

## Metasomatic alteration of a felsic metavolcanite to an actinolite skarn near Ställbergstorp: evidence for high LREE mobility

P.J. Valbracht<sup>1</sup> & H. Helmers<sup>2</sup>

<sup>1</sup> *Geologisch Instituut, Universiteit van Amsterdam, Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands;* <sup>2</sup> *Instituut voor Aardwetenschappen, Vrije Universiteit, Postbus 7161, 1007 MC Amsterdam, The Netherlands*



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### Abstract

Felsic metavolcanites of the Lower Leptite Group of the 1.9–1.8 Ga Svecokarelian Bergslagen Supracrustal Series, Sweden, are locally pervasively altered into actinolite-magnetite skarns, showing euhedral magnetite blasts in an amphibole matrix.

The alteration comprises two stages: after complete albitization the felsic metavolcanites are characterized by extremely low K and high Na contents and LREE depleted patterns relative to least altered metavolcanites. Incipient replacement of albite by amphibole leads to enrichment in MgO, CaO and FeO\*, whereas the light rare earth element (LREE) abundances remain unchanged. Subsequent massive actinolite growth in the matrix and in veins is characterized by a strong enrichment in MgO, CaO, FeO\* and LREE.

### Introduction

The more than 10 kilometres thick, predominantly felsic Bergslagen Supracrustal Series (BSS) of western Bergslagen forms part of the 1.90–1.86 Ga Svecokarelian of Central Sweden (Welin *et al.*, 1980; Oen *et al.*, 1982).

This felsic metavolcanic succession is cut by alteration zones, and numerous metabasic sills and dykes (Fig. 2).

The felsic metavolcanic sequence has been affected by at least two distinct types of alteration related to sub-seafloor processes. A first stage of regional scale alteration has produced a lower, generally Na-rich unit and an upper, generally K-rich unit, sub-parallel with the regional stratigraphy (Sundius, 1923; Geyer & Magnusson, 1944; Baker, 1985a; Lagerblad & Gorbatshev, 1985). The Na-

rich albitized rocks, developed during the first phase of regional scale alteration, have been locally altered into schistose, phlogopite- and muscovite-bearing metavolcanites, Mg-rich quartz-phlogopite-muscovite(-chlorite) schists or to actinolite-bearing metavolcanites and actinolite-magnetite skarns during later alteration phases (Baker, 1985a; Hellingwerf, 1986). Baker & De Groot (1983) have interpreted Mg-chlorite-rich schists zones as fossil conduits of a hydrothermal convection system related to a synvolcanic older granite of the Bergslagen Older Granite Suite (Oen, 1987) in the Hjulsjö area north of the terrain studied in this paper.

The actinolite-magnetite skarn described in this paper occurs near Ställbergstorp, a farm approximately 10 kilometres south of Hjulsjö, east of the road to Järnboås, in a subvertical, NNW striking

succession of felsic pyroclastic rocks, belonging to the Lower Leptite Group (Fig. 1) of the BSS.

We present details of the metasomatic changes accompanying the alteration of albitized felsic metavolcanites to actinolite skarns, and give evidence for a high LREE mobility during this alteration.

### Geological setting

The rocks of Central Sweden form part of the Precambrian Baltic shield, which also covers the Kola Peninsula in Russia, Finland, Sweden and parts of Norway and includes metamorphic belts formed during the Archean and Proterozoic (Bridgwater & Windley, 1973).

The Bergslagen ore province in Central Sweden is interpreted by Oen (1987) as a Proterozoic iron ore basin, filled by the felsic BSS and containing numerous occurrences of iron, manganese and base-metal sulfide ores.

The BSS is a weakly metamorphosed volcanosedimentary sequence with an apparent thickness of more than 12 kilometres (Baker, 1985a). It consists mainly of felsic pyroclastic rocks, with minor mafic extrusives and volcanoclastic sediments in the higher lithostratigraphical parts and is cut by granites and mafic intrusives.

The origin of the base metal sulfides and the related Mg-metasomatism has been described as hydrothermally related to the intrusion of the older granites (Geijer, 1917; Magnusson, 1925), as exhalative sedimentary (Koark, 1962; Boström *et al.*, 1979) and as hydrothermal, by leaching of the bimodal volcanic pile in a sub-seafloor environment (Oen *et al.*, 1982).

Oen *et al.* (1982) divided the BSS into three units based on lithostratigraphical and paleogeographical grounds. These three units (Fig. 1) are related to the first three stages during the development of a rifting system: the Lower Leptite Group consists of a huge pile of felsic metavolcanites (ignimbrites, rhyolites, tuffites, pyroclastic falls and flows) and corresponds to the Early Volcanic stage. The Middle Leptite Group is made up of felsic pyroclastics with thick intercalations of marble and strata

bound iron horizons and corresponds to the Initial Rift stage. The Upper Leptite Group is a series of volcanoclastic metasediments, metabasalts and felsic pyroclastic rocks and corresponds to the Rift stage. During the last two stages granites of the Bergslagen Older Granite Suite (Oen, 1987) and mafic rocks intruded and the major phase of extensional deformation is thought to have occurred. A Post Rift stage minor phase of tectonic compression, regional metamorphism and intrusion of Hyttsjö suite gabbros to granites has been dated at 1.84 Ga (Moorman *et al.*, 1982). Later events include the intrusion of Middle Svecokarelian granites (Malingsbo type), Younger Svecokarelian (Gothian) granites (Filipstad type) and associated metamorphism (Gaal & Gorbatshev, 1987).

### Local geology, petrography and mineralogy

A zone of banded actinolite skarns occurs on the eastern margin of a Mg-rich schist zone (Fig. 2), approximately 10 kilometres south of Hjulsjö, in a crystal-lithic pyroclastic flow. The contacts between skarn and felsic metavolcanite are diffuse. The main part of the skarn is a partly amphibolized metavolcanite in which patches and distinct bands of amphibole skarn occur (Fig. 2, inset).

The felsic pyroclastic rocks forming the country rocks consist predominantly of albitized quartz and plagioclase-phyric metavolcanites. HT-quartz pseudomorphs showing corrosive embayments and chess-board albite pseudomorphs after original K-feldspar phenocrysts occur in a matrix which is a polygonal aggregate of quartz and albite. Primary pyroclastic structures such as fiamme, pumice fragments and shards are locally well preserved in rocks of this type (Baker, 1985a). Biotite, partly chloritized, occurs as a minor constituent. Sericite, clinzoisite-epidote, tremolitic actinolite, tourmaline, orthite, sphene and opaques form accessory constituents of the metavolcanite.

Incipiently amphibolized parts of the metavolcanic rock are whitish to greenish in colour, and locally show dark-green amphibole-rich patches (Fig. 2, inset). Tremolite-actinolite is found to grow along cracks and grain boundaries of albitized

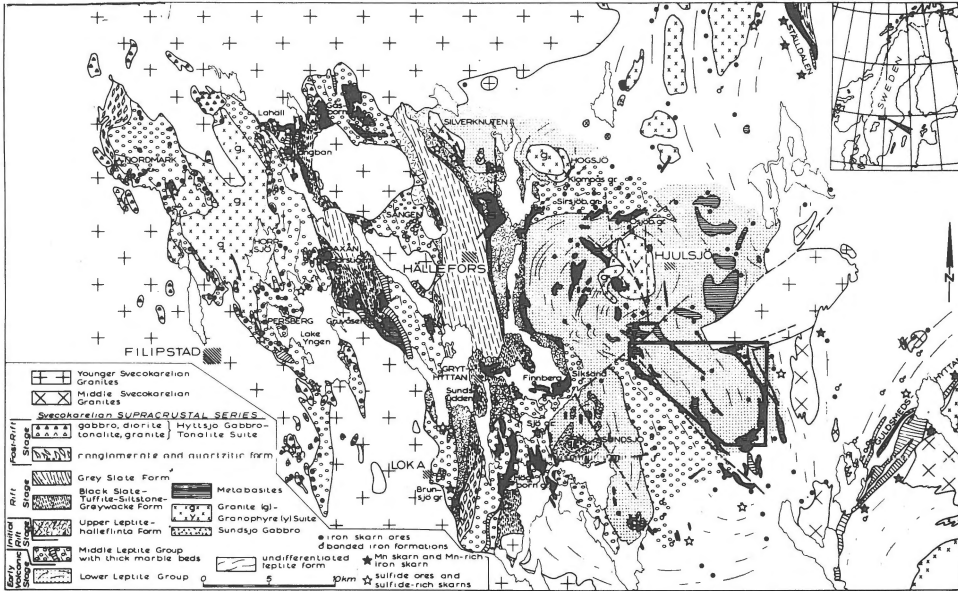


Fig. 1. Lithostratigraphical map of western Bergslagen compiled by Oen *et al.* (1982).

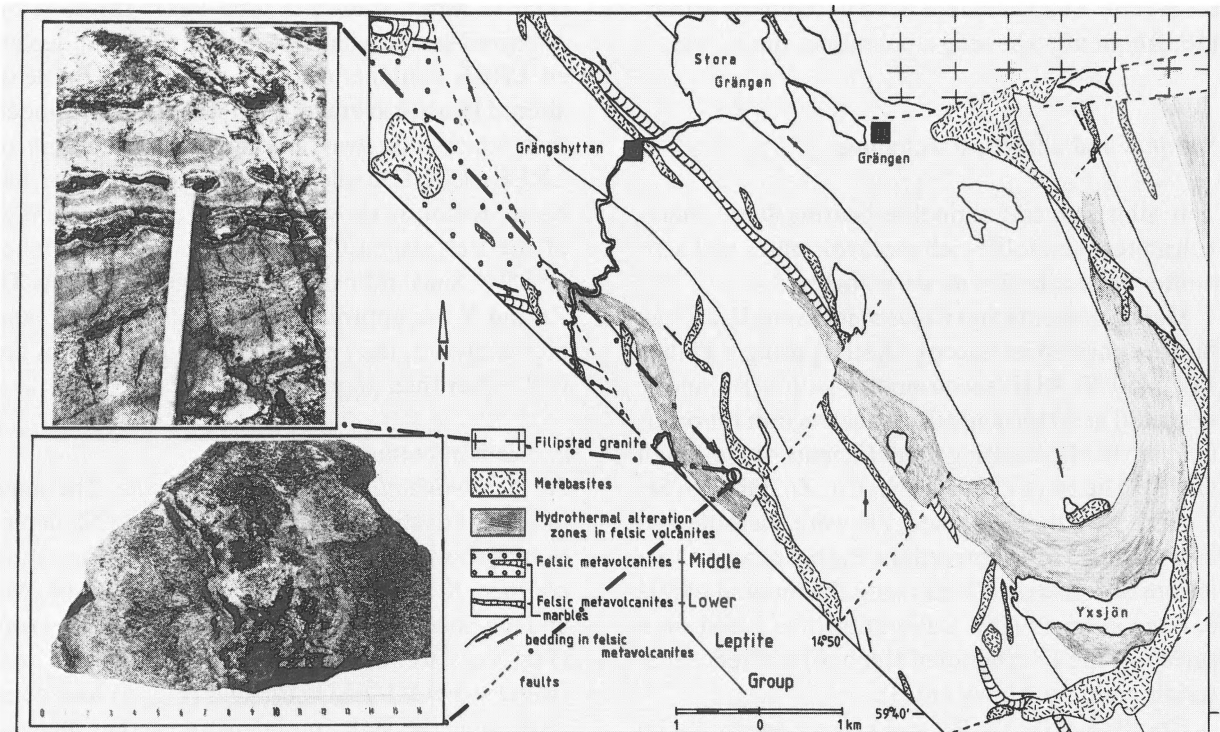


Fig. 2. Detailed map of the area outlined in Fig. 1, indicating the location of the skarn at Ställbergstorp. Outcrop density approximately 10–20 per square kilometre. Inset: photographs of the actinolite skarn (hammer: 60 cm in length, bar: cm scale).

plagioclase phenocrysts and their irregular albitic growth rims. HT-quartz pseudomorphs are commonly recrystallized to aggregates of sub- and new-grains, showing ductile deformation accompanying metasomatism. Yellowish orthite grains, which are surrounded by brownish pleochroitic haloes in the amphibole, occur both interstitially as well as in clots. Magnetite occurs in thin layers, intergrown with the quartz-albite matrix, and as large grains or concentrated in clots in the amphibole-rich parts of the rock.

In more extensively altered parts amphibole prisms grow along and in albite crystals, their orientation usually being determined by former grain boundaries of quartz and albite.

Extremely skarn-altered parts are macroscopically characterized by essentially monomineralic amphibole layers, patches, boudins and veins (Fig. 2, inset). The amphibole skarn generally shows a matrix of orientated amphibole prisms, occasionally enclosing euhedral magnetite blasts, up to 8 mm in diameter. The amphibole is shown by microscopic and XRD evidence to be a tremolitic actinolite, frequently showing a colourless rim.

### Samples and analytical technique

Ten albitized and actinolite-bearing felsic metavolcanites, actinolite-rich metavolcanites and actinolite-magnetite skarns were analysed.

Major elements and Cr were measured by X-ray fluorescence spectroscopy (XRFS) using a Philips PW 1450/20 AHP spectrometer with a Rh anode operated at 40 kV and 60 mA; correction for residual matrix effects using  $\alpha$ -coefficients of De Jongh (1973). The trace elements Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, (Th) and Pb were measured at 60 kV and 45 mA; corrections for background variations and matrix effects using the method of Viéle Sage *et al.* (1979). Calibration was based on a subset of the international standard reference materials cited by Abbey (1983).

Cr, REE, Hf, Ta, Th and U were measured by INAA at the Interuniversity Reactor Institute (IRI), Delft (see De Bruin, 1983).

### Geochemistry

Two stages of alteration, the presumed regional scale Na–K redistribution and the subsequent, more localized skarn alteration discussed above, have affected the major and trace element geochemistry of the rocks sampled here.

#### 1. Alteration effects related to the alkali redistribution

An average of 13 felsic metavolcanites from the Hjulsjö area considered by Baker & De Groot (1983) to represent least altered samples has been used as an estimate of the original chemistry of these felsic metavolcanites, since no unaltered metavolcanites have been found in the studied area. The metavolcanites presented in this paper are assumed to be the strongly albitized equivalents of the unaltered volcanites from a first stage of regional alteration and plot to the extreme left in the Igneous Spectrum (Fig. 3) of Hughes (1973). The metavolcanites have remained approximately constant in MgO, CaO and total FeO\* (Figs. 4, 5). Albitized samples have widely varying, but depleted LREE contents (Fig. 6), relative to the least altered Hjulsjö average, from which it is concluded that albitization was accompanied by a loss of LREE. LREE depletion during albitization has been previously shown for albitized older granites of the Bergslagen Older Granite Suite by Baker (1985b). Since ratios of the immobile elements Ti, Zr and Y are approximately constant for all samples analyzed, the enrichments and depletions are real rather than apparent.

#### 2. Skarn alteration

*2a. Actinolitization of the metavolcanite.* The stage of actinolitization is marked by a strong Na depletion as shown in the Igneous Spectrum (Fig. 3), in contrast K remains approximately constant. Mg and Fe increase in a positively correlated array (Fig. 4), a trend equally observable in the CaO–(MgO + FeO\*)–Al<sub>2</sub>O<sub>3</sub> triangle (Fig. 5) and demonstrating the shift in chemistry of the albitized metavolcanites towards the pure actinolite composition. This results in a replacement reaction such as:

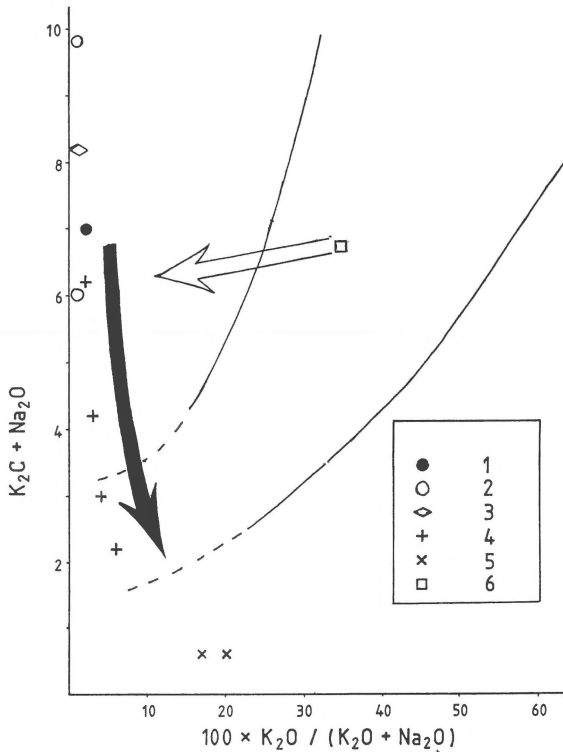
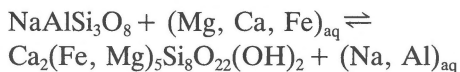


Fig. 3. Igneous Spectrum of Hughes (1973), showing the two stages of alteration described in the text. Symbols: 1 – Albitized metavolcanite. 2 – Albitized metavolcanite with actinolite specks (<5 vol.%). 3 – actinolite-bearing albitized metavolcanite (5–15 vol.%). 4 – actinolite-rich metavolcanite (15–85 vol.%). 5 – actinolite skarn (>85 vol.%). 6 – Least altered Hjulsjö metavolcanite average (Baker & De Groot, 1983).



Considering the albitized and partially actinolitized samples in Fig. 6 (symbols 1 to 3) it is apparent that initial actinolite growth due to the introduction of MgO, FeO\* and CaO into the rock (Figs. 4, 5) from hydrothermal fluids led to actinolite formation, but not to net changes in LREE contents.

**2b. Massive actinolite growth.** Actinolite-rich metavolcanites and the actinolite skarn plot near the stoichiometric composition of actinolite in the CaO–(MgO + FeO\*)–Al<sub>2</sub>O<sub>3</sub> ternary diagram and have the highest MgO and FeO\* values (Fig. 5). A strong enrichment in LREE (Fig. 6) is shown for these rocks in comparison to their albitized and

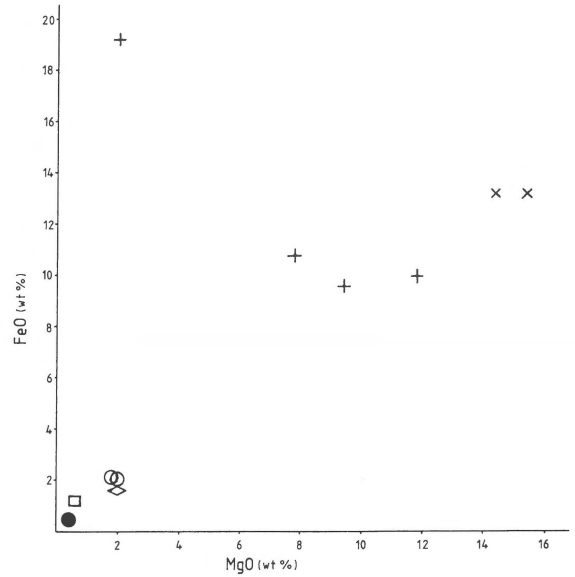


Fig. 4. FeO–MgO diagram, showing negligible depletion of FeO and MgO after albitization, minor enrichment related to incipient actinolite growth and a clearly correlated strong enrichment of FeO and MgO related to massive actinolite formation in matrix and veins (symbols as in Fig. 3). One sample shows high FeO and low MgO due to dispersed magnetite grains. Total iron as FeO.

actinolitized metavolcanic precursors.

Whole rock samples, as opposed to mineral separates, have been analyzed, thus the high LREE contents of the actinolite skarns may be partly due to small grains of orthite.

From Table 1 it can be seen that the LREE variation is large in comparison to the other hydro-magmatophile elements. The immobile elements Ti and Y and the alkali K remained nearly constant in all samples from the Ställbergstorp location. In the actinolite skarn Rb, Ba, Th, U, Ta, Nb, P, Hf, Zr and Tb are depleted by a factor 2–10 in respect to the actinolitized metavolcanites. Sr is considerably depleted in the actinolite skarn, illustrating its covariance with Al.

## Conclusions

During albitization felsic metavolcanites were enriched in Na and depleted in LREE by the hydrothermal fluids, based on a comparison with the

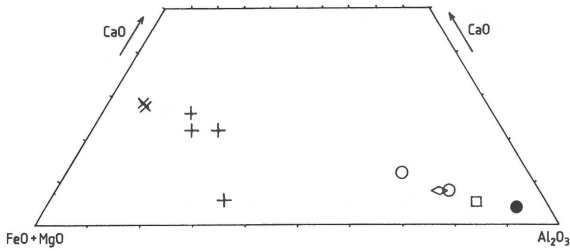


Fig. 5. CaO-(FeO\* + MgO)-Al<sub>2</sub>O<sub>3</sub> ternary diagram showing Al<sub>2</sub>O<sub>3</sub> enrichment relative to CaO and MgO + FeO\* during albitization and depletion in a linear trend towards the actinolite composition due to actinolitization (symbols as in Fig. 3). A high magnetite content for one sample results in the 'off-trend' position in this diagram. Total iron as FeO\*.

Hjulsjö least altered metavolcanite average.

Introduction of Mg, Ca and Fe, presumably from hydrothermal fluids led to the replacement of albite by actinolite. In this stage Na and Al are depleted. High concentrations of LREE in the actinolite skarns indicate that LREE might have been re-introduced from hydrothermal fluids.

An enrichment factor of approximately 100 is found comparing chondrite normalized values of the albitized and least actinolitized rocks with the actinolite skarn. This shows high LREE mobility during the skarn-forming process.

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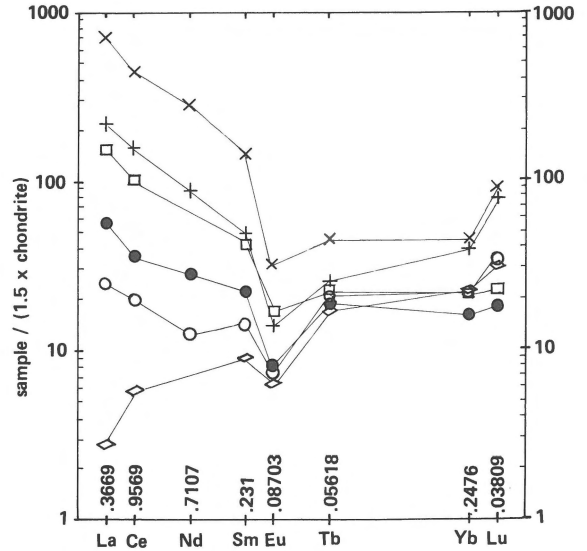


Fig. 6. REE diagram, normalized to 1.5 × values of 'CI' chondrite given by Evenson *et al.* (1978) showing LREE depletion related to albitization and actinolitization and introduction of LREE related to late stage massive amphibole formation (symbols as in Fig. 3). Concentrations of 1.5 × 'CI' chondrite values are given on the x-axis.

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Table 1. Major and trace element data of albitized and actinolite-bearing (1, 2, 3), actinolite-rich (4) and actinolite skarn (5) samples. Numbers in parentheses correspond with the symbols used in the diagrams. 102A – Albitized felsic metavolcanite. 102B – Ditto; actinolite-bearing felsic metavolcanite (5 vol.%). 102EL – Ditto; (5–10 vol.%). 296B – Ditto; (10–15 vol.%). 102CD – Actinolite-rich felsic metavolcanite (50 vol.%). 102CL – Actinolite-rich felsic metavolcanite (15–20 vol.%). 102ED – Actinolite-rich felsic metavolcanite (70–80 vol.%). 296I – Actinolite-rich felsic metavolcanite (80–85 vol.%). 102F – Actinolite skarn (95 vol.%). 296III – Actinolite skarn (100 vol.%).

	Albitized and actinolitized metavolcanites				Actinolite-rich metavolcanites				Actinolite skarns		Ave. least altered metavolcanites	
	102A	102B	102EL	296B	102CD	102CL	102ED	296I	102F	296III	<i>n</i> = 13	Std. Dev.
wt %												
SiO <sub>2</sub>	78.629	70.484	66.582	75.823	66.157	57.047	57.934	59.856	56.029	55.802	76.54	1.67
TiO <sub>2</sub>	0.088	0.112	0.136	0.104	0.063	0.108	0.084	0.053	0.071	0.065	0.149	0.029
Al <sub>2</sub> O <sub>3</sub>	12.18	14.266	17.182	10.914	5.372	11.458	6.095	8.206	2.31	2.267	11.89	0.51
Fe <sub>2</sub> O <sub>3</sub> *	0.487	1.729	2.118	2.188	12.035	21.423	11.19	10.649	14.65	14.798	1.518	0.514
MnO	dl	0.003	0.005	0.006	0.05	0.016	0.051	0.044	0.062	0.066	0.006	0.005
MgO	0.4	1.969	1.807	2.043	7.836	2.011	11.763	9.367	14.476	15.344	0.562	0.352
CaO	0.555	1.7	1.76	1.956	6.94	2.072	9.61	7.837	11.577	12.254	0.753	0.44
Na <sub>2</sub> O	6.876	8.121	9.739	5.951	2.084	6.151	2.874	4.108	0.493	0.462	4.367	1.93
K <sub>2</sub> O	0.119	0.075	0.113	0.089	0.123	0.104	0.116	0.126	0.098	0.113	2.331	1.45
P <sub>2</sub> O <sub>5</sub>	0.009	0.019	0.019	0.003	0.007	0.012	0.028	0.028	0.007	0.006	0.24	0.008
Total	99.343	98.478	99.461	99.077	100.667	100.405	99.745	100.274	99.773	101.183	nd	nd
ppm												
Cr	4.23	5.88	dl	dl	7.62	20.5	dl	dl	6.53	41.0	4.48	1.39
Ni	3.02	2.61	3.63	3.92	4.82	15.1	4.34		5.14	5.3	3.76	0.79
Cu	3.74	2.78	5.25	3.53	4.55	17.0	4.17		2.01	3.23	6.29	1.09
Zn	15.2	13.0	14.5	9.53	12.9	12.7	11.6		9.64	13.0	12.72	3.52
Ga	17.8	23.6	24.7	12.7	14.0	25.4	13.2		dl	11.1	15.58	1.33
Rb	19.0	16.4	17.0	8.22	8.07	5.79	7.68		2.58	3.8	49.65	28.82
Sr	28.8	22.2	29.0	26.2	14.6	32.9	14.1		2.77	2.32	62.03	33.04
Y	43.7	50.2	48.7	38.2	36.7	37.7	51.7		60.3	50.1	51.35	11.06
Zr	98.8	200.0	183.0	183.0	72.7	193.0	129.0		72.8	48.8	198.75	24.71
Nb	dl	dl	3.69	dl	4.49	20.1	7.15		10.1	7.69	10.99	1.09
Ba	34.7	56.7	dl	86.8	dl	dl	dl		dl	dl	873.6	264.0
La	19.5	1.013	8.85		74.28		86.15		252.0	67.87	56.3	30.4
Ce	33.86	5.27	19.29		129.7		149.5		409.6	107.0	98.0	54.61
Nd	19.9	dl	9.26		60.93		67.07		199.5	nd	nd	nd
Sm	5.39	2.02	3.29		10.9		11.7		32.0	8.52	9.77	5.42
Eu	0.688	0.547	0.615		1.24		1.27		2.84	1.2	1.45	1.05
Tb	1.12	0.983	0.958		1.03		1.39		2.61	1.48	1.28	1.47
Yb	3.92	5.8	5.423		3.897		10.06		11.07	10.52	5.26	1.12
Lu	0.65	1.15	1.302		1.074		3.113		3.355	2.98	0.87	0.16
Hf	4.372	7.61	6.19		2.18		4.054		2.06	1.29	6.21	0.82
Ta	1.209	1.24	1.33		0.345		0.432		0.297	0.421	1.02	0.12
W	55.75	17.0	21.6		34.5		25.0		18.99	dl	nd	nd
Pb	7.09	6.99	6.13	7.08	8.9	15.7	9.27		8.78	4.46	6.87	1.42
Th	8.46	5.85	2.23	12.6	4.17	4.91	4.96		5.64	3.57	12.33	1.67

Numbers in parentheses corresponding to the symbols in the diagrams.

\* Fe calculated as Fe<sub>2</sub>O<sub>3</sub>.

dl detection limit.

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