

Petrographic and geochemical evidence for major and trace element metasomatism in recrystallized felsic metatuffites from the Persberg area, Bergslagen, Central Sweden



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Received 20 June 1987; accepted in revised form 20 January 1988.

Key words: felsic metatuffites, hydrothermal alteration, zircon mobility, Proterozoic, Bergslagen, Sweden.

Abstract

Felsic rocks with randomly orientated biotite crystals up to 1.5 cm long, occurring NE of Persberg, Sweden, are strongly recrystallized felsic metatuffites. There is a gradual transition from the surrounding weakly recrystallized to the strongly recrystallized metatuffites. Recrystallization resulted from hydrothermal alteration of the metavolcanic rocks, which also caused the development of mafic aggregates, mainly consisting of biotite and/or cordierite. Considerable mobility of major, trace and rare earth elements accompanied the hydrothermal alteration: the strongly recrystallized metatuffites are depleted in K, Rb, Ba and Sr, and enriched in Na, Fe, Mg, Zn, Zr, REE, Hf and W. Compared to their host rocks the mafic aggregates are depleted in Na, Si, Y, W, Th and REE, and enriched in K, Fe, Mg, Sc, Cr, Co, Ni, Ti, Zn, Rb, Sr, Ba and Cs.

Mobility of Zr is illustrated by the morphological characteristics of the zircons present in the strongly recrystallized metatuffites and mafic aggregates. Many of the larger grains show a conspicuous zoning and it is argued that unusual clusters of small zircon grains, often occurring on the boundaries of quartz and albite grains, are probably non-magmatic. The hydrothermal alteration is thought to be driven by the ascending nearby Horsjö granite and enhanced by the Hyttsjö gabbro-tonalite-granite which intruded shortly after the Horsjö granite and probably before the collapse of the hydrothermal system.

Introduction and geological setting

It has long been recognized that the quartzo-feldspathic rocks occurring in the Bergslagen area had a magmatic origin (Sundius, 1923; Magnusson, 1925). These authors were able to describe textural characteristics of the metavolcanic rocks present in the area because in many places post-depositional processes had not destroyed primary volcanic features. Most of the metavolcanites were classified as

pyroclastics, locally showing micropoikilitic, vitroclastic (shards), spherulitic and granophyric textures. In this paper these rocks will be referred to as felsic metatuffites.

Since 1974 detailed field and petrographic work by students of the University of Amsterdam (unpublished reports) has confirmed the earlier conclusions regarding the volcanic nature of these rocks (see e.g. Hellingwerf, 1986; Van Meerten, 1988) and also led Oen et al. (1982) to propose a

new model concerning the origin of the Bergslagen Ore Province. Oen et al. (op. cit.) designated the metavolcanic rocks as the Bergslagen Supracrustal Series and considered them to have been deposited on the seafloor in an incipient rift zone. Welin (1987) gives a zircon U–Pb age of 1882 ± 24 Ma for the metavolcanic rocks. The NNW trending, steeply dipping metatuffites of the area northeast of Persberg, described in detail by Magnusson (1925), Magnusson & Granlund (1928) and Björk (1986), occur in the upper levels of the Bergslagen Supracrustal Sequence and are part of the Horrsjö block which constitutes the westernmost part of the Bergslagen area.

Post-depositional tilting of the volcanic rocks probably is a consequence of regional compression and intrusion of subvolcanic granites (e.g. the Horrsjö granite). The latter are thought to be coeval and comagmatic with the supracrustal rocks (Oen et al., 1982; Oen, 1987). Zircon U–Pb dating gives an age of 1860 ± 20 Ma for these granites (see Oen, 1987). Sub-seafloor hydrothermal metasomatic processes affected the felsic metatuffites on a regional scale, allowing a division to be made into a lower unit, in which albitized rocks predominate, and an upper unit, in which K-feldspathized rocks predominate (Frietsch, 1982; Baker, 1985a, b; Lagerblad & Gorbatshev, 1985). Primary textural features however, remained preserved. Later crosscutting hydrothermal alteration occurred locally and was more destructive with respect to volcanic textures. Examples of this kind of alteration are: (1) Mg-alteration zones described by Baker & De Groot (1983) in the Hjulsjö area and (2) potassic alteration related to ore formation and mafic magmatism in the Saxå area (Hellingwerf, 1986, 1987).

Felsic rocks that occur approximately 5 km northeast of Persberg (Fig. 1) were described as an extremely albitic granite by Magnusson & Granlund (1928). However, in this paper it will be shown that these rocks are felsic metatuffites which are more strongly recrystallized than the surrounding metavolcanic rocks. Presumably, strong recrystallization accompanied hydrothermal alteration related to the intrusion of Hyttsjö-type mafic to felsic magmas, which invaded the volcanic pile after tilt-

ing of the strata had started (Oen et al., 1982; Oen, 1987). This alteration is locally developed, cross-cutting and post-dating regional K–Na alteration. It is therefore believed to correspond to the above mentioned crosscutting hydrothermal events.

Petrographic and geochemical characteristics of the strongly recrystallized felsic metatuffites are described and it will be illustrated that these rocks as well as neighbouring moderately recrystallized felsic metatuffites were hydrothermally altered. Mobility of Zr and related trace elements is indicated by the morphology of the zircons present in these rocks.

Analytical methods

Most whole rock chemical analyses were made by X-ray fluorescence on a Philips PW 1450/20 AHP at the University of Amsterdam, using a Rh anode operating at 40 kV and 60 mA for major elements and at 80 kV and 35 mA for trace elements. REE, Sc, Cr, Co, Sb, Cs, Hf, Ta, W, Th and U were measured by INAA at the Interuniversity Reactor Institute in Delft. Electron-microprobe analyses were made with a Cambridge Instruments Co. Mark 9 microscan operating at an acceleration potential of 30 kV; standards used were: silicates for Si, Al, Fe, Ca and P; natural zircon for Zr and Hf and synthetic glasses for REE, Y, U and Th. Raw data were corrected for matrix effects with the Mark 9 on line ZAF correction computer program. Whole rock chemical analyses of samples 23B, 82A and 281/1 were carried out by X-Ray Assay Laboratories, Toronto, Canada, using XRF for major elements and Rb, Sr, Y, Zr, Nb and Ba; INAA for REE, Sc, Cr, Co, Sb, Cs, Hf, Ta, W, Th, and U, and DCP for Ni, Cu, Zn and Pb.

Field relations and petrography

The metatuffites in the investigated area (Fig. 1) consist of three types: (1) weakly recrystallized felsic metatuffites, (2) moderately recrystallized felsic metatuffites (RFM), locally distinctly gneissic and (3) strongly recrystallized felsic metatuffites with

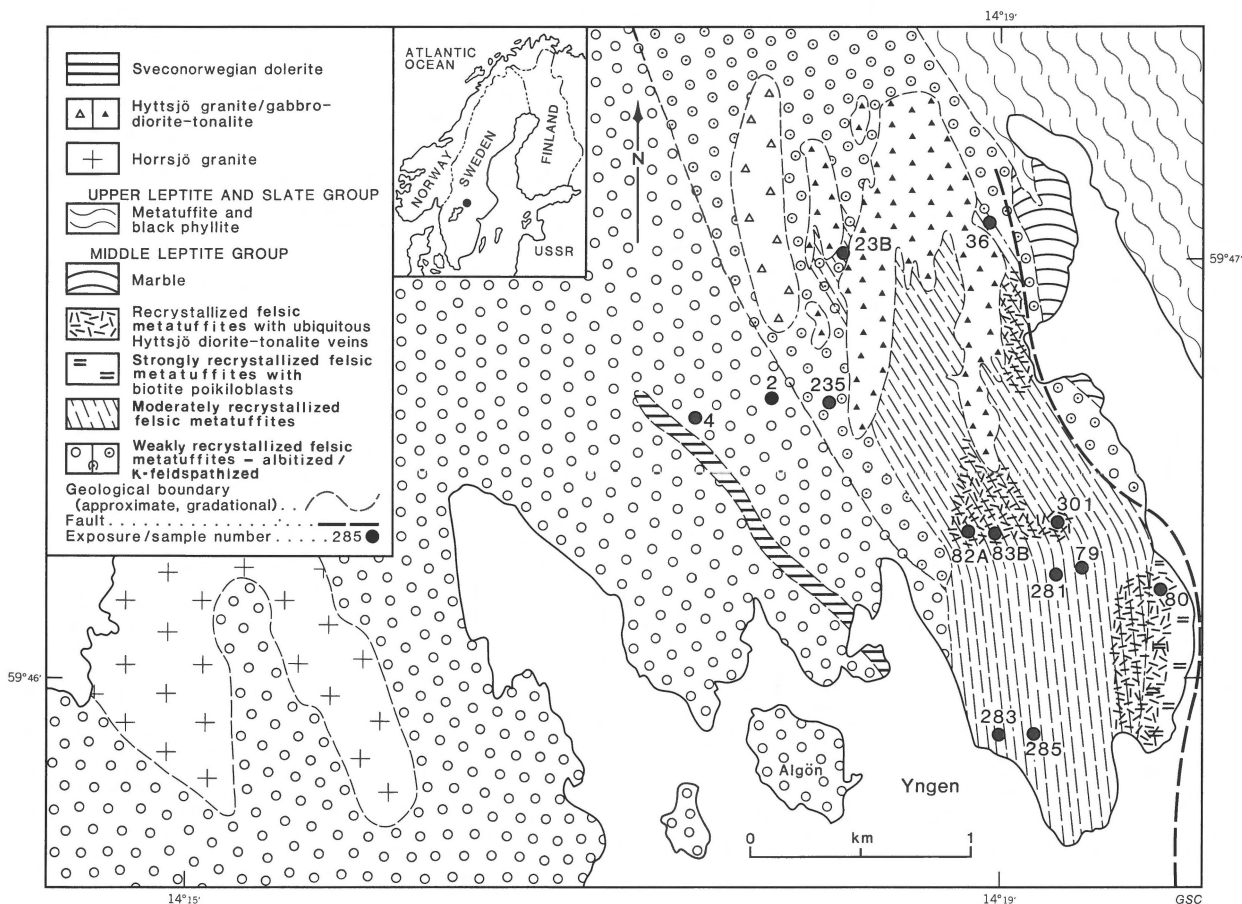


Fig. 1. Simplified geological map of the area north of lake Yngen, northeast of Persberg.

biotite poikiloblasts (RFMB, Fig. 2). Type (3) was described as an extremely albitic granite by Magnusson & Granlund (1928). The transition between types (1) and (2) is irregular, gradual and cross-cutting the bedding (see e.g. Fig. 5). The transition between types (2) and (3) is also gradual; transitions between types (1) and (3) have not been found. Figures 3a-f illustrate the gradual transition from type (1) through type (2) to type (3).

The weakly recrystallized felsic metatuffites generally are light grey to grey rocks with a more or less distinct schistosity. They consist of a very fine- to fine-grained groundmass of quartz, microcline, albite and minor biotite, colourless mica and chlorite. Pyroclasts of quartz, microcline and albite (often chessboard albite) are ubiquitous. One or more of the following minerals may be present:

epidote, actinolite, anthophyllite/gedrite, cordierite and rarely andalusite and chloritoid. Accessory minerals are zircon, apatite and sphene.

The moderately recrystallized felsic metatuffites (RFM) vary in colour from white to dark grey and yellow-brown. The rocks have a sugary appearance; schistosity is absent in most cases, but some show a gneissic banding. The RFM consist of a fine-grained, granoblastic groundmass with quartz, microcline (locally sericitized) and/or albite and biotite as the main constituents. Few pyroclasts of quartz and feldspar have survived the recrystallization. Minor constituents are colourless mica and chlorite. Some rocks contain subordinate cordierite (often altered to fine-grained mica) and anthophyllite/gedrite; andalusite is rare. Accessory minerals are zircon, opaques, apatite and rutile.

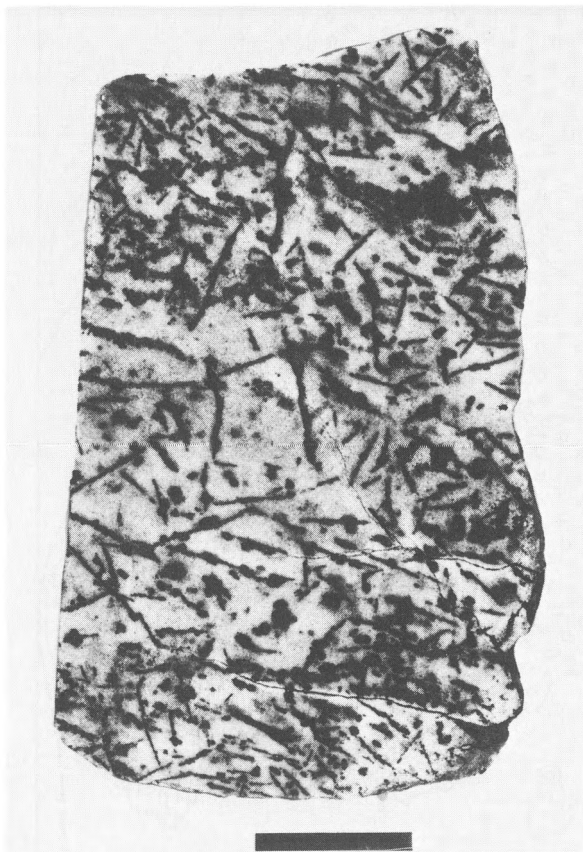


Fig. 2. Strongly recrystallized felsic metatuffite with thin, tabular biotite poikiloblasts (RFMB). Sample 80/5. Scale bar is 2 cm.

The strongly recrystallized felsic metatuffites with biotite poikiloblasts (RFMB) are white with a yellow-brown tinge. Characteristic are the randomly orientated thin tabular biotite crystals which are up to 1.5 cm long (Fig. 2). The sugary appearance is more pronounced than in the RFM. These rocks show a fine-grained, well developed granoblastic texture of quartz, albite and minor biotite; pyroclasts of quartz or feldspar are absent. Biotite forms large poikiloblasts overgrowing quartz and albite (Fig. 3e). Cordierite and/or anthophyllite/gedrite may be present; cordierite is usually altered to sericite and chlorite. Accessory minerals are zircon, opaques, rutile and xenotime.

Mafic aggregates

Locally, the RFM and RFMB contain grey to dark grey aggregates up to 50 cm long. The shape of the aggregates varies from round to irregular. In general they are more irregular in the RFMB (Fig. 4); these irregular aggregates may extend into the surrounding rock in a vein-like manner; they also may have diffuse contacts with the host rock (Fig. 4). Fig. 5 shows the close association of mafic aggregates with moderately and strongly recrystallized metatuffites: vein-like schlieren of strongly recrystallized metatuffites and mafic aggregates alternate with weakly recrystallized host rock which is almost barren of the latter.

The mafic aggregates have a lepidoblastic texture. They are mainly composed of biotite and cordierite. Minor constituents are chlorite, sericite, albite, microcline and quartz and occasionally anthophyllite/gedrite, almandine, hypersthene, corundum, hercynite or magnetite. Accessory minerals are zircon and apatite.

Figures 6 and 7 show the replacement of quartz and feldspars of the felsic metatuffites by mafic minerals.

Geochemistry

In Table 1 chemical analyses are given of the rock types described above, together with an average analysis of 13 least altered metavolcanites and average analyses of three Svecokarelian older granites: the Horrsjö granite from the western part of Bergslagen, the Hjulsjö granophyre from the central zone and the Yxsjöberg-Ställdalen granite from the northeastern part of Bergslagen.

The average composition of least altered metavolcanites of the Hjulsjö area, approximately 25 km east of Persberg, is considered to be also representative for the initial composition of the metatuffites of the Persberg area.

The Svecokarelian older granites are thought to be the subvolcanic equivalents of the felsic metatuffites (Magnusson, 1940; Oen *et al.*, 1982). Hence there should be a clear chemical similarity between unaltered compositions of these two types of rocks.

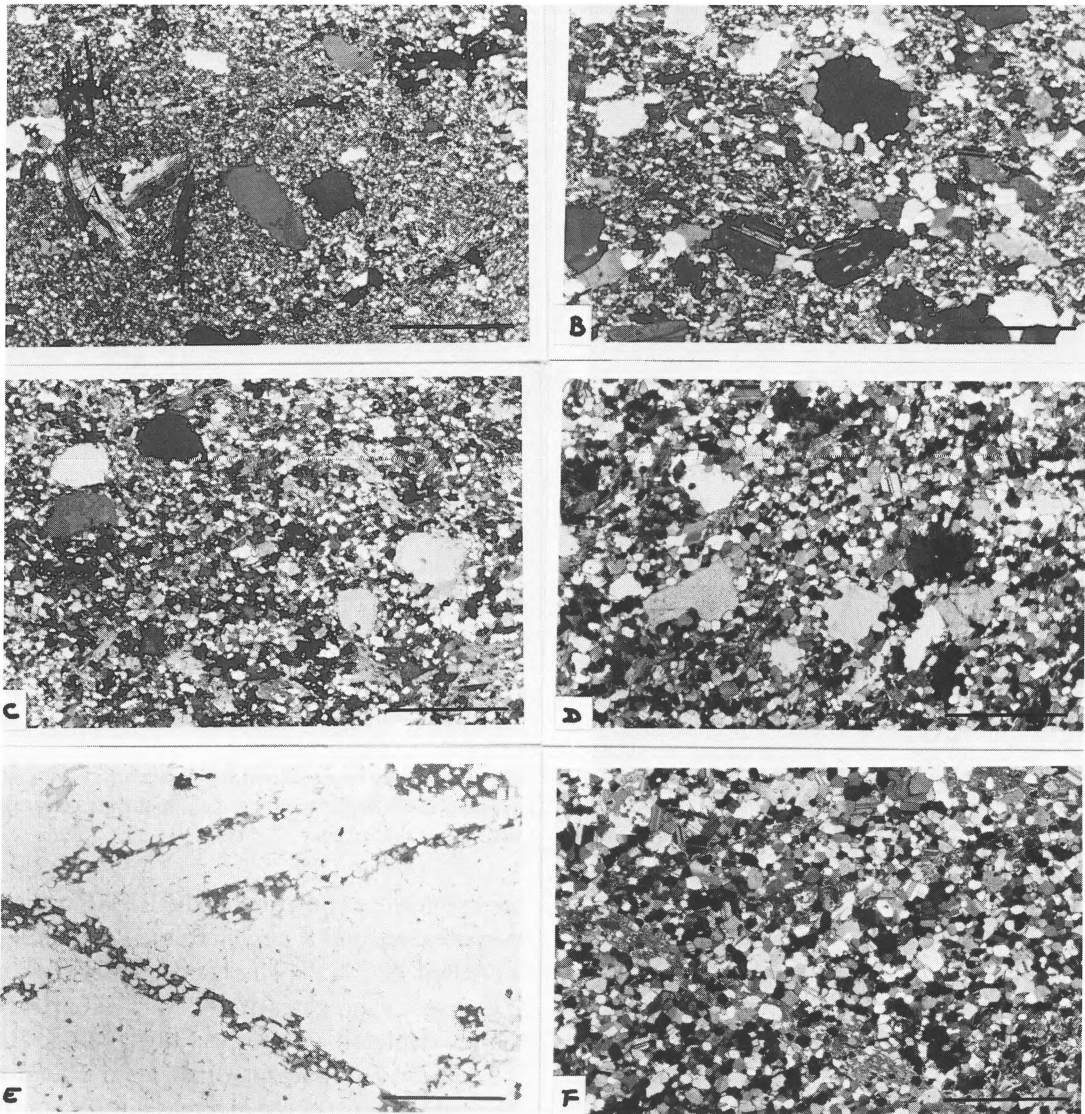


Fig. 3. Photomicrographs of felsic metatuffites showing increasing degree of recrystallization. Scale bar is 1 mm on all photographs. Photographs a–d, f crossed nicols, e plane polarized light. (a) Weakly recrystallized matrix of metatuffite with non-recrystallized pyroclasts; sample 4. A is anthophyllite/gedrite. (b) Same as 3a, but showing somewhat stronger recrystallization of the matrix; pyroclasts are still ubiquitous; sample 2. (c) Moderately recrystallized metatuffite; the matrix already shows a distinct, coarser grained granoblastic texture of quartz and feldspars; few pyroclasts are present; sample 235. (d) Moderately to strongly recrystallized metatuffite; the granoblastic character is still more pronounced and the grainsize further enlarged; only very few pyroclasts have survived; sample 79. (e) and (f) Strongly recrystallized metatuffite; the matrix shows a perfect granoblastic texture, biotite forms typical poikiloblasts; pyroclasts are absent; sample 80/7.

The diagram in Fig. 8 was developed by Hughes in 1973 to separate altered from unaltered rocks based on their Na and K content. Unaltered rocks are believed to plot inside the broad zone depicted in the diagram. The RFMB and mafic aggregates plot outside this 'Hughes Igneous Spectrum', in-

dicating anomalously high Na and K contents caused by alteration processes. The RFM plot in the andesite field which also points to alteration away from the original rhyolitic composition.

Figs. 9a–e illustrate the main chemical effects of the alteration process. Compared to the average



Fig. 4. Strongly recrystallized felsic metatuffite (RFMB) with irregular biotite rich aggregate. Note the vein-like extensions of the dark material and the locally diffuse contacts with the host rock. Exposure 80.

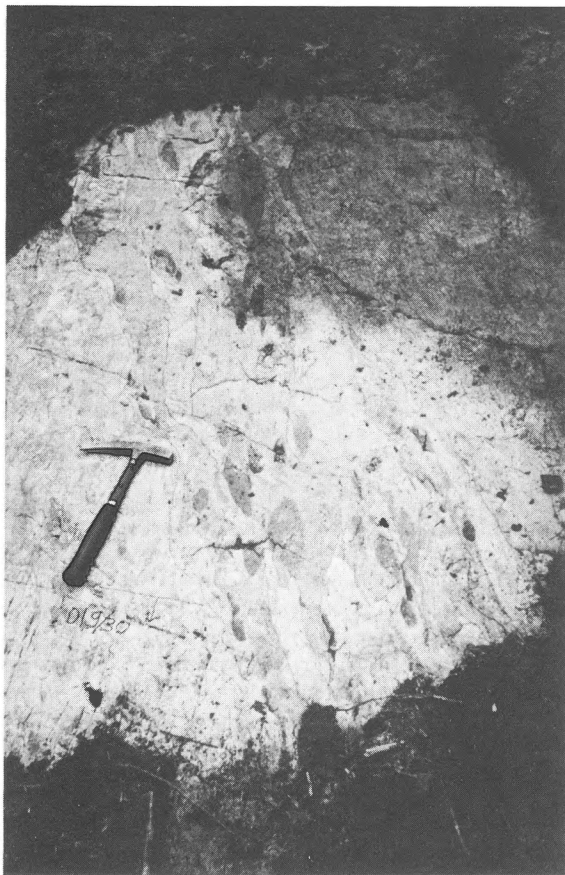


Fig. 5. Vein-like schlieren of moderately recrystallized felsic metatuffites (RFM) containing ellipsoid mafic aggregates; host rock is weakly recrystallized felsic metatuffite. The outline of recrystallization is accentuated with marker lines. Bedding is approximately perpendicular to plane of view. Exposure 36.

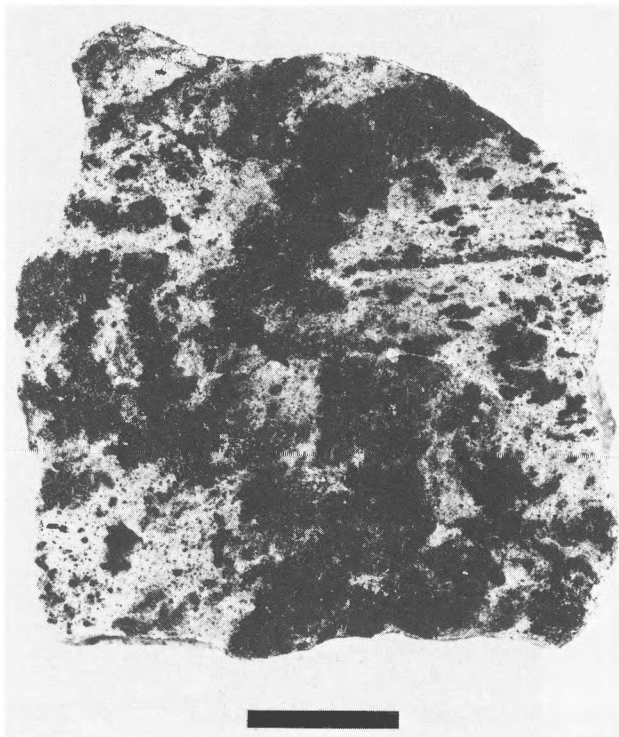


Fig. 6. Strongly recrystallized felsic metatuffite with mafic aggregates consisting of biotite and anthophyllite/gedrite; sample 80/2. Scale bar is 2 cm.

metavolcanite and granites the RFMB are Na, Fe, Mg enriched and K depleted; the RFM are Fe, Mg enriched, K, Na depleted and slightly Si enriched. The mafic aggregates are K, Mg, Fe enriched and Na, Si depleted with respect to RFM and RFMB. Comparison of the major element chemistry of altered and less altered metabasites from the neighbouring Saxå area (Hellingwerf & Oen, 1986) with that of the mafic aggregates reveals unusually high K and low Ca content, and also a somewhat higher Fe and Mg content in the mafic aggregates. Figs. 9d and 9e show that a higher Na content in the rocks generally is accompanied by lower contents of K and Fe + Mg. From Figs. 9a–e it is apparent that the RFMB composition tends to be closer to that of the average metavolcanite than to that of the average granites.

The REE content of the RFMB is somewhat higher than the REE content of the average granites (Fig. 10a). The REE pattern of the average metavolcanite is intermediate between the patterns of RFMB and average granites (Fig. 10a), which is

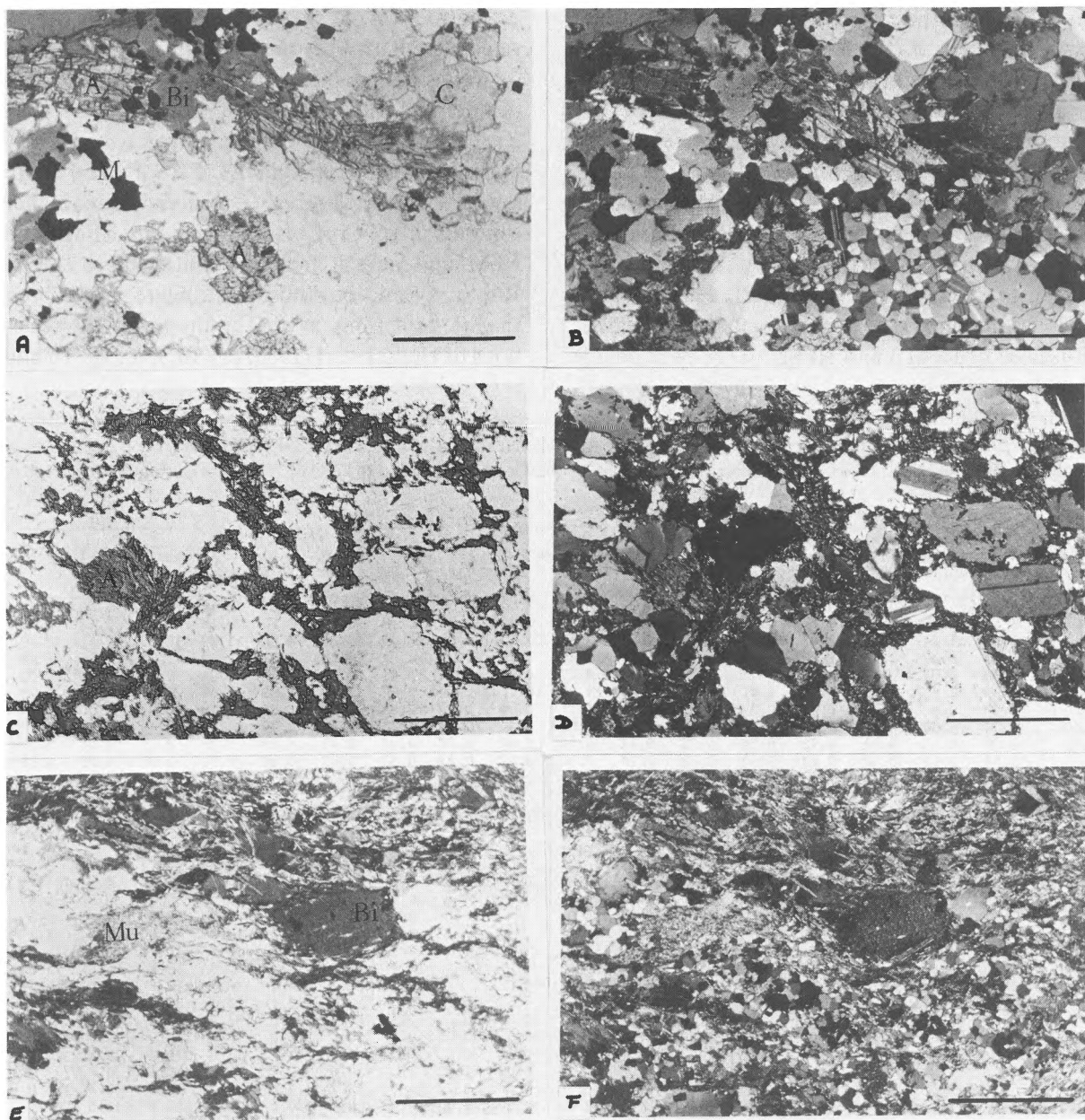


Fig. 7. Photomicrographs showing replacement of quartz and feldspars of recrystallized felsic metatuffites by mafic minerals in samples 80/1, 283 and 36 respectively. Scale bar is 1 mm on all photographs. Figs 7a, c and e plane polarized light; Figs 7b, d and f crossed nicols. (a) and (b) Strongly recrystallized felsic metatuffite (RFMB) containing anthophyllite/gedrite (A), biotite (Bi), cordierite (C) and magnetite (M). (c) and (d) Moderately recrystallized felsic metatuffite (RFM) consisting of quartz and albite grains rimmed with anthophyllite/gedrite (A). (e) and (f) Moderately recrystallized felsic metatuffite (RFM) containing biotite (Bi) and muscovite (Mu); mica content increases towards top of picture.

consistent with the major element characteristics illustrated in Fig. 9. The REE patterns of the RFM overlap with those of the RFMB and the average metavolcanite (Fig. 10b). The REE patterns of the mafic aggregates are either lowered or elevated compared to the RFMB and RFM patterns (Fig. 10c); lowered patterns are also somewhat flattened and slightly reminiscent of the patterns of biotite-schist intercalations occurring in felsic metavolcanites of the Saxå area (Hellingwerf, 1986, p. 41). Elevated patterns show a striking resemblance with those of RFMB and RFM.

Comparison of other trace element contents reveals a similarity between RFMB and RFM, and between average metavolcanite and average granites. RFMB and RFM have higher contents of Zn, Zr, Hf and W than average metavolcanite and average granites; their contents of Rb, Ba and Sr are lower. The mafic aggregates generally have higher contents of Sc, Cr, Co and Ni than the RFMB and RFM, and most of them also contain more Ti, Zn, Rb, Sr, Cs and Ba. Most mafic aggregates exhibit similar depletions as the biotite-schist intercalations of Hellingwerf (1986, p. 43ff.): Y, W, Th and

Table 1. Major and trace element contents of moderately and strongly recrystallized felsic metatuffites (RFM and RFMB respectively), mafic aggregates, average of least altered metavolcanites (avMvt, taken from Baker & De Groot, 1983) and averages of Svecofennian granites (avHoG, avHuG, avYxG, taken from Baker, 1985a). *: total iron is calculated as Fe₂O₃; **: Zr/Ti is calculated as Zr/(100 × TiO₂).

sample	RFMB				Mafic Aggregates						RFM			Average Compositions				
	80/1A	80/1B	80/2	80/5	23B	80/5A1	80/5A2	80/5A3	82A	281/1	79	285	301L	avMvt	avHoG	avHuG	avYxG	
wt. %																		
SiO ₂	75.63	75.89	64.60	79.51	49.60	43.71	46.63	48.23	42.05	48.90	80.19	79.43	82.02	76.54	77.75	75.85	76.90	
TiO ₂	0.14	0.15	0.23	0.12	0.51	0.57	0.60	0.60	0.39	0.23	0.18	0.21	0.20	0.15	0.12	0.12	0.13	
Al ₂ O ₃	11.05	11.24	13.20	12.67	18.30	16.32	14.81	13.99	21.43	8.92	10.42	10.86	9.86	11.89	12.09	12.61	12.30	
Fe ₂ O ₃ *	6.52	6.24	9.45	1.13	15.20	13.35	14.15	14.40	14.18	34.70	2.93	3.25	1.74	1.52	1.73	1.26	1.49	
MnO	0.06	0.06	-	-	-	0.09	0.14	0.17	0.07	-	0.01	0.02	-	0.01	0.02	0.01	0.02	
MgO	2.87	2.71	4.80	0.75	6.01	14.88	13.95	13.20	10.42	5.90	2.08	1.20	1.69	0.56	0.21	0.13	0.19	
CaO	0.06	0.06	0.13	0.10	0.39	0.61	0.83	1.11	0.04	0.10	0.08	0.09	0.02	0.75	0.05	0.55	0.66	
Na ₂ O	4.34	4.56	4.20	6.55	0.49	1.56	1.44	1.50	0.44	0.47	3.24	3.17	2.70	4.37	3.49	3.80	3.56	
K ₂ O	0.34	0.39	0.61	0.72	6.25	5.73	5.11	4.74	8.89	0.32	0.84	2.41	1.28	2.33	4.17	4.34	4.10	
P ₂ O ₅	0.04	0.03	0.03	0.02	0.24	0.12	0.10	0.90	0.02	0.03	0.03	0.02	0.02	0.24	0.03	0.03	0.03	
LOI	-	-	1.62	-	1.00	-	-	-	1.77	.31	-	-	-	-	-	-	-	
Total	101.05	101.33	98.88	101.57	97.99	96.93	97.76	98.84	99.70	99.88	100.00	100.68	99.53	98.36	99.65	98.70	99.38	
ppm																		
Sc	4.2	3.8	6.5	2.3	31.8	40.7	46.2	48.7	10.6	6.1	4.2	6.4	7.8	5.1	3.7	3.6	2.9	
Cr	12.5	8.2	-	8.7	61.9	1323.0	1159.0	1142.0	15.9	24.0	8.5	7.8	7.8	4.5	12.3	4.5	25.1	
Co	9.9	7.3	2.0	4.8	26.7	51.0	49.6	47.5	4.9	2.3	13.2	9.9	9.9	10.4	0.6	9.3	1.4	
Ni	3.4	3.7	2.0	1.4	45.0	145.0	134.0	124.0	-	-	2.2	3.4	1.5	3.8	3.3	2.6	3.3	
Cu	4.1	4.7	-	2.4	12.0	1.7	1.8	4.4	-	-	3.5	2.6	2.3	6.3	8.6	6.3	7.2	
Zn	90.0	85.5	150.0	15.4	170.0	140.0	147.0	151.0	97.0	200.0	27.6	28.6	17.0	12.7	18.7	13.0	13.6	
Ga	19.7	19.9	-	17.4	-	20.9	19.3	19.5	-	-	16.1	17.9	14.4	15.6	16.8	14.6	13.6	
Rb	15.0	16.2	20.0	14.5	10.0	206.0	185.0	167.0	370.0	-	28.4	58.3	31.1	49.7	110.8	75.5	112.3	
Sr	10.7	11.2	-	21.1	-	30.8	30.5	35.7	-	-	17.5	13.0	10.4	62.0	29.9	62.7	42.4	
Y	75.4	77.7	140.0	53.5	-	24.2	33.2	34.4	110.0	20.0	59.3	49.1	48.5	51.4	54.5	39.5	42.4	
Zr	201.0	238.0	350.0	231.0	20.0	57.3	257.0	331.0	530.0	280.0	310.0	332.0	264.0	198.8	158.8	149.6	120.2	
Nb	16.9	20.0	40.0	-	20.0	7.2	9.8	11.0	50.0	30.0	3.7	6.1	-	11.0	19.4	10.4	9.9	
Sb	-	-	-	-	0.02	-	-	-	0.03	-	-	0.6	0.7	-	0.6	0.7	1.0	
Cs	-	0.9	1.8	0.4	1.5	6.3	6.4	6.1	4.8	0.7	-	0.7	1.0	1.1	0.6	0.4	0.9	
Ba	56.6	37.3	110.0	56.0	1030.0	444.0	436.0	442.0	510.0	170.0	215.0	488.0	140.0	873.6	653.8	841.9	738.5	
La	50.7	41.9	63.2	81.7	9.1	15.8	21.1	26.8	86.1	52.6	47.5	50.3	34.4	56.3	52.6	42.4	44.0	
Ce	98.4	93.0	136.0	159.4	13.2	35.2	40.8	57.1	164.3	79.5	95.0	102.5	62.9	98.0	92.7	73.1	74.2	
Sm	13.5	11.6	14.0	11.4	1.7	3.9	4.9	5.8	18.1	7.7	9.6	10.5	6.7	9.8	9.4	6.2	6.8	
Eu	1.7	1.6	1.5	1.4	0.8	0.9	1.2	1.2	2.0	2.1	1.9	1.9	1.6	1.5	0.7	0.8	0.7	
Tb	2.4	2.3	3.0	1.4	0.3	-	-	1.5	3.9	1.7	1.8	1.4	1.7	1.3	1.4	0.9	1.0	
Yb	8.4	8.4	13.2	6.3	2.1	1.9	3.7	4.5	10.4	5.4	7.4	6.8	6.5	5.3	5.6	3.8	4.6	
Lu	1.5	1.5	2.2	1.0	0.3	0.5	0.8	1.1	1.9	0.9	1.3	1.2	1.1	0.9	1.0	0.7	0.8	
Hf	8.1	9.0	12.0	8.9	1.4	1.3	7.4	9.9	16.7	8.2	11.4	11.0	9.1	6.2	6.8	5.0	5.0	
Ta	3.4	3.4	3.0	1.2	-	0.8	-	1.9	4.1	1.0	1.5	1.2	1.2	1.0	1.3	0.9	1.4	
W	86.6	54.1	6.0	43.0	3.3	-	10.3	12.9	9.2	3.0	114.0	94.3	98.9	-	2.8	68.6	4.2	
Pb	11.3	12.3	2.0	7.0	2.0	8.1	8.6	8.5	-	-	10.8	14.9	6.3	6.9	13.5	8.4	11.1	
Th	20.1	19.2	21.0	18.0	2.3	4.9	6.4	8.7	33.9	12.0	17.3	15.8	12.1	12.3	18.7	14.7	15.6	
U	6.5	3.2	10.2	-	2.4	-	4.4	5.0	11.1	2.6	6.1	6.2	4.4	3.6	4.5	3.4	3.3	
Zr/Ti**	14.4	15.9	15.2	19.3	0.4	1.0	4.3	5.5	13.6	12.2	17.2	15.8	13.2	13.3	13.2	12.5	9.2	
Y/Zr	0.4	0.3	0.4	0.2	-	0.4	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.4	

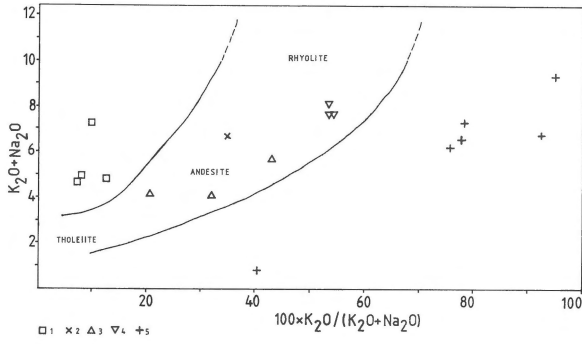


Fig. 8. The Igneous Spectrum diagram of Hughes (1973) with plots of: 1 = RFMB, 2 = average metavolcanite, 3 = RFM, 4 = average granites, 5 = mafic aggregates. See text for explanation.

total REE are depleted; Hf and U characteristics are ambiguous. Mafic aggregate 82A however, shows enrichments in Y, total REE, Hf, Th and U.

In Table 1 the ratios $Zr/100Ti$ and Y/Zr are given as additional illustration of trace element mobility. Despite variabilities within the various groups of rocks it is apparent that both ratios generally are lower in the mafic aggregates than in metavolcanic rocks and granites. In altered and less altered metabasites from the Saxå area (Hellingwerf & Oen, 1986) $Zr/100Ti$ in most cases is much lower and Y/Zr is somewhat higher than in the mafic aggregates.

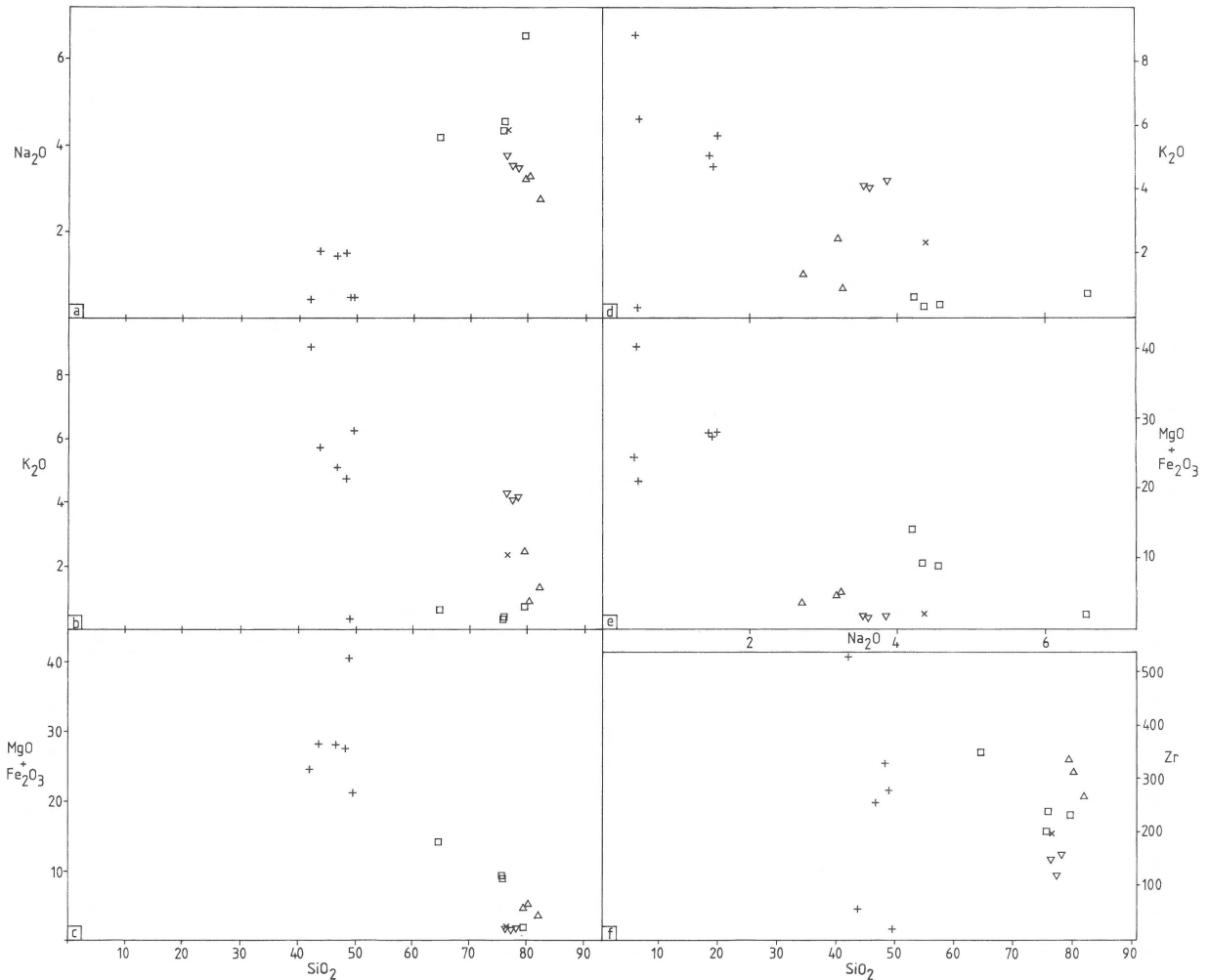


Fig. 9. Variation diagrams illustrating some important chemical characteristics of the various rock types. Symbols as in Fig. 8. See text for explanation.

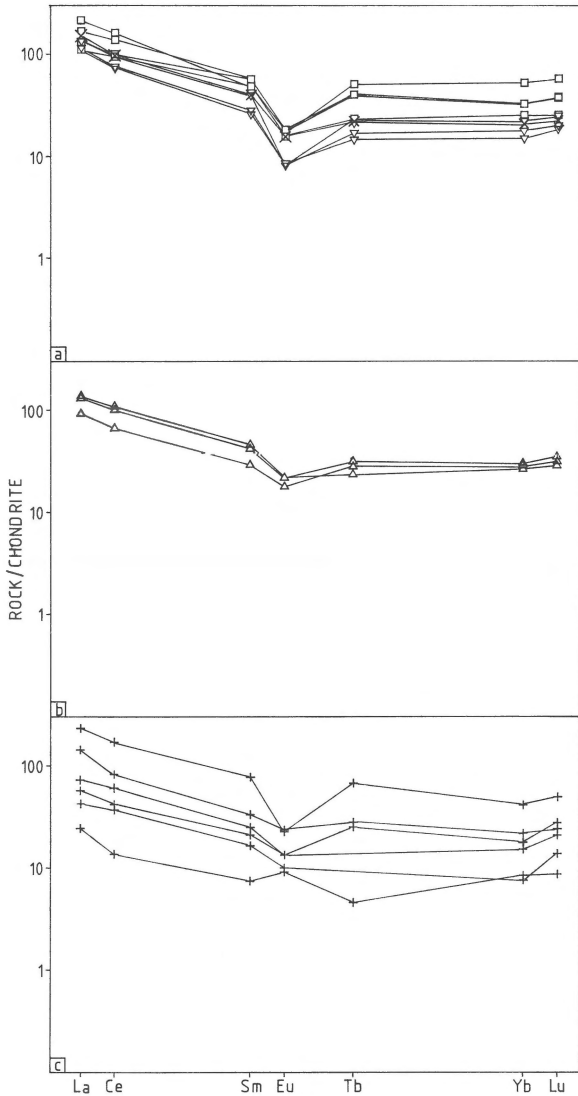


Fig. 10. Chondrite normalized rare earth element patterns of the various rock types (normalizing factors $\times 1.5$ from Evenson *et al.*, 1978). Symbols as in Fig. 8. See text for explanation.

Zircons

Zircons in the RFM, RFMB and mafic aggregates show a wide variety in morphology (Fig. 11). Most solitary grains are zoned with euhedral (Figs 11a, b) or sub- to anhedral (Fig. 11c) cores. Overgrowths may be euhedral, fully developed (Figs 11a, b) or sub- to anhedral, partially developed (Fig. 11c). Clusters of anhedral grains are common (Figs 11a,

d to h); some clustered grains have a mutual overgrowth (Fig. 11d). Zircon grains may be typically embayed (Figs 11f, h), others have sub- to euhedral outgrowths (Figs 11i, j). Many zircon grains are typically located on the rims of quartz and albite grains (e.g. Figs 11d, e), others are enclosed in biotite grains and here they always exhibit a pleochroic halo (Figs 11f, i). Some zircon grains are found associated with apatite and magnetite grains (Fig. 11f).

Some petrographic observations suggest that at least part of the zircons present in the RFM, RFMB and mafic aggregates have a non-magmatic origin. (1) The location of zircon grains between quartz and albite grains indicates zircon growth during or after recrystallization of the host rocks, e.g. Figs 11d and e show good evidence for metasomatic growth of zircon and in Figure 11d zircon grains seem to have grown along an already existing corner of an albite grain. (2) Clusters of zircon grains in magmas will probably be fragmented by an (explosive) extrusion process. Hence, such clusters are not to be expected in the pyroclastic rocks of the Persberg area, especially since broken zircon grains have been found in the metatuffites. Moreover, larger aggregates of closely spaced grains that are not in contact with each other (Figs 11g, h) would most certainly have been dispersed during extrusion. (3) The association of zircon with apatite and magnetite points to metasomatic formation of zircon. In the metavolcanic rocks around Persberg magnetite is commonly formed by sub-seafloor hydrothermal processes (see e.g. Oen *et al.*, 1982). In addition, mobility of Zr is indicated by its enrichment in the recrystallized felsic metatuffites and the mafic aggregates as compared to the average metavolcanite and granites (Fig. 9f).

An attempt was made to discriminate between primary and possible secondary zircon. Cores and rims of 23 larger zircon grains from RFMB samples were analyzed for major and trace elements and REE with the electron microprobe. No significant chemical differences were found between zircon cores and rims. Nevertheless analyses of four zircons in Figures 11a, b, c are given for completeness (Table 2).

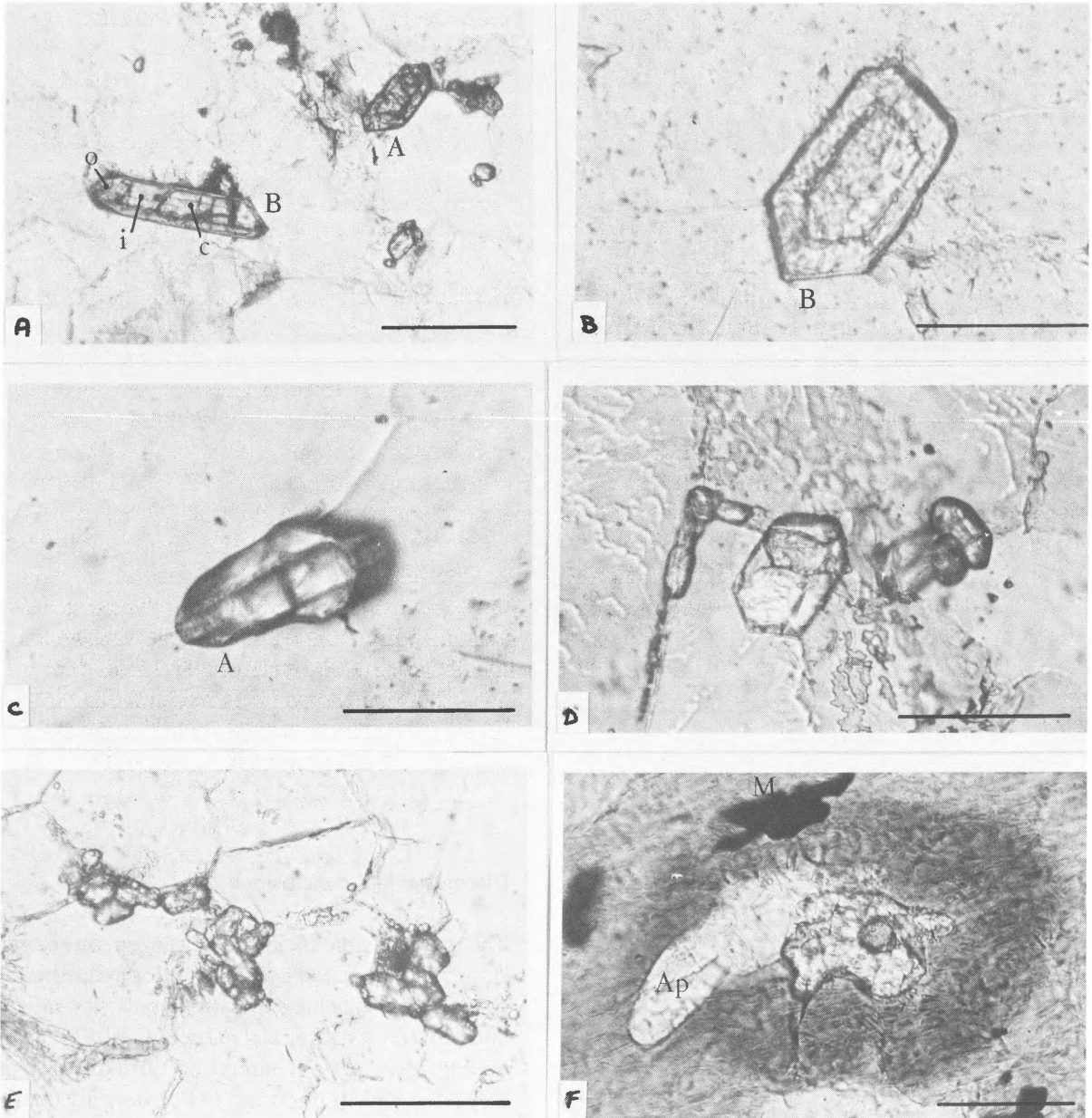
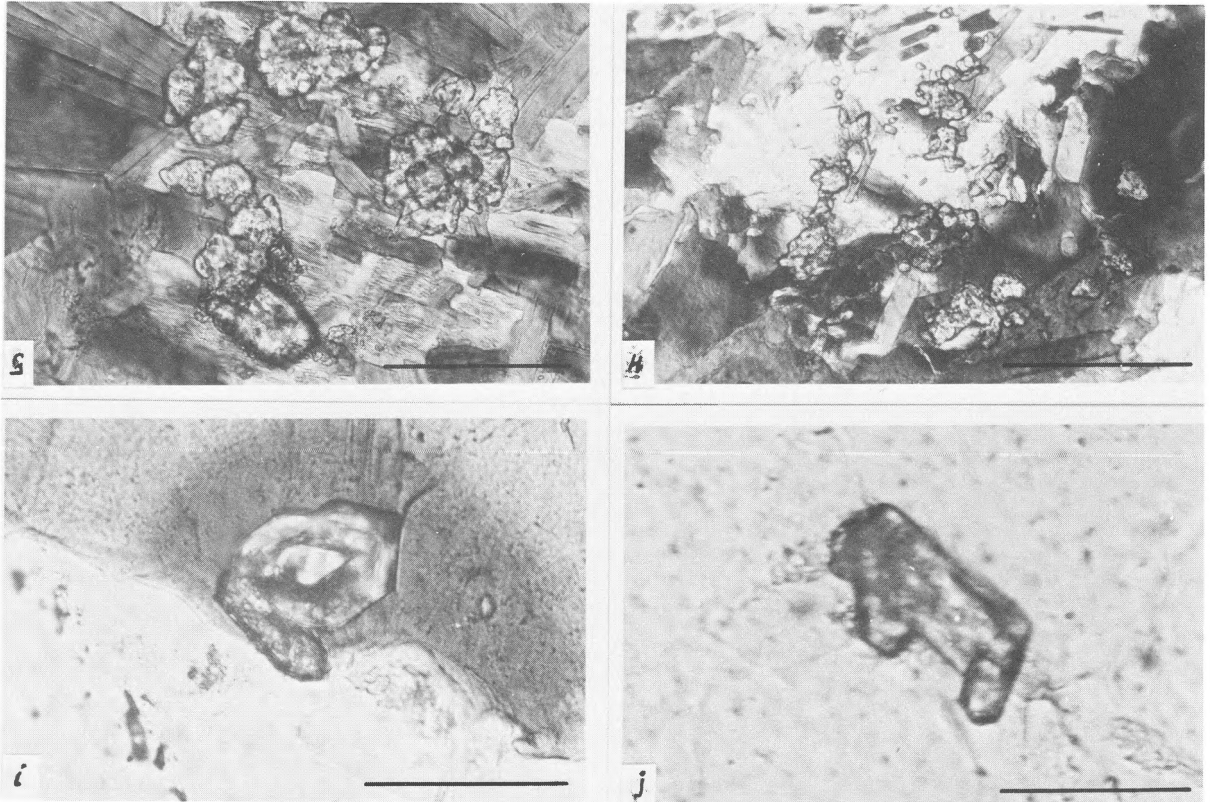


Fig. 11. Photomicrographs of zircons from moderately (Fig. 11h) and strongly (Figs 11a–e, i and j) recrystallized felsic metatuffites, and mafic aggregates (Figs 11f and g), showing different types of morphology. All photographs with plane polarized light. (a) Large grains with euhedral cores and euhedral overgrowths together with two clusters of smaller grains. E-probe analyses of grain A and B are given in Table 2; c = core, i = inner rim, o = outer rim; sample 80/6. Scale bar is 0.15 mm. (b) Grain with euhedral core and euhedral overgrowth. E-probe analysis is given in Table 2 (grain B); sample 80/5. Scale bar is 0.05 mm. (c) Grain with subhedral core and anhedral, partially developed overgrowth. E-probe analysis is given in Table 2 (grain A); sample 80/5. Scale bar is 0.05 mm. (d) Two intergrown anhedral grains with a mutual euhedral overgrowth, and two clusters of intergrown, small anhedral grains. Note position of one cluster on rim of albite grain; sample 80/6. Scale bar is 0.05 mm. (e) Clusters of intergrown, small anhedral grains, typically located between quartz and albite grains; sample 80/6. Scale bar is 0.08 mm. (f) Irregular, embayed grain enclosed in biotite and associated with apatite (Ap) and magnetite (M); sample 80/5A. Scale bar is 0.06 mm. (g) Cluster of partially intergrown, anhedral grains; grain on righthand-side encloses anhedral core; sample 82A. Scale bar is 0.09 mm. (h) Cluster of anhedral embayed grains, partially intergrown and partially enclosed in biotite; sample 79. Scale bar is 0.30 mm. (i) Euhedral, zoned grain with subhedral overgrowth, enclosed in biotite; sample 80/6. Scale bar is 0.06 mm. (j) Subhedral grain with subhedral overgrowths; sample 80/6. Scale bar is 0.05 mm.



(Fig. 11. Continued)

Table 2. Electron microprobe analyses of 4 zircon grains (Figs. 11a, b, c). Detection limits (wt%): Al and Fe: 0.02, Ca and P: 0.01, Hf: 0.08, Y: 0.035; det. lim. (ppm): Th: 263, U: 344, Dy: 401, Er: 420, Yb: 325. *: total iron is calculated as FeO.

sample	80/5 grain A		80/5 grain B		80/6 grain A		80/6 grain B		
	core	rim	core	rim	core	rim	core	inner rim	outer rim
wt. %									
SiO ₂	32.70	32.30	32.20	32.60	32.50	32.60	—	29.60	32.30
Al ₂ O ₃	0.14	0.09	0.09	0.09	0.09	0.09	0.07	0.25	0.09
FeO*	0.04	0.04	—	—	0.04	0.04	0.05	0.86	0.05
CaO	—	—	—	0.05	—	—	—	1.52	—
P ₂ O ₅	—	0.16	0.08	0.19	0.05	0.19	0.08	0.31	0.28
ZrO ₂	65.30	64.70	65.00	64.60	65.20	65.20	65.80	59.40	60.40
HfO ₂	0.81	1.17	0.87	1.44	1.02	1.60	0.89	1.42	1.54
Y ₂ O ₃	0.49	0.49	0.23	0.22	0.20	0.16	0.39	0.97	0.45
Total	99.48	98.95	98.47	99.19	99.10	99.88	67.28	94.33	95.11
ppm									
Th	—	—	—	—	—	—	—	1406	527
U	—	529	970	882	529	970	529	3085	1499
Dy	—	784	—	—	—	—	—	1046	—
Er	1312	1487	787	875	—	787	612	962	787
Yb	527	790	615	790	351	790	878	1756	527

Discussion and conclusions

The metavolcanic rocks of Bergslagen, after deposition, were affected by sub-seafloor hydrothermal processes, producing a regional subdivision into Na and K altered rocks, and subsequent local, cross-cutting Mg and/or K alteration during which the RFM and RFMB northeast of Persberg are considered to have been developed. The RFMB were previously described as 'extremely albitic granite' (Magnusson & Granlund, 1928). This term implies an albite rich rock, which nonetheless contains, in recognizable form, the essential 'granitic' minerals quartz and K-feldspar, and which still shows granitic textures. The RFMB cannot be classified as granite because:

1. no granitic textures were found, the texture is metamorphic;

2. K-feldspar is absent, even in albitized form;
3. there is a gradual transition from weakly recrystallized metatuffites through RFM to RFMB;
4. a close relationship between RFM and RFMB is indicated by their strong textural and mineralogical similarity.

The geochemical data are less convincing. Although in most variation diagrams the RFMB plot closer to the average metavolcanite than to the average granites, a compositional relationship between the RFMB and average metavolcanite is obscured by metasomatic alteration of the RFMB. The REE plots on the other hand, provide good evidence for a compositional link between the RFMB and least altered metavolcanites.

The petrographic and geochemical data also suggest that the mafic aggregates are produced by hydrothermal alteration of RFM and RFMB. The veins in and diffuse contacts with the host rock are strong evidence for a hydrothermal metasomatic origin of the mafic aggregates. Replacement of felsic minerals by mafic minerals and the occurrence of transitional types of rocks between recrystallized felsic metatuffites and mafic aggregates clearly illustrate that the former are the parent rocks of the latter. Local association of mostly ellipsoid mafic aggregates with schlieren of recrystallized rocks renders a sedimentary origin highly improbable. In the Hughes diagram mafic aggregates plot in the K enriched field, indicating an anomalous, non-magmatic composition and a metasomatic provenance. From discrepancies in major element chemistry and trace element ratios between mafic aggregates and both altered and less altered metabasites from the Saxå area it is apparent that the mafic aggregates are not altered mafic igneous rocks. Lowered REE patterns of mafic aggregates are similar to those of the biotite schists of Hellingwerf (1986), for which a hydrothermal metasomatic origin was also suggested (Hellingwerf, *op. cit.*, p. 25ff.). In addition, elevated REE patterns of mafic aggregates show a clear resemblance to the patterns of the RFM and RFMB, which is yet another indication for a genetic relation between these two types of rocks.

The recrystallization of the felsic metavolcanic

rocks northeast of Persberg was not a strictly thermal process but was related to percolation of hydrothermal fluids which also caused alteration of the metatuffites. This can be concluded from (1) the irregular, locally vein-like distribution of recrystallized rocks and (2) the association of metasomatic phenomena, particularly the mafic aggregates, with recrystallized rocks.

The morphological features of zircons in recrystallized felsic metatuffites and mafic aggregates, and trace element characteristics of these rocks illustrate that significant mobility of trace elements accompanied hydrothermal alteration of the metavolcanic sequence. Balashov & Krigman (1975) and Alderton et al. (1980) have suggested that fluorine is a possible Zr transporter under hydrothermal conditions. Zr may also be transported as PO_4^{3-} -complexes (Gieré, 1986). Precipitation of (fluor-)apatite would release Zr from the fluorine and phosphorus complexes and this may lead to crystallization of zircon.

It is suggested that circulating hydrothermal fluids that caused alteration and recrystallization of the felsic metavolcanic rocks, were driven by the nearby ascending Horrsjö granite. The process is thought to have been enhanced by the Hyttsjö gabbro-tonalite-granite which intruded shortly after the Horrsjö granite.

Acknowledgements

The authors gratefully acknowledge the advice and support of J. Baker during the preparation of this paper. J.A. Winchester, I.S. Oen, R. Hellingwerf and an anonymous reviewer gave critical comments on the manuscript. F. Beunk and Th. Van Meerten are thanked for carrying out whole rock analyses. J. Wiersma provided photographs for Figs 3, 7 and 11. Sincere thanks are due to the Geological Survey of Canada for producing Figs 1, 2, 4, 5 and 6. The authors also wish to express their gratitude to W. Lustenhouwer of ZWO-WACOM (working group for analytical chemistry of minerals and rocks subsidized by the Netherlands Organization for the Advancement of Pure Research), for carrying out electron microprobe analyses of zir-

cons at the electron microprobe laboratory of the Instituut voor Aardwetenschappen, Vrije Universiteit, Amsterdam.

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