Disparate Geochemical Patterns from the Snåsavatn Greenstone, Nord-Trøndelag, Central Norway

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Greenstone volcanites of Middle Ordovician age from the Snåsavatn area of the Central Norwegian Caledonides can be divided into two distinctive groups on the basis of their geochemical patterns. The bulk of the lavas sampled are tholeiites of ocean floor affinity, though with a hint of transition towards within-plate features in some minor and trace element contents. These OFB rocks are positioned structurally and stratigraphically above the second group of greenstone lavas which are basalts of calc-alkaline chemical character. The CAB lavas are, in turn, stratigraphically underlain by the Snåsa limestone which contains a varied fauna of Lower to Middle Ordovician age. Regional-geological, biostratigraphic and volcanite-geochemical considerations pinpoint similarities between the palaeotectonic situations for the Snåsavatn volcanosedimentary assemblage and that from the island of Smøla some 200 km along strike to the southwest. The influx of OFB volcanites at Snåsavatn, however, is not recorded on Smøla. This upward transition to more primitive tholeiitic basalts is thought to relate to a subduction zone and arc migration, with ocean accretion occurring in an extensional, back-arc marginal basin setting.

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Introduction

Studies of the geochemical character of Lower Palaeozoic basaltic and andesitic greenstones over the past decade have provided valuable contributions to Caledonide research in the central Norwegian part of the mountain belt. In 1979, systematic sampling of the schistose greenstone volcanites of the Snåsavatn area of Nord-Trøndelag was carried out as a part of an ongoing NGU project 'Grønnstein geokjemi innen de sentrale norske kaledonidene'. Preliminary results of this investigation of the Snåsavatn lavas revealed an interesting bipartite grouping, with the bulk of the volcanites showing ocean floor tholeiite characteristics and a smaller population of samples from a structurally lower zone having a distinctive calc-alkaline chemistry (Roberts 1980a). Subsequent sampling was concentrated on determining the extent of the calc-alkaline association. This short article aims at reporting the principal results of this study and briefly discussing their regional significance.

Geological setting

The greenstone unit sampled forms part of an association of lithologies which Foslie (1958) collectively termed the Snåsa Group. Earlier, Carstens (1956) had noted that these greenschist to epidote-amphibolite facies rocks – schists, limestones, greenstones, conglomerates and sandstones – were deformed in a narrow, NE–SW-trending syncline, his Snåsa Syncline. Further mapping, aided by fossil finds in the Snåsa limestone, led Carstens (1960) to the view that the greenstones and limestones at least (Fig. 1), formed part of the Lower Hovin Group

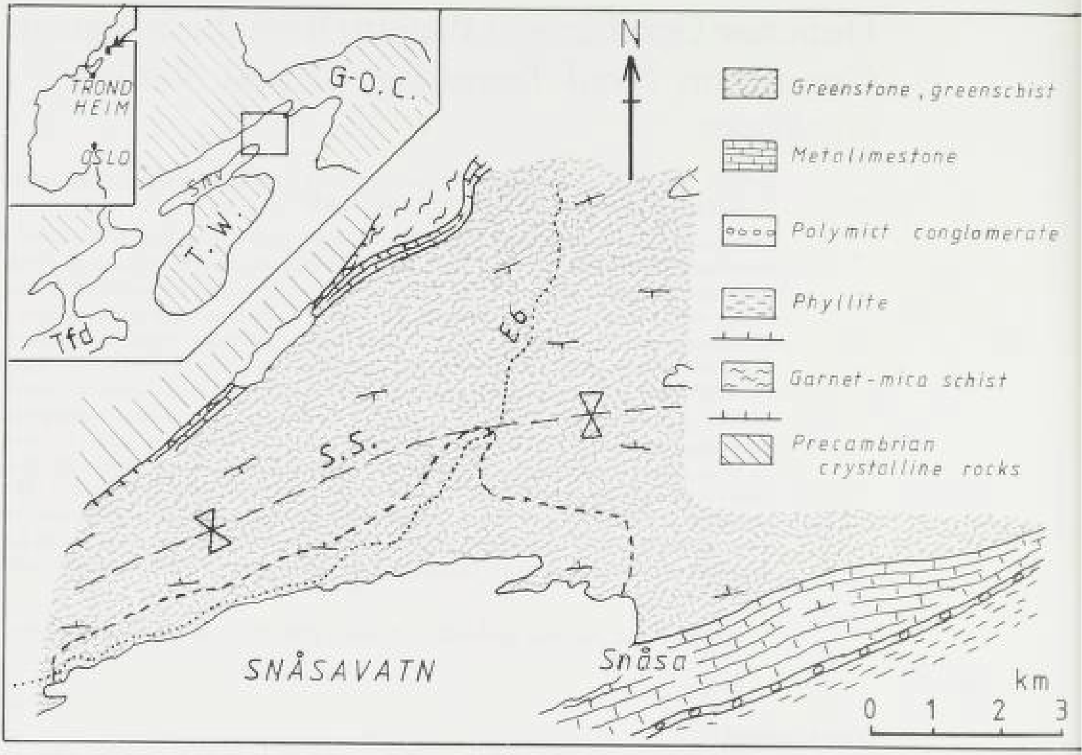

Fig. 1. Simplified geological map of the NE Snåsavatn area. S.S. – Snåsa Synform. All except 2 of the samples analysed in this study are from the area contained by the dashed line between the shores of Snåsavatn and the synform axial trace. In the inset map. T.W. – Tømmerås window; G.–O.C. – Grong–Olden Culmination; Snv – Snåsavatn; Tfd – Trondheimsfjord. The geology is taken from Roberts (1967). The E6 highway is indicated by the dotted line.

of the classical Trondheim region stratigraphy (Vogt 1945), which is part of the Støren Nappe (Gale & Roberts 1974). Both Springer Peacey (1964) and Roberts (1967) adopted the informal Snåsa Group designation in their reconnaissance studies. In the NE Snåsavatn area the sequence is essentially a structural one since no primary structures have yet been found. Moreover, as the major 'syncline' deforms the penetrative regional schistosity and associated sub-isoclinal folds (Roberts 1967) it is more appropriate to refer to it as a synform.

More recent work in the area from the Tømmerås Antiform across the northeastern termination of the Snåsa Synform into the Grong–Olden Culmination (Fig. 1, inset) has pointed to tectonostratigraphical similarities between this region and areas in Sweden (e.g. Gee 1977, Andreasson & Johansson 1982), denoting that Foslie's (1958) original Snåsa Group embraces lithologies from 4, or maybe 5, separate nappes. Similar subdivisions have been traced southwestwards into the Steinkjer and Inderøy–Leksdalsvatn areas by Tietzsch–Tyler (in prep.) and Roberts (unpubl. mapping), respectively. Some elements of this tectonostratigraphy are shown on the 1:250 000 map-sheet 'Trondheim' (Wolff 1976), although amendments have been noted (Roberts & Wolff 1981) and other revisions will follow.

The Snåsavatn greenstone

The predominant lithology of the unit, here informally termed the Snåsavatn greenstone, is a green to pale green moderately schistose rock of generally medium- to medium-fine grain. Some parts are more schistose and may represent mafic tuffs; however, these sometimes correspond to zones of higher strain. Other lithologies represented sporadically within the 1.5–1.8 km-thick unit are intermediate tuffs, keratophyric horizons and agglomerates. Limestone bands and ribs are not uncommon within the basal parts of the volcanic pile (Roberts 1967). Despite an extensive search for pillow structure, nothing has been observed which could be classified as definite pillow form. Carstens (1956) also noted that pillow structure had not been found over an extensive area from Malm to Snåsa. This contrasts with other Ordovician greenstone sequences from other parts of Trøndelag, where pillow structure is sometimes prominently developed (e.g. Grenne & Roberts 1980).

PETROGRAPHY

The greenstones show complete recrystallisation to greenschist to epidote-amphibolite facies assemblages. Primary igneous textural relics are rare, although these may be discerned in some thin-sections through a blanket of saussuritised plagioclase and chloritised and epidotised amphibole. The amphibole is an actinolite which, together with chlorite, defines the foliation in the rock. Other minerals present are epidote, Ti-magnetite, apatite, calcite and assessory leucoxene.

Geochemistry

SAMPLING

The initial sampling was concentrated along a traverse across the southeastern limb of the Snåsa Synform (Fig. 1), with the well exposed road-cuts along the new E6 highway as principal targets (Roberts 1980a). Thirty-six fresh samples of variably schistose greenstone were taken. Follow-up sampling, subsequent to examination of the initial analytical data, provided a further 10 analyses. Analytical procedures are given in an appendix.

MAJOR ELEMENT CHEMISTRY

On initial examination of the raw analytical data from 1979 it was evident that a small number of analyses from one part of the greenstone formation were different from the bulk of the samples in showing higher Al_2O_3, Na_2O, K_2O and P_2O_5 weight percentages and lower MgO, CaO and TiO_2 (Roberts 1980a). These differences were also reflected quite clearly in AFM, FeO *vs.* FeO/MgO and TiO_2 *vs.* FeO/MgO diagrams, with the high-alumina, alkali-rich greenstones displaying calc-alkaline features. Samples collected subsequently served to confirm this chemical disparity (Table 1). Oxide concentrations for the main group of analyses, on the other hand, invite comparison with values for ocean-floor tholeiites (Table 1, group A). Again, this trend appears to be confirmed in graphic representation of the data (Fig. 2).

TABLE 1. Averaged major and trace element contents of the Snåsavatn greenstones (major elements in wt.%, trace elements in ppm). For comparison, mean element concentrations are presented for selected basalt series or types

	Snåsavatn greenstone			*Mean values, diverse basalts*			
	Group A (n=27)	Group B (n=13)	OFB	W.-P. CON	CAB	Smøla CAB	Sunda arc H-K.CAB
SiO_2	45.67	48.01	49.91	48.81	51.31	49.62	49.60
TiO_2	1.66	1.35	1.43	2.47	0.88	0.93	1.15
Al_2O_3	16.01	18.96	16.20	14.41	18.60	18.10	18.20
Fe_2O_3	3.53	4.46	–	13.20^2	2.91	2.43	–
FeO	6.45	3.39	10.24^1	–	5.80	5.02	9.80^1
MgO	7.83	4.72	7.74	5.96	5.95	6.87	5.10
CaO	10.69	6.53	11.42	10.05	10.30	8.64	10.20
Na_2O	2.65	4.92	2.82	2.90	2.93	2.99	3.00
K_2O	0.34	1.58	0.24	0.95	0.74	1.21	2.18
MnO	0.17	0.16			0.15	0.14	0.20
P_2O_5	0.16	0.63			0.12	0.18	0.40
L.O.I.	4.09	4.00				3.69	
Zr	112	230	92	149	106	120	113
Y	31	32	30	25	23	23	28
Sr	246	1143	131	401	375	557	540
Rb	6	26	3	15	23	39	61
Zn	79	128				63	
Cu	46	88	73	99	35	38	110
Ni	102	44	106	68	50	87	19
Cr	305	74	310	139	130	251	39
Ba	68	525	8	338	260	301	480
Nb	5	17	5	25	4	6.5	11
V	323	234	229		174	222	280

Analysts: Gjert Faye and Per-Reidar Graff. NGU.

Data sources for mean values: OFB – Pearce 1975: W.-P.CON – Pearce (1975): CAB – Nockolds & Le Bas (1977), Pearce (1975): Smøla CAB–Roberts (1980b): Sunda arc high-K CAB – Whitford et al. (1979).

1) – Total Fe given as FeO. 2) – Total Fe given as Fe_2O_3

With a total alkali content of 6.5 wt.% for the calc-alkaline basaltic greenstones (CAB), which is more than double that of the ocean-floor type tholeiitic basalts (OFB group), it is tempting to ascribe this relative and absolute increase solely to some form of pre-deformational alteration, notably spilitisation. This is unlikely, however, since the K_2O and Al_2O_3 contents are consistently and sharply higher (quite the opposite of spilitisation trends) in the CAB. Moreover, a Hughes (1973) diagram shows that virtually all the Snåsavatn greenstone samples fall clear of the 'spilite' field (Fig. 3). The depletion of CaO requires some explanation; possibly it may relate to an increase in calcite and epidote veining within this level of the volcanic pile. This needs further investigation.

TRACE ELEMENT CHEMISTRY

Extensive research has shown the value of incompatible trace elements in discriminating between the tectonic settings of diverse magmatic associations. Of

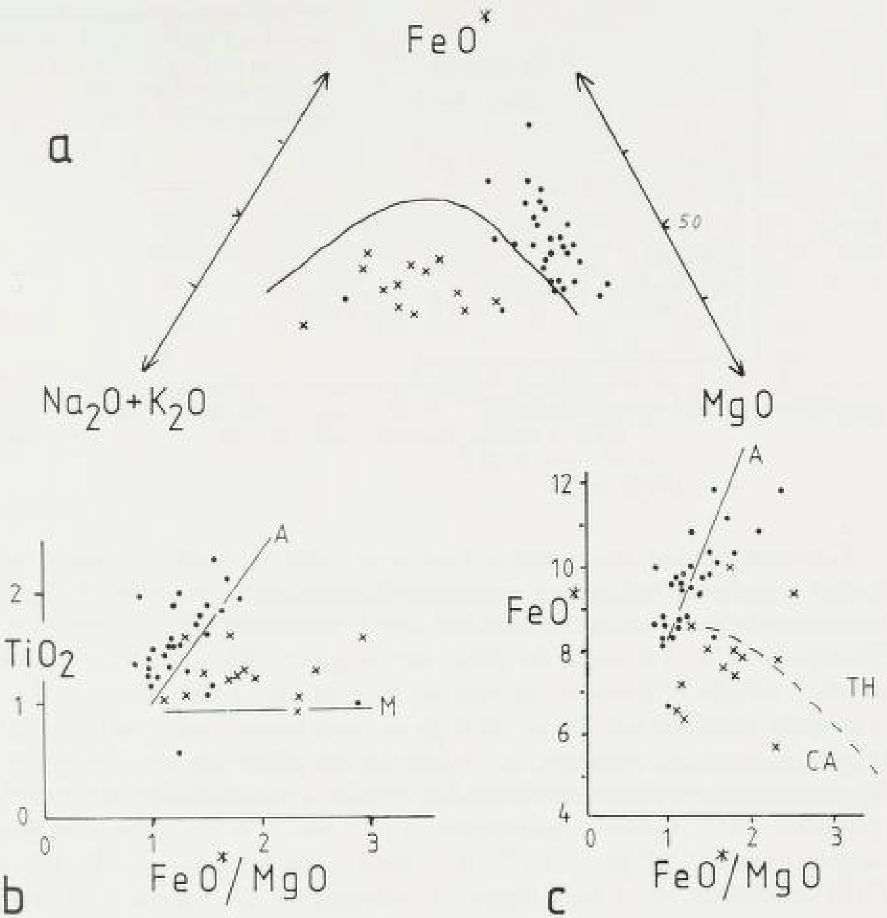

Fig. 2. Plots of the Snåsavatn greenstone analyses on (*a*) an AFM diagram, (*b*) TiO_2 *vs.* FeO/MgO and (*c*) FeO *vs.* FeO/MgO diagram. (FeO^* = total Fe as FeO). Symbols: *dots* – samples of the OFB (group A in Table 1); *crosses* – samples of the CAB (group B in Table 1). In *b* and *c*, A – trend for average ocean floor tholeiites. In *b*, M – trend for Macauley island arc tholeiites. In *c*, the dashed line separates the fields for tholeiites (TH) and calc-alkaline basalts (CA).

these elements, Y, Nb, Zr and the heavy rare-earths (HREE) are the most stable, closely followed by the light REE, and these have proved applicable in distinguishing volcanic settings in both modern and ancient magmatic assemblages (for examples from central Norway, see Grenne & Roberts (1980) and Roberts (1980b)). Here again, plots of particular element ratios provide immediate graphic discrimination, but a visual comparison of mean element concentrations with those from known modern settings is equally valuable (Table 1).

For the Snåsavatn greenstones the dual grouping, OFB and CAB, noted from the major element plots, is even more distinctive from trace element ratio diagrams. In the Ti-Zr-Y plot (Fig. 4), some of the OFB group analyses exhibit an overlap into the field of within-plate basalts, i.e. they show slightly 'transitional' characteristics.

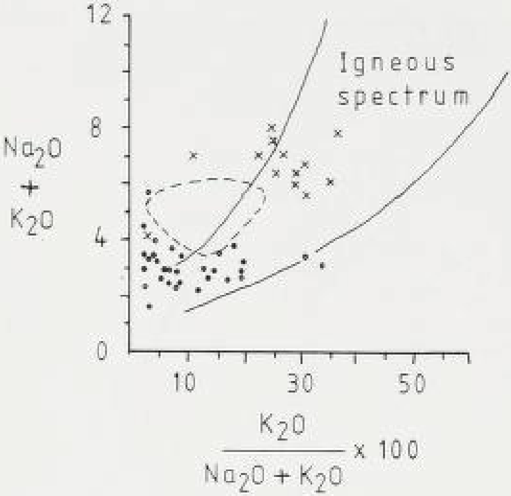

Fig. 3. Snåsavatn greenstone samples plotted in a Hughes' (1973) diagram. Symbols as in Fig. 2. The area enclosed by the dashed line represents the field of spilites.

Rare-earth element abundances and patterns, relative to chondritic values, are known as important indicators of magmatic affiliation, even though the LREE can sometimes be prone to spilitisation and low-T weathering process (Ludden & Thompson 1978). Following the initial sampling and analytical work, 6 representative samples of Snåsavatn greenstones were chosen for REE determination, 4 from the tholeiites and 2 from the high-alumina basalt group (Table 2). The chondrite-normalised patterns (Fig. 5) from the two groups are quite distinctive. The tholeiite analyses show more or less flat, chondritic profiles though with a quite prominent LREE depletion characteristic of mid-oceanic ridge basalts. The two samples from the CAB group, on the other hand, reveal parallel trends of marked LREE-enrichment and a high degree of fractionation. The lightest REE show

TABLE 2. Rare-earth element and Sc, Hf, Ta, Th and U contents (ppm), and selected ratios, from representative samples of Snåsavatn metabasaltic greenstones, Nord-Trøndelag, Norway. The first four samples are classified in group A (Table 1) and the last two in group B.

Sample no.	SN. 5	SN. 8	SN. 16	SN. 36	SN. 23	SN. 24
La	3.36	5.00	5.31	5.67	57.6	70.5
Ce	11.1	14.6	14.6	17.0	124.0	160.0
Nd	10.6	11.6	11.8	13.1	57.8	76.8
Sm	3.59	3.61	3.47	4.03	9.17	12.10
Eu	1.41	1.30	1.29	1.52	2.58	3.44
Tb	0.85	0.78	0.74	0.86	0.87	1.18
Yb	3.01	2.84	2.60	3.06	2.01	2.65
Lu	0.45	0.47	0.41	0.48	0.33	0.41
Sc	46.0	39.3	34.4	38.4	9.46	13.4
Hf	2.42	2.37	2.22	2.70	4.27	5.28
Ta	0.17	0.25	0.16	0.30	0.94	1.05
Th	<0.2	0.46	0.51	0.44	16.3	16.8
U	<0.2	<0.2	0.17	<0.2	3.43	6.85
$(La/Yb)_N$	.67	1.05	1.20	1.11	16.90	15.92
$(La/Sm)_N$	.59	.86	.94	.88	3.84	3.57

Analyst: Dr. Jan Hertogen, Department of Physico-Chemical Geology, Catholic University of Leuven, Belgium.

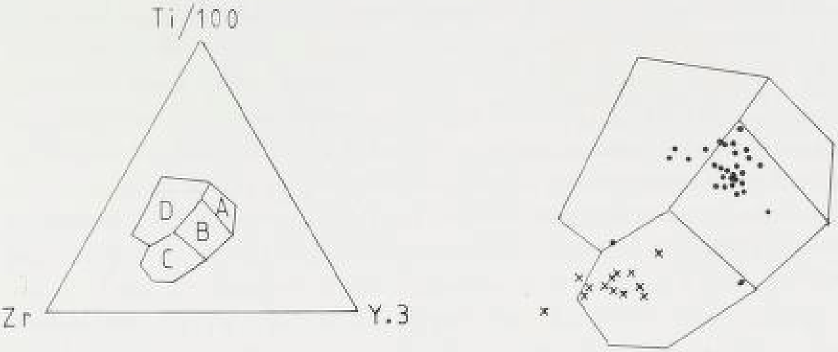

Fig. 4. Ti-Zr-Y diagram for the Snåsavatn greenstones. Symbols as in Fig. 2. Field A – low–K tholeiites; field B – ocean floor tholeiites; field C – calc-alkaline basalts; field D – within-plate basalts. The diagram to the right is an enlargement of fields A to D.

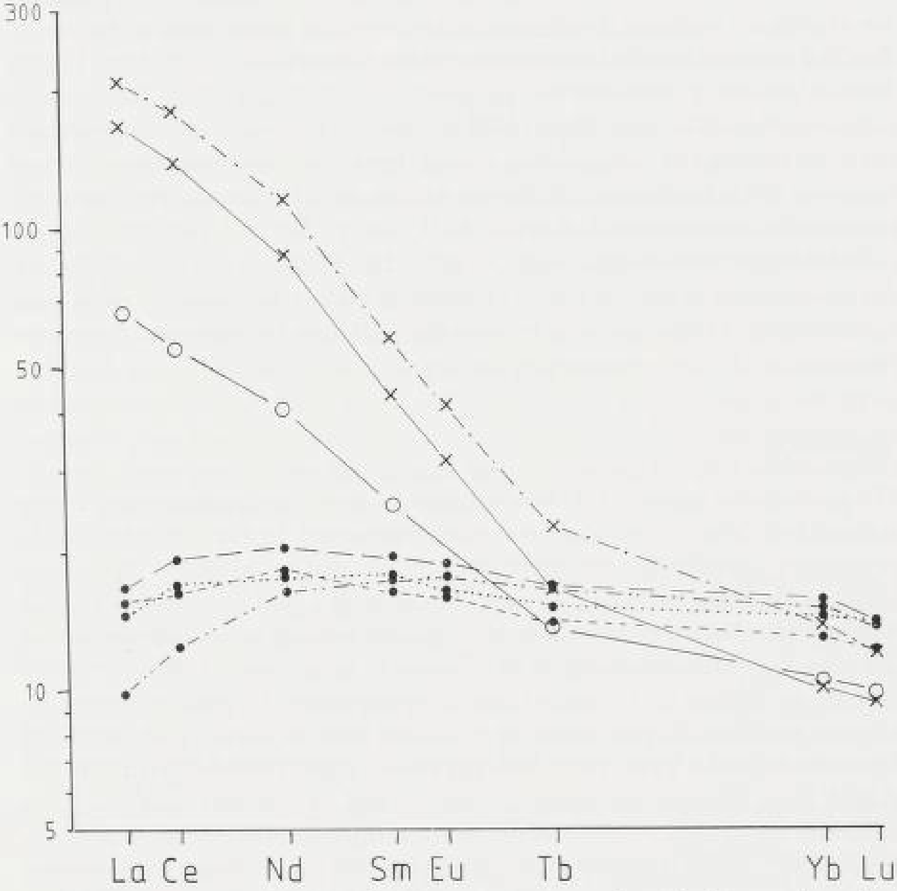

Fig. 5. Chondrite-normalised REE profiles for representative samples of the Snåsavatn lavas. Dot and cross symbols correspond with groups A and B, respectively, as in Fig. 2. Open circles – average values for REE data from the Smøla volcanites. Source of chondritic values: Masuda et al. (1973), Nakamura (1974), Evensen et al. (1978). Details of samples and analyses are contained in an NGU report (Roberts 1981).

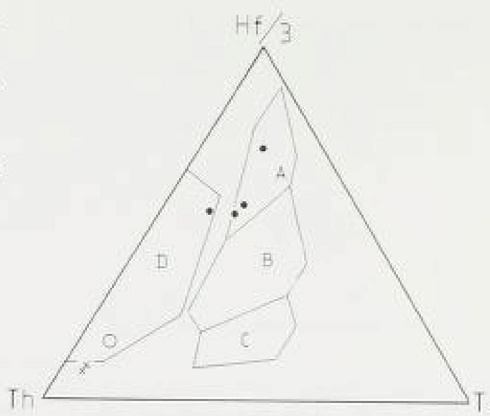

Fig. 6. Hf–Th–Ta diagram showing the plots of the REE-analysed samples. Symbols – dots and crosses as in Fig. 2; open circle – average value for basalts from Smøla (Roberts 1981). Field A – normal MORB. Field B – LREE-enriched MORB. Field C – within-plate basalts. Field D – basalts formed at convergent plate margins (both island arc and Andean type).

c. 170–200 times chondritic abundances, which is a somewhat greater figure than the average for modern calc-alkaline basalts, and also higher than in the case of the CAB from the island of Smøla, west-central Norway (Fig. 5) (Roberts 1980b, 1981); but the general profiles are otherwise similar to those from typical calc-alkaline basaltic lavas. High LREE abundances such as these are known from some of the high-K calc-alkaline basalts from the Quaternay Sunda arc of Indonesia (Whitford et al. 1979). In relation to SiO_2 content the Snåsavatn metabasalts, with nearly 1.6 wt.% K_2O, do in fact fall into the high–K calc-alkaline series of volcanic rocks as defined by Peccerillo & Taylor (1976). In Fig. 6, separation of the two groups of Snåsavatn lavas is again clearly visible, with a good degree of correspondance between the CAB from Snåsavatn and those from Smøla.

Discussion

The geochemical signatures of these greenstones show that lavas generated in two separate and distinctive volcanic settings are represented. In this particular area the structurally lowest volcanites are of calc-alkaline affinity, while the bulk of the lavas are tholeiites of ocean-floor type though with a hint of transition towards within-plate character. Aspects of the regional geology are of importance in assessing the palaeoenvironments of effusion of these lavas. Although way-up features are lacking in the studied area, there appears to be good evidence from adjacent areas that the greenstones are positioned stratigraphically above the Snåsa limestone (Carstens 1956, 1960, Springer Peacey 1964, Tietzsch–Tyler, in prep.). Rapid facies changes are present, however, and in one area near southwest Snåsavatn the limestone represents almost the entire Lower Hovin Group (Springer Peacey 1964, p. 19), greenstones interdigitating with the limestone and increasing rapidly in volume northeastwards. It would thus appear that quite evolved calc-alkaline basalts, associated with shallow-marine limestone deposition, were replaced up-sequence by tholeiites of ocean-floor character.

The Snåsa limestone fauna is of importance in that the fossils (Roberts 1980c) show striking similarities to those occurring in the late Arenig-Llanvirn Skjølberg Limestone on the island of Smøla (Bruton & Bockelie 1979) some 200 km further southwest along strike. Since the Smøla volcanites (closely associated with the limestone) are of mature, calc-alkaline type (Roberts 1980b), there are obviously parallels to be drawn with the Snåsavatn situation, at least for the lower CAB lava unit. An allied feature is that mineralisation in the volcanites from Smøla, and northeastwards through an important iron-ore district (Fosdalen, near Malm) to Snåsavatn, is of a similar magnetite-pyrite-chalcopyrite association (Carstens 1956, 1960). There are, however, small differences in certain minor and trace element abundances (e.g. Zr, Nb and LREE) and this may reflect a positioning of the Snåsavatn magmatic arc closer to the palaeo-continental margin than in the case of the Smøla arc rocks.

The OFB volcanites at Snåsavatn, coming in without a visible break above the island arc CAB/limestone association, were clearly not extruded in a major ocean, spreading-ridge setting. On the other hand, the indications of 'transitional' chemistry, towards WPB, are typical of an extensional, marginal basin, back-arc milieu of spreading. Such an interpretation fits very well with what we know of other Middle Ordovician magmatic assemblages in Trøndelag (Grenne & Roberts 1980, Roberts, Grenne & Ryan, in prep.). The actual location of the marginal basin spreading centre in this particular case (prior to nappe translation) could be considered as being related to oceanward migration of the arc and subduction zone with time (Roberts et al. in press), a feature well known from modern island arc/subduction zone situations, for example in the western Pacific, thus facilitating the behind-arc marginal basin distension and ocean accretion. Alternatively, the OFB lavas may have been associated with a splitting of the fairly mature, carbonate-fringed magmatic arc during a changing stress regime – from essentially convergent and compressive to extensional, perhaps itself related to changing vectors of plate motion in which the subduction zone gradually became inactive. Assessing these possibilities will require further detailed mapping and sampling over a much wider area.

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Appendix

ANALYTICAL PROCEDURES

Major element analyses for the first batch (36) of samples were determined by classical wet-chemical methods for SiO_2, Al_2O_3, CaO, MgO and total Fe, and by a method outlined by Langmyhr & Graff (1965) for TiO_2, MnO, Na_2O, K_2O and ferrous iron. Majors for the 10 samples collected in 1981, as well as common trace elements for all 46 samples were analysed on rock powders using an automatic

Philips 1450/20 XRF. All analyses were carried out at the Section for Analytical Chemistry, NGU, Trondheim. Calibration curves were made with international standards.

Rare-earth elements, together with Hf, Ta, Th and U, were analysed by instrumental neutron activation, by Dr. Jan Hertogen at the Department of Physico-Chemical Geology, Catholic University of Leuven, Belgium. Samples were irradiated at the Ghent University nuclear reactor. Standard deviations were calculated from counting statistics and the observed spread among results from different countings and/or different gamma-energies. In cases where counting statistics were smaller than 1%, a realistic standard deviation of 1% was assumed. REE normalisation average values used are as follows: – La (0.34), Ce (0.89), Nd (0.65), Sm (0.209), Eu (0.0806), Tb (0.052), Yb (0.20), Lu (0.035); normalising values from Masuda et al. (1973), Nakamura (1974) and Evensen et al. (1978).