) Ti/100-Zr-Yx3 diagram of Pearce et al. (1973) for basaltic rocks. D) Cr-Y diagram of Pearce et al. (1982) for basaltic rocks. E) Ti-Zr diagram for basalts (Pearce 1982). F) Zr/Y-Zr diagram of Pearce et al. (1979) for basalts. FIELDS in diagrams: CAB, calc-alkaline basalts; IAT, island arc tholeiites; OIT, ocean-island tholeiites; OIAB, ocean-island alkali basalts, MORB, mid-ocean ridge basalts; OFB, ocean floor basalts; WPB, within-plate basalts. Symbols as in Fig. 4.

ed in HFSE. The T2 diabases of the Koli-Kaltimo area are markedly enriched with LILE and considerably depleted in HFSE and their distribution is thus similar to that of the low-K tholeiites of the island arc type. The T1 diabases differ from these to a great extent in their geochemistry which is markedly similar to the distribution found in continental tholeiites (Fig. 17b), in that they are greatly enriched with LILE (Rb, K, La, Ce but not Sr) and slightly enriched HFSE (Nb, P, Zr, Eu, Ti) and have roughly similar Y and Yb to the N-type MORB.

In the light of the above geochemical chracteristics, both the discrimination diagrams and the general geochemical distribution, the generalization may be put forward that the 2.1 Ga T1 diabases in the area developed in a continental environment, while the 1.97 Ga T2 diabases represent magmatism of the island arc type.

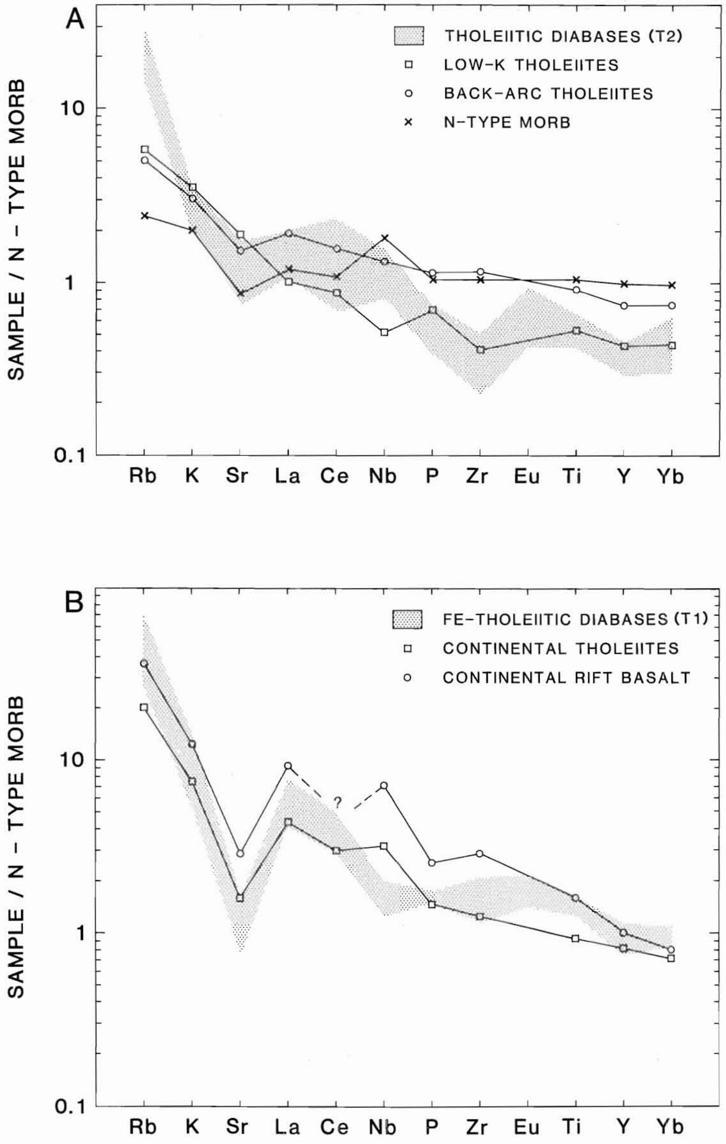

Fig 17 A) Spider diagrams for the tholeiitic (T2) diabases of the Koli-Kaltimo area (line pattern) and representative samples of low-K tholeiite (Holm 1985), back-arc tholeiite (Holm 1985) and N-type MORB (Pearce 1982) normalized to N-type MORB (Saunders and Tarney 1984). B) Spider diagrams for the Fe-tholeiitic (T1) diabases of the Koli-Kaltimo area (line pattern) and representative samples of continental tholeiite (Holm 1985) and continental-rift tholeiite (Condie 1985) normalized to N-type MORB (Saunders and Tarney 1984).

Geological implications

These results can be used as a basis for assessing stratigraphic interpretations (see Fig. 2). The older diabase dyke swarms extends over the whole site, being found in both the Archaean formations and the Proterozoic Sariola and Jatuli ones. Lavas from the same magmatism are found further south in the marine Jatuli formations in the Kiihtelysvaara-Tohmajärvi area (Pekkarinen, 1979; Pekkarinen et al. 1991) and diabases in the Archaean formations of Ilomantsi in the east (Nykänen, 1971; Tuukki et al., 1987). All in all, these Fe-tholeiitic lavas and dykes of age about

2.1 Ga extend over a vast area of eastern and northern Finland.

The younger (1.97 Ga) magmatism has produced dykes only in the quartzites of the Jatuli formations, but has not spread into the western metagreywacke and phyllite formations (Höytiäinen province; Ward, 1987), from which the magmatic rocks (serpentinites, gabbros and volcanites) belonging to the Outokumpu association are also absent. Metaturbidites at the Höytiäinen province can therefore be likened to the Kalevian mica schists in the Koli-Kaltimo area and are likely younger than the 1.97 Ga old T2 diabases. Since the Savo province suggested by Ward (1987) has magmatic rocks of the Outokumpu association which are of the same age as the T2 diabases in the Koli-Kaltimo area, its turbidites must have been deposited before the emplacement of the Outokumpu ophiolite.

These results also raise an interesting question concerning the wider examination of the whole schist area. The younger T2 tholeiites are of the same age as the Outokumpu ophiolite complex in the western part of the area (Huhma, 1986), so that the dykes intersecting the continental crust and ocean floor must have developed at the same time, referring to a break-up event in the history of the area at the time of 1.97 Ga.

Altered volcanites, which have retained their original volcanic structures in places (pillow lavas, vesicular lava, agglomerate and tuff; Park, 1984) in the Outokumpu ophiolite complex are, according to Park (1988), island arc basalts, so that their composition thus corresponds to the T2 diabases in the Koli-Kaltimo area. In this case the island arc affinity probably means that the rocks are genetically connected with subduction. Thus, in the ophiolite terminology, the Outokumpu ophiolite is of the supra-subduction type (Pearce et al., 1984).

Two tholeiitic magmatic phases can thus be distinguished in the Koli-Kaltimo area by reference to the diabases. Associated volcanites are entirely absent due to the deep level of erosion, but the results obtained here are comparable to those for the greenstone area of central Lapland, for instance. The Kittilä-Sodankylä area has large quantities of early Proterozoic tholeiitic volcanites, as examined by the Geological Survey of Finland in their volcanite project (Lehtonen et al., 1989). They divide the upper-Lapponi volcanites into three groups, the lowermost being komatiitic V1 volcanites, above of which are Fe-tholeiitic V2 volcanites and finally Mg-tholeiitic V3 types.

The diabases of the Koli-Kaltimo area can be related geochemically to the above, the Fe-tholeiitic diabases (T1) at Koli corresponding to the V2 volcanites in Lapland and the Mg-tholeiitic diabases (T2) to the V3 volcanites. The geotectonic interpretation of both areas is similar, i.e. the Fe-tholeiites in Lapland and at Koli represent a continental environment and the Mg tholeiites bear similarities to island arc tholeiites.

CONCLUSIONS

The main conclusions are the following:

1. The tholeiitic diabase dyke swarms in the Koli-Kaltimo area are divided into two groups, Fe-tholeiitic (T1) and tholeiitic (T2) diabases, which are of different ages and have different geochemical characteristics. The younger T2 diabases are 1.97 Ga and the T1 diabases about 2.1 Ga old.

2. Zircon from the T2 dykes provides an age of 1965 ± 10 Ma, which is supported by the Sm-Nd mineral age of 1985 ± 80 Ma. The initial $\varepsilon_{Nd} = +1.8 \pm 0.6$ suggest that the mantle source had

a time-integrated LREE depleted characteristics.

3. The T2 diabases have been found only in connection with Proterozoic quartzites, whereas the T1 diabases occur in swarms throughout the Archaean basement and Proterozoic metasediment cover excluding the Kalevian formations. Both dykes run predominantly in NW directions.

4. The T1 diabases were altered markedly and recrystallized when the metamorphism was in the albite-epidote-amphibole facies, while the T2 were metamorphosed to actinolite facies, indicating low water/rock ratios.

5. The T1 diabases are characterized by high TiO_2 (av. 2.0 %), Fe_2O_{3tot} (av. 16.4 %), K_2O (av. 0.8 %) and P_2O_5 (av. 0.2 %) concentrations and have evolved Mg^* values (49 — 36), whereas the T2 diabases have relatively low TiO_2 (av. 1.0 %), Fe_2O_{3tot} (av. 12.8 %), K_2O (av. 0.5 %) and P_2O_5 (av. 0.1 %) concentrations and slightly evolved Mg^* values (71 — 50).

6. The T1 diabases are clearly enriched in LREE ($[La/Yb]_N = 2.8$ to 4.1) and total REE 15 — 70 times chondrites, while the T2 diabases have almost flat to slightly LREE-enriched ($[La/Yb]_N = 1.6$ to 2.6) patterns (5 — 30 times chondrites). The T1 diabases are markedly enriched in LILE and HFSE, whereas the T2 diabases have high LILE, but are depleted in HFSE.

7. The diabase dykes can be divided into two major groups on the basis of their observed magnetic properties. Both T1 and T2 have a low magnetic susceptibility, but their NRM intensities vary (av. T1 0.03 Am^{-1} and T2 0.2 Am^{-1}), while also being very low. The Koenigsberger ratio is thus more than one (av. 3.4) in the T2 diabases, but less than one (av. 0.8) in the T1 diabases, indicating a lower degree of alteration for the T2 diabases.

8. The parental magmas of these two suites are tholeiitic, but they differ in terms of their partial melting degrees (T1 ~ 10 — 20% and T2 ~ 30%) and also in their source material, in that T1 is more clearly enriched in incompatible elements.

9. The T1 diabases have originated in a continental setting, whereas the T2 diabases imply similarities to island arc tholeiites and were connected with a subduction.

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