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ε_{Nd}(T) variation in an Early Proterozoic actinolite skarn, Sweden, reflecting felsic volcanite-seawater interaction

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Abstract

Two neodymium isotopic analyses of least-altered metavolcanites from the Hjulsjö area and six analyses of albitized and actinolitized metavolcanites from Ställbergstorp farm south of Hjulsjö show variations in ε_{Nd}(T) values that point to two-stage mixing involving seawater- and rock-dominated fluid-rock interaction.

In a first stage felsic volcanites are albitized and leached in LREE. Some of these extremely LREE-leached felsic volcanites show very negative ε_{Nd}(T) values. Thus, leaching occurred by a fluid with a long crustal history, probably modified seawater containing Nd derived from an Archaean erosional area.

In a second stage redeposition of LREE previously leached from the volcanic pile accompanies the formation of actinolite aggregates in the leached metavolcanite and results in an increase of ε_{Nd}(T).

Introduction

The 1.89–1.85 Ga old Svecofennian Bergslagen Supracrustal Series (BSS) of western Bergslagen (Central Sweden) is predominantly composed of a felsic metavolcanic succession with a thickness of over 10 kilometres; the volcanites were originally deposited in a shallow marine environment (Oen et al., 1982; Oen, 1987). The succession is cut by alteration zones and by metabasic sills and dykes. Two stages of alteration are recognized, both related to (sub-) seafloor processes. A first stage of regional alkali alteration is held responsible for the development of a Na-rich unit corresponding to the lower part, and a K-rich unit corresponding to the upper part of the succession, both subparallel to the regional lithostratigraphy or paleoseafloor (Baker, 1985). The Na-rich albitized rocks locally show the effects of a second stage of alterations, leading to the development of schistose, phlogopite- and muscovite-bearing metavolcanites, Mg-rich quartz-phlogopite-muscovite (-chlorite) schists (Baker & De Groot, 1983), actinolite-bearing metavolcanites and actinolite-magnetite skarns (Baker, 1985; Valbracht & Helmers, 1988).

The actinolite-magnetite skarn near Ställbergstorp farm, approximately 10 kilometres south of Hjulsjö, occurs in a subvertical, NNW striking succession of albitized felsic pyroclastic rocks of the Lower Leptite Group (Early Volcanic Stage, Fig. 1) of the BSS. Valbracht & Helmers (1988) have described the local geology, petrography and mineralogy, the metasomatic changes that brought about the transformation of albitized felsic metavolcanites into actinolite skarns and the high mobility of light rare earth elements (LREE) during this process. The regional Na-K redistribution and the subsequent, more localized skarn alteration have affected the chemistry: (1) albitized felsic metavolcanites are characterized by LREE-depletion

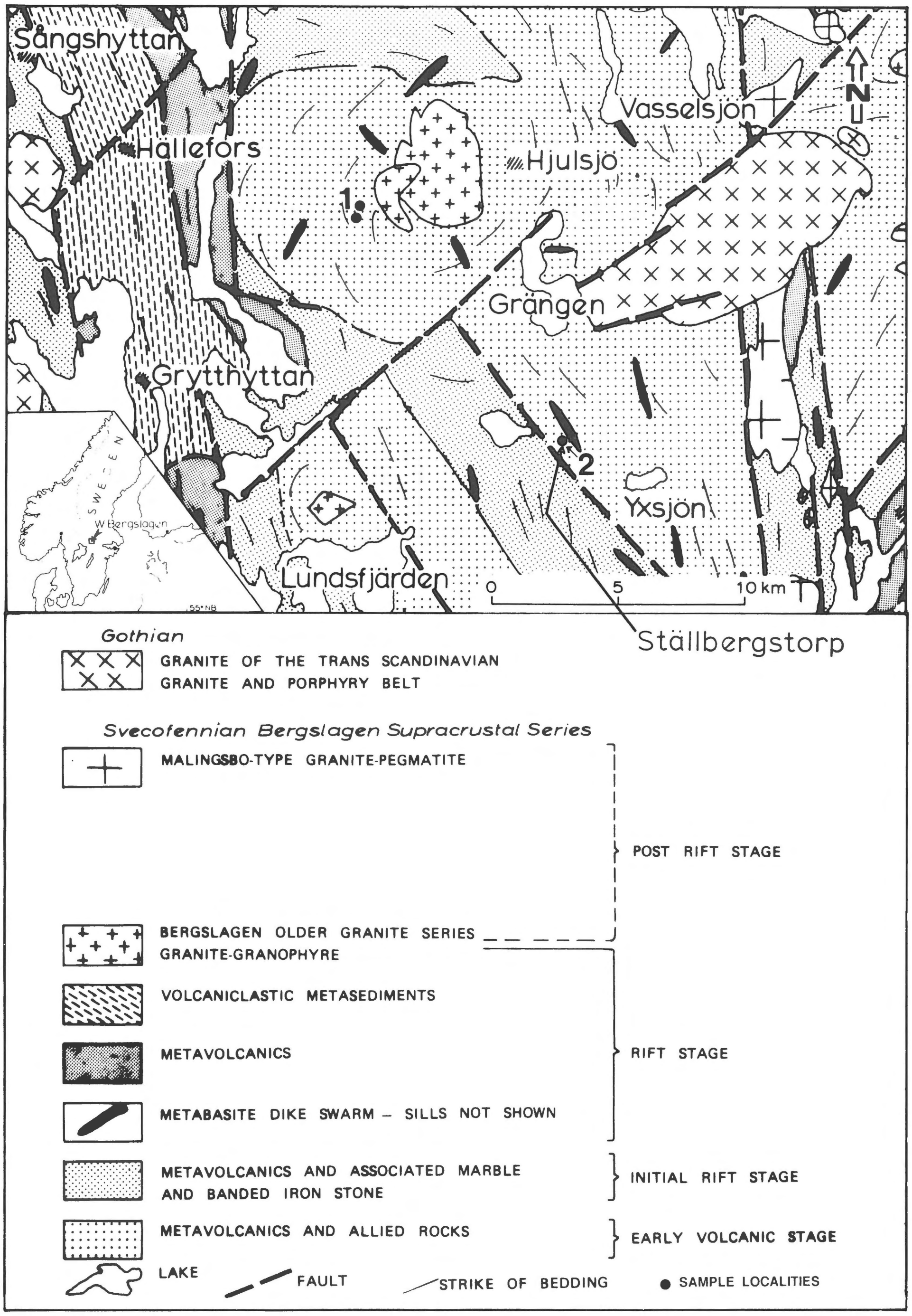

Fig. 1. Lithostratigraphical map of western Bergslagen, modified from Oen et al. (1982). Samples 346 and 349 were collected at location 1, all other samples (102, 296) at location 2 (Ställbergstorp).

relative to the least altered metavolcanites, (2) incipient replacement of albite by actinolite is associated with enrichment in MgO, CaO, FeO* and LREE and (3) massive actinolite growth in the matrix and in veins is characterized by strong enrichment in MgO, CaO, FeO* and LREE.

Results and discussion

Eight samples were analyzed for Nd isotopes, following the procedures described in Valbracht (1991a). The results are given in Table 1. $\varepsilon_{Nd}(T)$ is calculated at 1880 Ma, which is the best approximation of the emplacement age of the felsic volcanites according to the conventional U-Pb zircon age of (1882 ± 24)Ma reported by Welin (1987) and the Sm-Nd age of (1896 ± 58)Ma (Valbracht, 1991a).

The mean $\varepsilon_{Nd}(T)$ value of two least-altered metavolcanites from the Lower Leptite Group west of Hjulsjö is + 1.2 ± 0.2 (346, 349; see Fig. 1 for location of samples). For two samples of the Ställbergstorp albitized metavolcanites, leached in LREE (102B, 102Bb), $\varepsilon_{Nd}(T)$ is + 1.4 ± 0.4 and − 0.3 ± 0.2, respectively. Three actinolitized albitized felsic metavolcanites (296B, 102A, 102EL) show $\varepsilon_{Nd}(T)$ values increasing from − 4.5 to − 1.2, with increasing actinolite content and decreasing LREE-depletion. A massive actinolite vein (102F) shows an $\varepsilon_{Nd}(T)$ value of + 0.8 ± 0.2.

To explain the observed variations in $\varepsilon_{Nd}(T)$ and Sm/Nd (Table 1) for the set of variably altered metavolcanite samples, a two-stage 'mixing' model between the felsic metavolcanite component and a component with high Sm/Nd ratio and negative $\varepsilon_{Nd}(T)$ is proposed.

Negative $\varepsilon_{Nd}(T)$ is usually interpreted as indicating a prolonged crustal history, in this case the involvement of an Archaean component. However, the observed $\varepsilon_{Nd}(T)$ and Sm-Nd systematics cannot be explained in terms of simple local assimilation of an Archaean crustal component by the felsic magma. It is most unlikely that such assimilation would have led to an increase of the Sm/Nd ratio of the magma, since it may be assumed that both crustal components have followed comparable crustal evolution lines.

A hydrothermal cell or sea-floor alteration system, on the other hand, may cause large variations on a local scale in both the Sm/Nd ratio and $\varepsilon_{Nd}(T)$. The local processes involve the interaction of convecting seawater-related hydrothermal fluids with the pyroclastic rocks. Such processes of seawater-

Table 1. Sm-Nd data of the amphibole skarn near Ställbergstorp and metavolcanites near Hjulsjö

Sample	$Sm_{[ppm]}$	$Nd_{[ppm]}$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd_M$	$^{143}Nd/^{144}Nd_T$**	ε(0)*	ε(T)
Least altered metavolcanites							
346	8.94	44.23	0.1222	0.511770 ± 7	0.510258	− 16.9 ± 0.1	+ 1.1
349	9.55	48.83	0.1182	0.511740 ± 15	0.510278	− 17.5 ± 0.3	+ 1.4
Albitized metavolcanites							
102B	1.79	4.53	0.2384	0.513224 ± 20	0.510275	+ 11.4 ± 0.4	+ 1.4
102Bb	1.47	3.61	0.2464	0.513236 ± 11	0.510188	+ 11.7 ± 0.2	− 0.3
Actinolitized metavolcanites							
296B	5.23	21.94	0.1440	0.511924 ± 8	0.510143	− 13.9 ± 0.2	− 1.2
102A	4.83	15.37	0.1899	0.512403 ± 14	0.510054	− 4.6 ± 0.3	− 3.0
102EL	2.98	9.14	0.1973	0.512415 ± 7	0.509974	− 4.4 ± 0.1	− 4.5
Massive actinolite vein							
102F	26.98	158.13	0.1031	0.511523 ± 11	0.510248	− 21.8 ± 0.2	+ 0.8

Analytical procedures are described in detail in Valbracht (1991a, b). $T_{formation}$ = 1.88 Ga. * $\varepsilon = (^{143}Nd/^{144}Nd_M/^{143}Nd/^{144}Nd_{CHUR}-1) \times 10^4$ (DePaolo and Wasserburg, 1976). ** $T_{formation}$ = 1.88 Ga. Errors for $^{143}Nd/^{144}Nd_M$ and ε(0) are 1s internal precision and correspond to the last two significant numbers, errors for $^{143}Nd/^{144}Nd_T$ and ε(T) are calculated with s($^{147}Sm/^{144}Nd$) = 0.2% and are identical to the error of $^{143}Nd/^{144}Nd_M$. CHUR: $^{143}Nd/^{144}Nd$ = 0.512638 (Wasserburg et al., 1981), $^{147}Sm/^{144}Nd$ = 0.1967 (Jacobsen and Wasserburg, 1980), CHUR(T): $^{143}Nd/^{144}Nd$ = 0.510205. LaJolla = 0.511853 ± 7(n = 29).

felsic volcanite interaction have been described for rocks of the BSS by Baker & De Groot (1983).

In view of the short residence time of Nd in seawater in comparison to the mixing time of the oceans (Fryer, 1983), the Nd isotopic composition of seawater may be taken to approximate the average composition of the adjacent continents. The most ancient Archaean crust in the Baltic Shield is predominantly 2.7–2.6 Ga old, while locally ages of 3.1–2.9 Ga have been reported (Gaál and Gorbatchev, 1987).

Results of $\varepsilon_{Nd}(T)$ calculations based on these model-ages of Archaean crust are given in Table 2. From Table 2 the $\varepsilon_{Nd}(T)$ values of Early Proterozoic seawater that is buffered by Archaean crust in the Baltic Shield, can be estimated to lie between − 8 to − 12. For the Sm/Nd ratio of the leachate a minimum value of 0.40 is taken on the basis of the Sm/Nd ratio of strongly albitized metavolcanites (Valbracht, 1990; Valbracht, 1991a), which equals a $^{147}Sm/^{144}Nd$ ratio of 0.25 ($Sm/Nd \approx 1.654\, ^{147}Sm/^{144}Nd$).

The observed variations in $\varepsilon_{Nd}(T)$ (Table 1) can be explained by two stages of felsic volcanite-seawater interaction. In a general bulk mixing model (Langmuir et al., 1978) at least 50% Nd contribution from seawater to a leached metavolcanite (*stage 1*) was followed by redeposition of leached LREE during actinolitization (*stage 2*). Results of general mixing equations based on $\varepsilon_{Nd}(T)$ and LREE concentration parameters are given in Table 3. An LREE-rich seawater-derived component is proposed, because normal present-day seawater with LREE concentrations of 10^{-4} to 10^{-6} ppm would necessitate extremely high water/rock ratios.

Table 2. ε_{Nd} (1880) calculations on average Archaean crustal sources

ε_{Nd}(1880)	Sm/Nd*	T_{CHUR}	T_{DM}**
− 8	0.18	2.6	2.8
	0.20	2.7	2.9
− 10	0.18	2.8	3.0
	0.20	2.9	3.1
− 12	0.18	2.9	3.1
	0.20	3.1	3.3

* A Sm/Nd ratio of 0.18 corresponds to an average granodioritic Archaean crust, 0.20 to an average granitic Archaean crust (Taylor and McLennan, 1985; Faure, 1986). ** DM of De Paolo (1981).

Summary of the two-stage mixing model

1. Seawater-dominated seafloor alteration

During deposition and albitization the felsic meta-

Table 3. Nd mixing calculations

Stage 1. Albitization and LREE-leaching Seawater (%)*	C_{rock} [ppm]	C_{MIX}	ε_{Nd}(MIX)	Rock description
–	45	–	+ 1.2	least altered metavolcanite
0	1	1	+ 1.2	albitized metavolcanite
10	1	1	0.0	
50	1	1	− 4.5	
90	1	1	− 8.9	
Stage 2. Actinolitization and LREE-redeposition Actinolite (%)	**C_{rock} [ppm]**	**C_{MIX}**	**ε_{Nd}(MIX)**	**Rock description**
3	1	8.8	− 4.5	actinolitized and
5	1	11.8	− 3.0	albitized metavolcanite
10	1	20.1	− 1.2	
100	1	160	+ 0.8	actinolite skarn

* seawater-derived component. Parameters for mixing calculations: ε_{Nd} (seawater-derived component) = − 10. ε_{Nd} (albitized metavolcanite) = − 10. ε_{Nd} (rock) = 1.2. $C_{seawater\text{-}derived\ component}$ = 1 ppm. $C_{albitized\ metavolcanite}$ = 1 ppm. $C_{actinolite\ skarn}$ = 160 ppm.

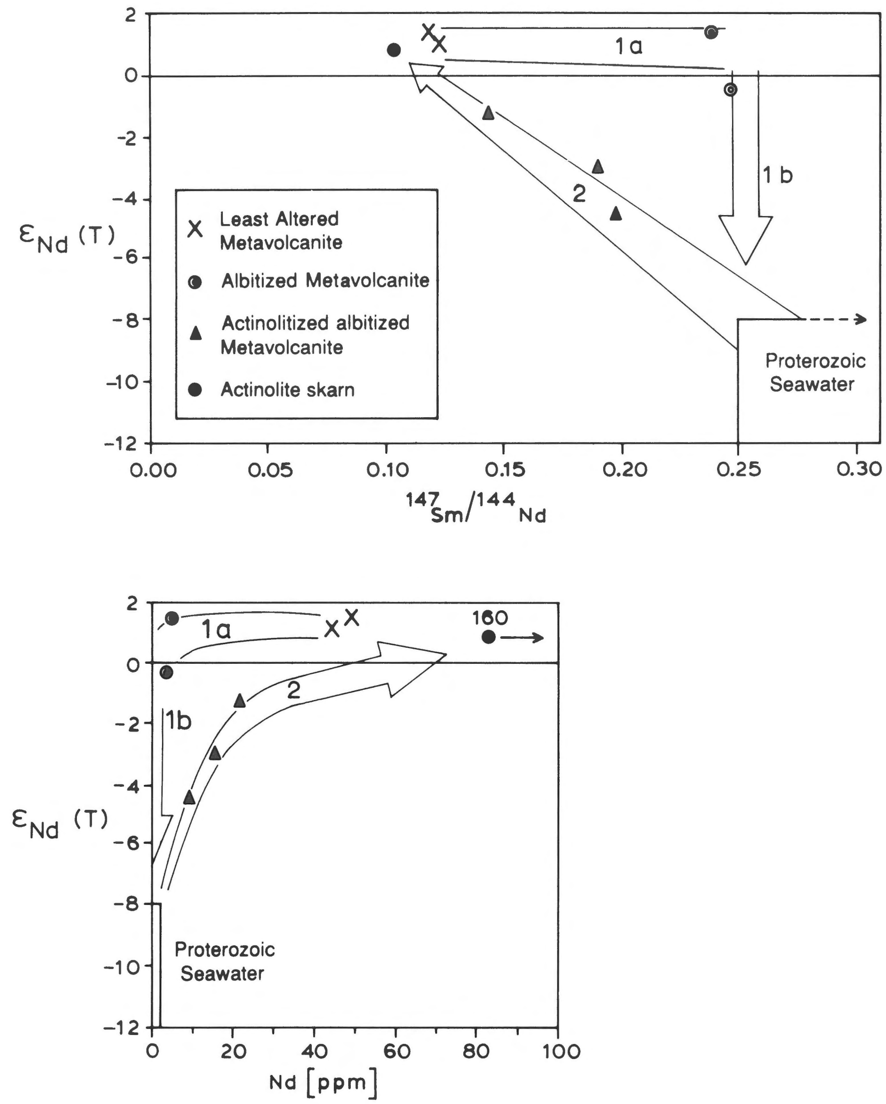

Fig. 2. The two-stage 'mixing' model. (*Above:*) Albitization (1a) due to seafloor water-rock interaction leads to increasing Sm/Nd ratios as a result of Nd being more strongly leached than Sm. Strongly albitized and LREE-depleted samples (1b) have a 'seawater-like' Nd isotopic composition (Valbracht, 1990; 1991a). Actinolitization (2) results in the reinstatement of the Sm/Nd ratio and $\varepsilon_{Nd}(T)$ of the pristine felsic volcanite. (*Below:*) Albitization (1a) results in leaching of LREE, with extremely leached samples partly reflecting the Nd isotopic composition of seawater (1b). Actinolitization (2) shows redeposition of LREE previously leached from the volcanic pile, with reinstatement of the $\varepsilon_{Nd}(T)$.

volcanites were leached in LREE, while the original Nd isotopic signature was approximately retained (Fig. 2, below). Samples strongly leached in LREE have been affected locally by a seawater-dominated component and show lowered $\varepsilon_{Nd}(T)$ values along with high Sm/Nd ratios (Fig. 2, above), in extreme cases down to -14 (Valbracht, 1990; 1991a).

2. Sub-seafloor skarn alteration

Subsequent actinolitization of the albitized, seawater-altered felsic metavolcanite (having a negative $\varepsilon_{Nd}(T)$) involved redeposition of the LREE previously leached from the volcanic pile (with a positive $\varepsilon_{Nd}(T)$). This resulted in an increase of $\varepsilon_{Nd}(T)$ (Fig. 2), with massive actinolite in veins and patches showing the reinstated Nd isotopic composition of the felsic metavolcanite. Redeposition of the LREE occurred as the physico-chemical conditions of the hydrothermal cell changed.

Thus, along with the conclusion of Valbracht & Helmers (1988) concerning high LREE mobility, Nd isotopes point to syn- to post-albitization hydrothermal alteration involving a seawater-derived component preceding the actinolitization process involving a reintroduction of the felsic volcanite component.

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