

PEGMATITE VEINS AND THE SURROUNDING ROCKS

IV. Genesis of a discordant pegmatite vein, St. Hansholmen, Risør, Norway

BY

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Abstract: A detailed petrographic study was made of the banded gneiss surrounding a pink, microcline rich, discordant pegmatite vein crossing the western end of the island St. Hansholmen near Risør, southern Norway. The banded gneiss is part of the pre-Cambrian Kongsberg—Bamble formation and consists of alternating, quite regular bands of amphibolite and granodioritic to quartz dioritic gneiss.

Modal analyses of five series' of samples of the gneiss and one of the amphibolite reveal a K metasomatism of the gneiss adjacent to the pegmatite vein, the intensity of which diminishes with distance from the vein. This is rendered even clearer by the calculated cation percent compositions of the samples. The amphibolite has been very little if at all affected by the emplacement of the vein.

Volume change calculations indicate that the material which constitutes the vein entered into a crack across the banded gneiss. It is concluded that the material which filled the crack was derived from the nearby granulite facies rocks.

Temperature determinations using the feldspar thermometer, both of the pegmatite and the gneiss, indicated that the pegmatite formed at a higher

temperature than the surrounding gneiss (ca. 570° C vs. 460° C), although lack of equilibrium between co-existing feldspars in the gneiss near the vein makes it impossible to determine temperature differences in the gneiss as related to distance from the vein, if such existed.

The nature of the pegmatite forming fluid is considered. Four possibilities are discussed: 1) magma; 2) hydrothermal solution; 3) fluidized gas-solid system; and 4) disperse phase of relatively high energy particles. Possibility 2) is discarded because of the large quantity of water which would be required and because 10 km³ of rock would have had to have been «dehydrated» to yield solution sufficient to form a vein 500 m × 2 m × 500 m. Possibly 3) is not advocated because none of the characteristic features of veins formed by such a system have been found. None of the observations which were made are found to constitute either decisive proof for or evidence fatal to possibilities 1) and 4); no conclusion can be drawn except that the vein formed from a fluid (magma or disperse phase) «injected» into a crack in the banded gneiss.

Introduction

In this paper the pink, microcline rich pegmatite crossing the western end of the island St. Hansholmen, which lies about 1 km from the town Risør on the south coast of Norway, is described; the changes in and the relations of the vein to the surrounding banded gneiss are discussed. This pegmatite vein was mentioned in the first paper of this series (REITAN, 12), although discussion of the genesis of the vein was deferred until such time as detailed studies of the pegmatite and the immediately adjacent rocks had been made. The petrography and structure of the banded gneiss on St. Hansholmen and the genesis of the very small, white, plagioclase pegmatites within and between the boudins of the amphibolite bands have been discussed previously (REITAN, 12). The most detailed geological map of the Søndeled district (including Risør) is by J. A. W. BUGGE (3, fig. 3, p. 13). Other literature pertinent to the geology of the Kongsberg—Bamble formation has been listed previously in this series (REITAN, 12).

As is the case on other parts of St. Hansholmen, the dips in the area near the pink pegmatite crossing the western tip of the island are essentially vertical, as are the dips of the contacts between the pegmatite vein and the banded gneiss. The distribution of the rock types within the area under consideration and the locations at which samples were taken and upon which the petrographic and chemical data are based are shown in the map, fig. 1.

LEGEND



Pink pegmatite

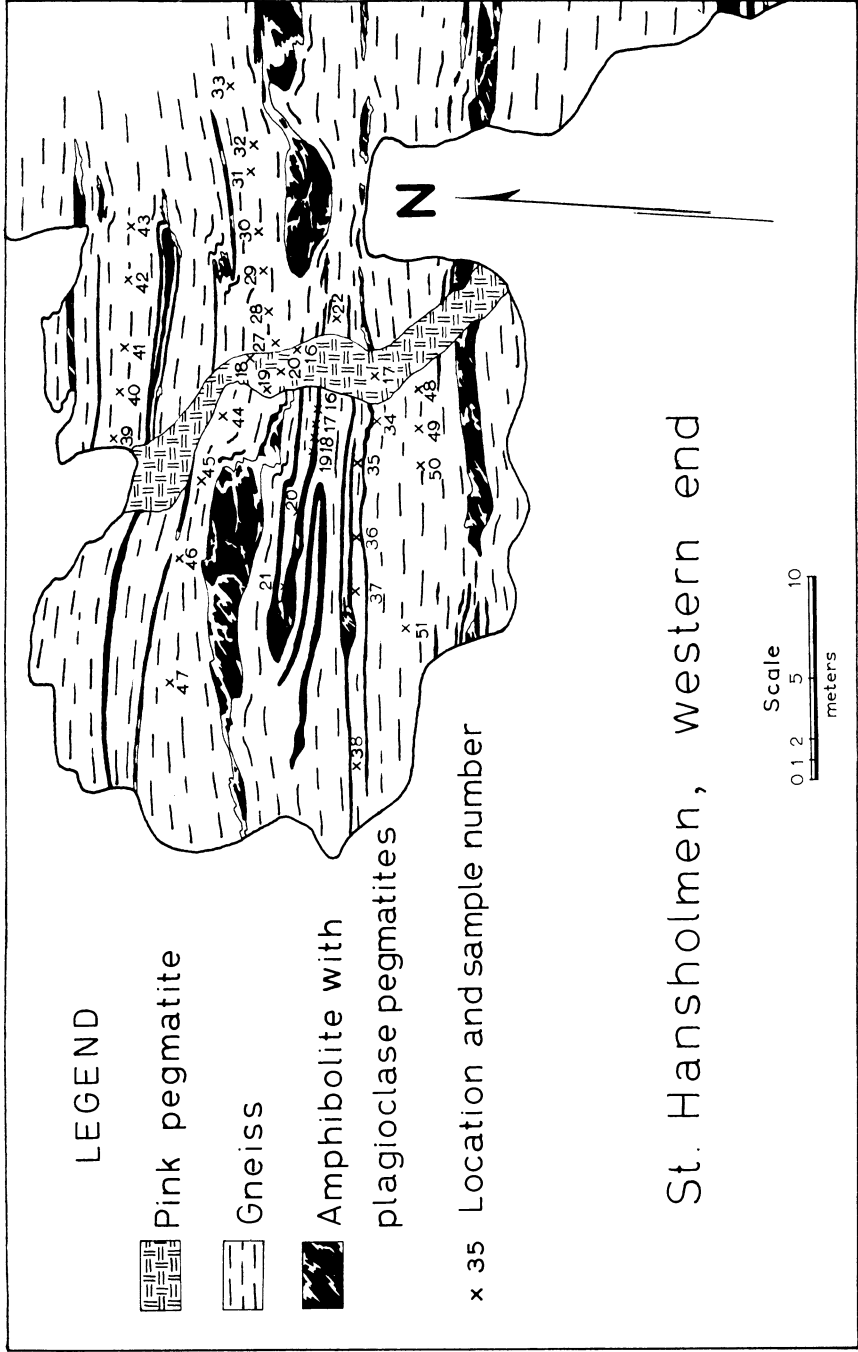


Gneiss



Amphibolite with
plagioclase pegmatites

x 35 Location and sample number



St. Hansholmen, western end

Petrography

Petrographic descriptions of the gneissic and amphibolitic bands of the banded gneiss and of the small plagioclase pegmatites have been given earlier (REITAN, 12); there the characteristic features and variations of these rocks are discussed. The banded gneiss at the western end of St. Hansholmen is essentially similar to that of the rest of the island; the petrographic descriptions here will be primarily for the purpose of elucidating changes in the gneiss as related to distance from the pegmatite vein.

PEGMATITE

The cross-cutting, pink pegmatite vein at the western end of the island varies between 1 and 3 meters in width. Microcline occurs in crystals up to 10 cm in largest dimension; it contains very fine perthite lamellae. Biotite occurs in plates up to ca. 4 cm. Plagioclase occurs in unzoned grains up to 2 cm. Quartz occurs in small grains graphically intergrown in microcline. Hornblende has been seen in a few grains up to 2 cm long. Microcline is the overwhelmingly dominant mineral in the pegmatite vein.

Changes in the composition of the feldspars in the pegmatite with distance from the nearest boundary have been observed. Microcline from three samples of the pegmatite has been analyzed for K_2O and Na_2O : from sample ÖP19 (ca. 10 cm from the boundary) it contains 80.7 Or and 19.3 Ab (molecular proportions); from ÖP18 (ca. 40 cm from the boundary) it contains 79.8 Or and 20.2 Ab; from ÖP17 (ca. 120 cm from the boundary) it contains 78.0 Or and 22.0 Ab. The plagioclase from samples ÖP16, ÖP18, and ÖP19 (all within 50 cm of the vein boundary) contains 31 An and 69 Ab while the plagioclase from samples ÖP17 and ÖP20 (both about at the center of the vein) contains 27 An and 73 Ab. In other words, both feldspars become more Na rich towards the center of the vein.

The triclinicity of the microcline from three samples from the pegmatite was determined (ÖP17–19). It was found to be very high (see table 2), indicating a high degree of Si–Al order in the microcline lattice. No differences other than those attributable to experimental error could be detected.

No zoning, either in terms of grain size, textural relations, or mineralogy could be observed in the pegmatite, except just at the vein boundaries where the pegmatite becomes quite abruptly more fine-grained, although there is no line of demarkation. The contacts with the gneiss are gradational over a few centimeters, but against the amphibolite bands they are absolutely sharp.

BANDED GNEISS

The banded gneiss consists of dark bands of amphibolite and light bands of gneiss of granodioritic to quartz dioritic composition. The light bands are generally thicker than the dark bands, though both are quite variable. Within the dark bands there are numerous, small, white, plagioclase pegmatites. White, plagioclase pegmatites are also frequently found between boundaries of the amphibolite bands (cf. map and description, REITAN, 12).

The gneissic bands near the pegmatite vein contain the following minerals: quartz, always; plagioclase, always; microcline, almost always though in highly variable amounts; biotite (partly altered to pennine), always; zircon, always; opaques (mostly magnetite), almost always; garnet, sometimes; apatite, sometimes; muscovite, rarely; and epidote, rarely. The amphibolite contains hornblende, always; plagioclase, always; biotite (partly altered to pennine), always; opaques (mostly magnetite), always; apatite, always; and quartz, almost always.

Five series' of samples from gneissic bands and one from an amphibolite band were taken. Modal analyses of these samples were made in order to determine the quantitative mineralogical variations in the rocks surrounding the pegmatite vein as a function of distance from the vein. The results of these modal analyses are presented in table 1 and graphically in figs. 2 to 7. For the locations of these samples see the map, fig. 1.

Certain general trends are apparent and some of the deviations from regularity can be accounted for.

In all of the series' from the gneiss the amount of microcline is greatest nearest the pegmatite vein. The amount of quartz seems to bear no consistent relationship to distance from the vein. The same can be said of biotite. The amount of plagioclase varies essentially

Table 1 Modal analyses of thin-sections

Sample no.	An ¹		Plagioclase		Quartz	Micro-cline	Biotite (+ chlorite)	Muscovite	Horn-blende	Opagues	Zircon	Garnet	Apatite	Epidote
	Total	Albite	Anorthite											
ÖG 22	20	19.4	15.5	3.9	43.2	28.0	9.2	—	—	—	—	—	—	—
27	20	15.2	12.2	3.0	43.1	33.9	7.7	—	—	—	—	—	—	—
28	27	44.4	32.4	12.0	47.2	1.7	5.1	1.5	—	—	0.1	—	—	—
29	30	43.2	30.2	13.0	42.0	11.6	2.8	0.3	—	—	0.1	—	—	—
30	30	33.9	23.7	10.2	42.2	17.8	6.0	—	0.1	—	—	—	—	—
31	24	35.0	26.6	8.4	40.6	18.8	5.6	—	—	—	—	—	—	—
32	29	50.3	35.7	14.6	38.7	5.0	5.9	—	—	—	—	—	—	—
33	30	36.7	25.7	11.0	47.1	8.6	7.5	—	—	—	0.1	—	—	—
34	20	30.6	23.9	6.7	45.7	18.1	5.5	—	—	—	—	—	—	—
35	29	47.3	33.8	13.5	43.9	2.6	5.5	—	—	—	0.4	0.2	—	—
36	32	49.1	33.4	15.7	45.5	0.4	4.5	—	—	—	0.5	—	—	—
37	20	46.8	37.4	9.4	45.3	—	6.8	—	—	—	0.7	0.1	0.1	—
38	22	51.3	40.0	11.3	42.7	0.7	4.8	—	—	—	0.5	—	—	—
39	25	20.2	15.2	5.0	42.0	30.0	7.0	—	—	—	0.2	0.5	—	—
40	28	28.3	20.4	7.9	43.7	17.8	9.7	—	—	—	0.2	0.2	0.1	—
41	29	30.8	21.9	8.9	43.7	18.9	6.0	—	—	—	0.2	0.3	—	—
42	30	31.0	21.7	9.3	44.1	19.7	4.8	—	—	—	0.1	—	—	—
43	29	36.4	25.9	10.5	40.9	13.2	8.3	0.2	—	—	0.1	0.1	—	—
44	20	24.0	19.2	4.8	39.5	29.6	6.8	—	—	—	—	—	0.1	—
45	28	38.3	27.6	10.7	42.5	13.8	5.2	—	—	—	—	—	—	—
46	28	49.5	35.9	13.6	44.8	0.2	4.9	—	—	—	0.4	0.2	—	—
47	29	32.0	22.6	9.4	48.0	14.8	4.6	—	—	—	0.5	0.1	—	—
48	20	24.4	19.5	4.9	36.7	32.4	6.3	—	—	—	0.2	—	—	—
49	28	43.6	31.4	12.2	43.9	6.2	6.2	—	—	—	—	—	—	—
50	29	48.5	34.2	14.3	38.7	3.9	8.0	—	—	—	0.4	0.1	—	—
51	31	48.7	33.4	15.3	42.7	2.7	4.2	—	—	—	1.6	0.1	—	—
ÖA 16	32	36.4	24.8	11.6	0.5	—	3.3	—	—	—	58.3	1.2	—	—
17	32	32.2	22.2	10.0	0.9	—	4.5	—	—	—	61.0	1.1	—	—
18	32	32.3	22.3	10.0	0.2	—	1.5	—	—	—	64.4	1.3	—	—
19	32	39.0	26.8	12.2	0.3	—	1.4	—	—	—	57.6	1.6	—	—
20	32	37.4	25.7	11.7	0.6	—	0.3	—	—	—	59.7	1.8	—	—
21	30	33.0	23.1	9.9	—	—	0.1	—	—	—	65.6	1.0	—	—

¹ An content of the plagioclase determined by the extinction angle in the plane \perp (001) and (010); in a few cases by the maximum angle in the zone \parallel (010).

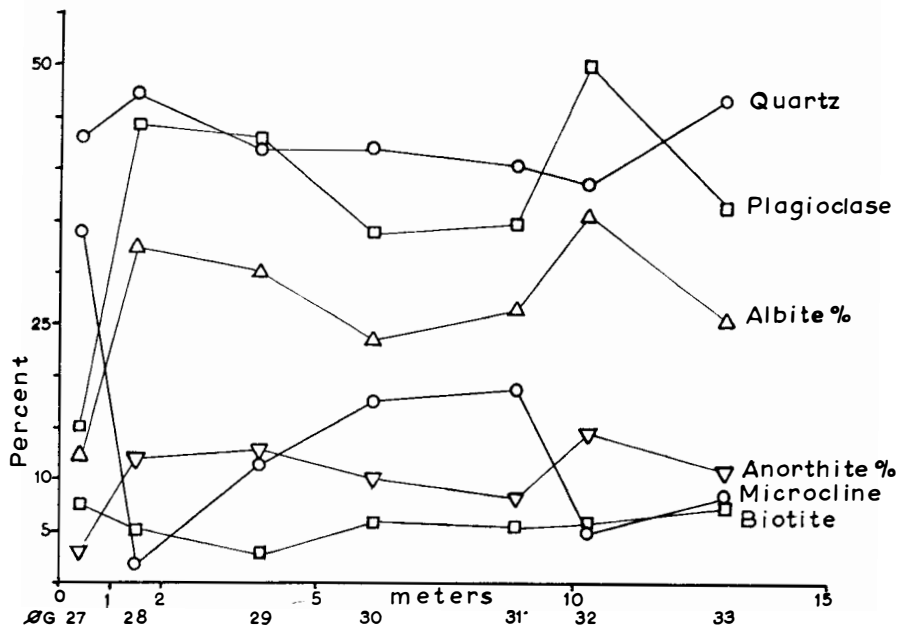


Fig. 2. Modal analyses of series of gneiss samples ÖG27-33. Volume percent vertically; distance from pegmatite horizontally.

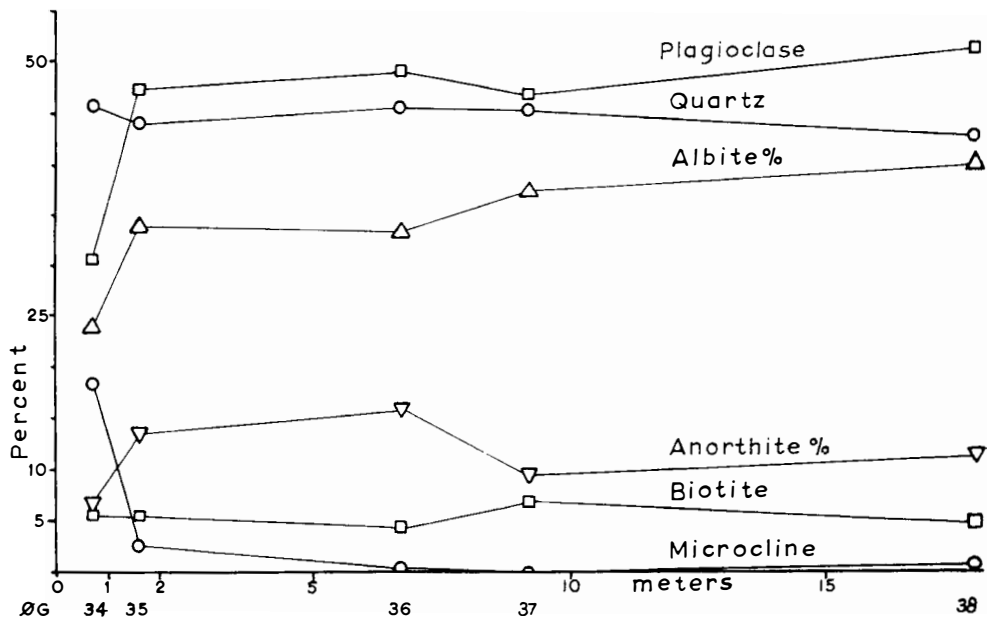


Fig. 3. Modal analyses of series of gneiss samples ÖG34-38.

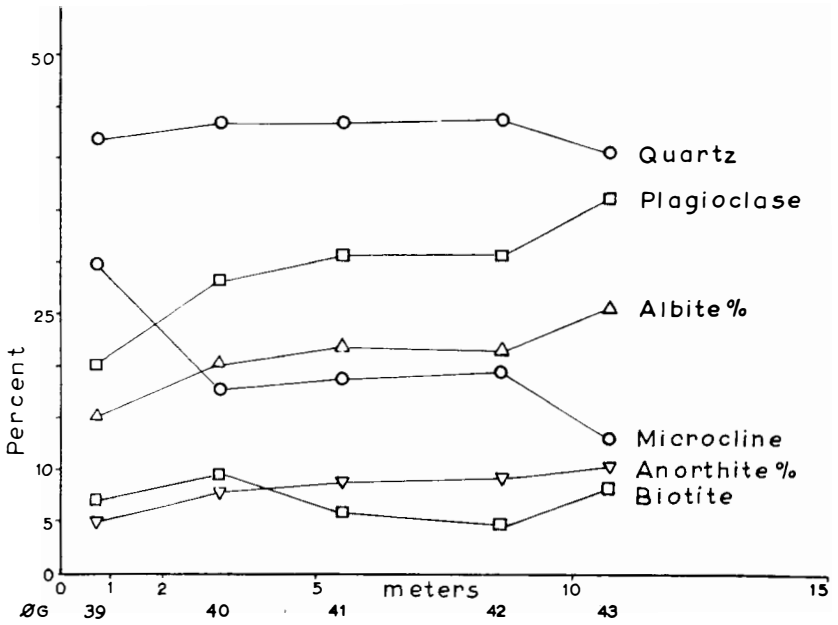


Fig. 4. Modal analyses of series of gneiss samples ÖG39-43.

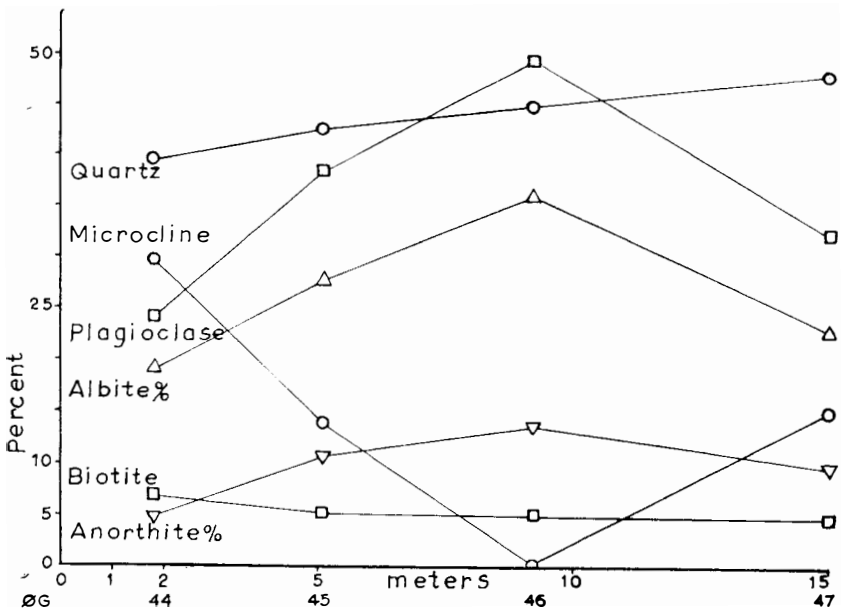


Fig. 5. Modal analyses of series of gneiss samples ÖG44-47.

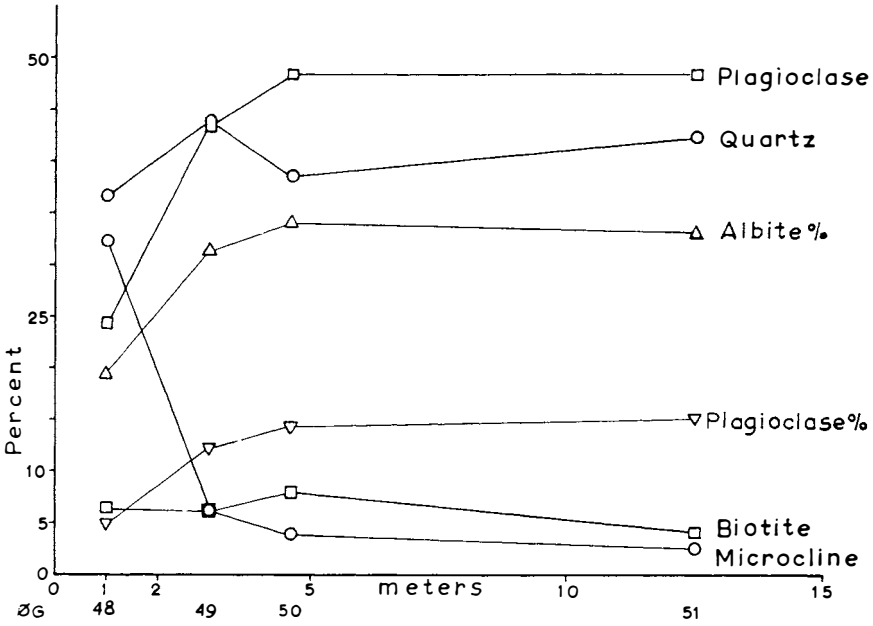


Fig. 6. Modal analyses of series of gneiss samples ÖG48—51.

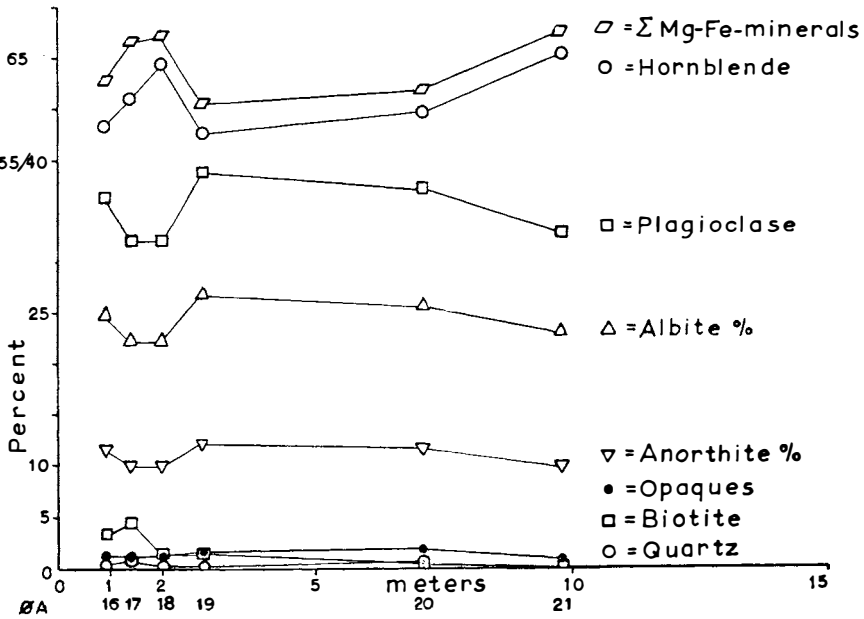


Fig. 7. Modal analyses of series of amphibolite samples ÖA16—21.

complimentarily to that of microcline and is always least nearest the pegmatite vein.

The amount of microcline in the gneissic bands is less near the amphibolite bands than in the middle of the gneissic bands (REITAN, 12). For this reason the amount of microcline is very low in the series of samples ÖG35–38, all of which were taken very close to the boundary of an amphibolite band. Sample ÖG34 was also taken very close to the boundary of an amphibolite band but within 1 m of the pegmatite vein, and although the amount of microcline is appreciable it is only a little more than half of that found in the other samples from within 1 m of the pegmatite vein. The amount of microcline in sample ÖG46 is also low; it was taken close to an amphibolite band. The reason for the amount of microcline being as low as it is in sample ÖG28 is unknown.

The only variation in the series of samples from an amphibolite band to which any degree of significance could possibly be attached is the slight increase of biotite near the pegmatite vein. The variations of the other minerals with distance from the vein are inconsistent and the maximum deviations of the major minerals from the average amount present are 10 % or less of the amount recorded.¹

Certain textural features of the gneiss are worthy of mention. The grain size of the gneiss is generally medium- to medium-fine-grained, although quartz sometimes occurs in quite large grains. The grain size of microcline is highly variable; close to the vein it always occurs both as large grains and as interstitial grains and stringers, then usually between quartz and plagioclase. In the sections within 0.7 m of the vein microcline appears to be in part replacing plagioclase, as occasional microcline grains can be seen to include small plagioclase grains which have the same optical orientation and may have the same orientation as an adjacent plagioclase grain; they appear to be unreplaced remnants of a formerly larger plagioclase grain. With increased distance from the vein the microcline occurs as interstitial grains and stringers which follow the grain boundaries of the larger

¹ The curves for plagioclase, hornblende, and sum of dark minerals resemble those found in the partly amphibolitized olivine gabbro surrounding three pegmatite veins near Risør (REITAN, 13), but the deviations from the average in the amphibolite band are significantly smaller (10 % as compared to about 30 %) and result in only very small changes in the calculated chemical compositions (compare table 4 and fig. 13 with REITAN, 13, p. 291, 296, 297).

grains and seem to occur preferentially along the boundaries between quartz and plagioclase. When the total amount of microcline exceeds about 13 percent there occur irregularly shaped grains (not interstitial stringers) as well as tiny interstitial grains and stringers. When the total amount of microcline is below 10 percent it occurs predominantly as interstitial grains and stringers. This would suggest the possibility that in the gneiss bands there is a variable amount of original microcline and a certain amount of secondary microcline which diminishes with distance from the vein. The above observations might be attributable entirely to secondarily grown microcline which, when in sufficient quantity, also forms non-interstitial grains; however, observations from the gneiss from other parts of St. Hansholmen (REITAN, 12) would tend to support the suggestion that the microcline in the gneiss near the pink pegmatite vein belongs to two generations. The older is variable in amount, varying both from band to band and within each band as a function of distance from the amphibolite bands; the younger in part replaces plagioclase near the vein and otherwise occurs as irregular grains and interstitial grains and stringers, the total quantity of microcline diminishing as the distance from the veins increases until the secondary microcline present occurs only as tiny interstitial grains and stringers.

The triclinicity of the microcline from six samples from the gneiss was measured (table 2, ÖG27, 29—33). No differences other than those attributable to experimental error could be measured. In all cases the degree of triclinicity is quite high (though lower than that found in the pegmatite), indicating a high degree of Si—Al order in the lattice.

The degree of sericitization¹ of the plagioclase in the gneiss is not uniform. In general, the sericitization within about 2 m of the vein is intense; further from the vein the sericitization is somewhat variable though always rather slight. The composition of the plagioclase is variable.² The samples taken nearest the veins contain relatively albite rich plagioclase (An₂₀ except for ÖG39 which is An₂₅). Those

¹ That the alteration product is sericite and not paragonite is indicated by the fact that it (along with microcline, muscovite, and biotite) became yellow after the staining process to which the thin sections were subjected.

² Variable from sample to sample. Along plagioclase-microcline contacts there can frequently be seen an extremely thin, unsericitized rim on the plagioclase grain (not always continuous) which has a very slightly different extinction angle and probably slightly lower index. The rims are so thin that no quantitative differences could be determined.

Table 2.

Triclinicity of microcline			
Sample no.	Rock type	Distance from contact	Triclinicity Δ
ÖG 27	Gneiss	0.3 m	0.85
	»	3.9 m	0.85
	»	6.1 m	0.85
	»	8.9 m	0.85
	»	10.3 m	0.80
	»	13.0 m	0.80
ÖP 17	Pegmatite	1.2 m	0.95
	»	0.4 m	0.95
	»	0.1 m	0.98

more than 2 m from the veins contain more calcic plagioclase which, with three exceptions, lies between An_{28} and An_{32} .

Few changes in the minerals of the amphibolite can be noted. The plagioclase is uniformly An_{32} except for that from sample ÖA21 in which the plagioclase was determined to be An_{30} ; i.e. the plagioclase is of essentially uniform composition. Sericitization of the plagioclase is not uniform; in the sample nearest the vein the sericitization is generally strong, in the next sample it is patchy and moderately strong, and in the remaining samples it is strong except for the one most distant from the vein where it is patchy but locally very strong. The sample most distant from the vein is medium-fine-grained, the others fine-grained, and the hornblende in the sample most distant from the vein is slightly lighter in color and not quite so strongly pleochroic as that from the remaining samples. Very thin quartz veinlets are occasionally to be seen in the amphibolite.

Petrochemical calculations

In order to facilitate the comparison of changes within the series' of samples and between series' and in order to elucidate the chemical changes which the observed mineralogical changes imply, the cation percent composition of the samples was calculated on the basis of the modal analyses of the samples.

Table 3

Mineral formulas used in petrochemical calculations.

Quartz	SiO_2
Microcline	KAlSi_3O_8
Albite	$\text{NaAlSi}_3\text{O}_8$
Anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$
Biotite ¹	$\text{KAlMg}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$
Hornblende ¹	$\text{Ca}_2\text{Mg}_4\text{Al}_2\text{Si}_7\text{O}_{22}(\text{OH})_2$
Muscovite	$\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$
Opaques	Fe_3O_4

¹ The formulas used for these minerals are those suggested by Barth (1) for use in calculating the mesonorm, with Fe substituting for Mg and other simplifications.

To do this standard formulas for the minerals involved were used. These are listed in table 3. The amounts of albite and anorthite are dependent on the composition of the plagioclase in the sample as determined optically. The formulas used for biotite and hornblende are those suggested by BARTH (1) for use in calculating the mesonorm from chemical analyses.

All of the formulas are simplified; the distribution of Mg, Fe, and Mn is ignored, Na in microcline is ignored, K in plagioclase is ignored, alkalis in hornblende are ignored, and all formulas are ideal. Accessory minerals are also ignored in the calculations. No claim is made for exact reproduction of the actual chemical composition of the rock. However, it is believed that these calculations make important changes in the chemistry of the rocks evident, much more so than would be the case simply by inspecting the modal analyses, and comparison is considerably facilitated.

The method of calculation is the reverse of a norm calculation, stopping at cation percents. The results of these calculations are given in table 4 and are shown graphically in figs. 8 to 13 where the changes in cation percent are plotted against the distance of the sample from the pegmatite vein; the distance is measured along the strike.

In table 5 the cation percent of the sample closest to the vein in each of the series' is compared with the average percent of each of the cations obtained from the remaining samples of the series.

Table 4
Calculated compositions in cation %

Sample no	Si	Al	Mg Fe	Ca	Na	K
ÖG 22	74.6	11.4	3.4	0.8	3.1	6.7
27	74.8	11.4	3.0	0.6	2.4	7.8
28	75.2	12.9	1.9	2.4	6.5	1.2
29	73.6	13.9	1.1	2.6	6.1	2.7
30	73.6	13.1	2.2	2.0	4.7	4.4
31	73.3	13.1	2.1	1.7	5.3	4.5
32	71.5	14.7	2.1	2.9	7.1	1.7
33	75.2	12.2	2.7	2.2	5.1	2.6
34	75.8	11.7	2.1	1.3	4.8	4.3
35	73.7	13.5	2.1	2.7	6.8	1.2
36	74.0	13.7	1.8	3.1	6.7	0.7
37	74.9	12.2	2.5	1.9	7.6	0.9
38	74.0	13.3	1.8	2.2	8.0	0.7
39	74.3	12.0	2.7	1.0	3.0	7.0
40	73.8	12.1	3.6	1.6	4.1	4.8
41	74.4	12.5	2.3	1.8	4.4	4.6
42	74.7	12.6	1.8	1.9	4.4	4.6
43	72.5	13.2	3.1	2.1	5.3	3.8
44	73.4	12.4	2.6	1.0	3.8	6.8
45	73.7	13.2	2.0	2.1	5.5	3.5
46	74.3	13.3	1.8	2.7	7.3	0.6
47	76.3	12.0	1.7	1.9	4.5	3.6
48	72.2	13.2	2.4	1.0	3.9	7.3
49	73.8	13.2	2.3	2.4	6.3	2.0
50	71.0	14.4	3.0	2.9	6.9	1.8
51	75.3	10.8	3.1	3.1	6.7	1.0
ÖA 16	48.6	17.9	18.0	10.1	5.0	0.4
17	48.6	17.2	19.0	10.1	4.5	0.6
18	48.5	17.3	19.0	10.5	4.5	0.2
19	48.7	18.2	17.4	10.1	5.4	0.2
20	48.8	17.9	17.9	10.3	5.1	—
21	48.6	17.4	18.6	10.7	4.6	—

The following differences can be noted for the samples from the gneiss. K is always higher near the vein than the average or the maximum values of the rest of the series. Na and Ca are always lower than the average or the minimum values of the rest of the series. Mg + Fe is in two cases higher than the average and the maximum values

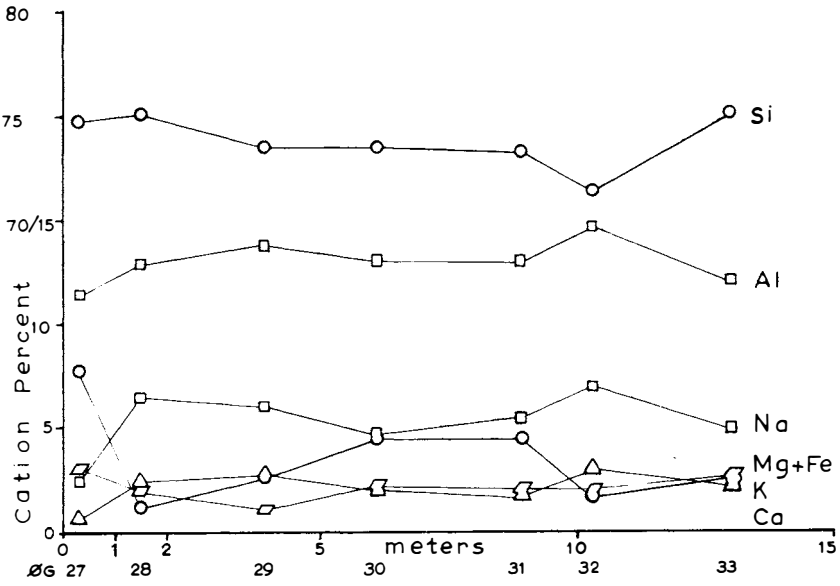


Fig. 8. Calculated cation percent composition of gneiss series ÖG27 —33. Cation percent vertically; distance from pegmatite horizontally.

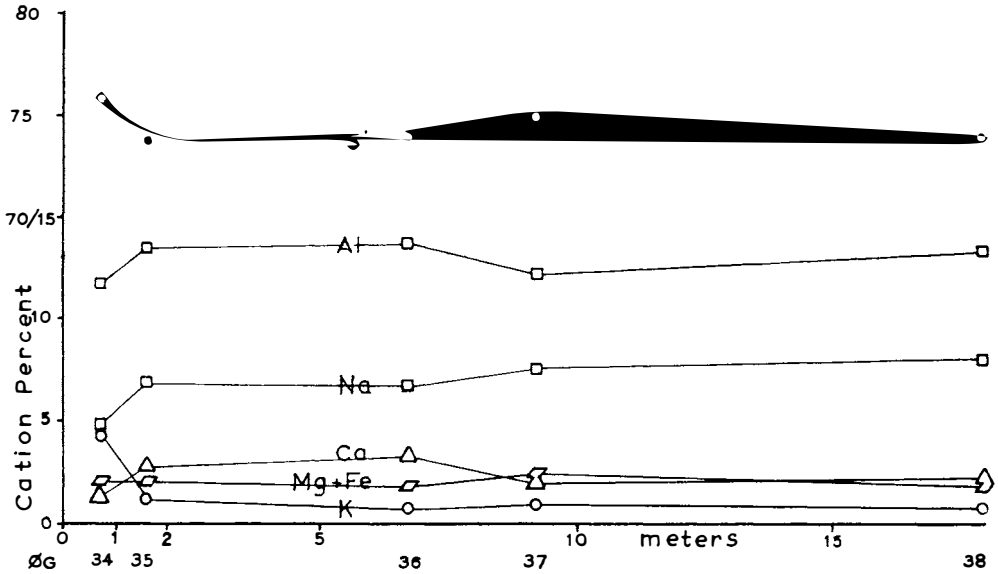


Fig. 9. Calculated cation percent composition of gneiss series ÖG34 —38.

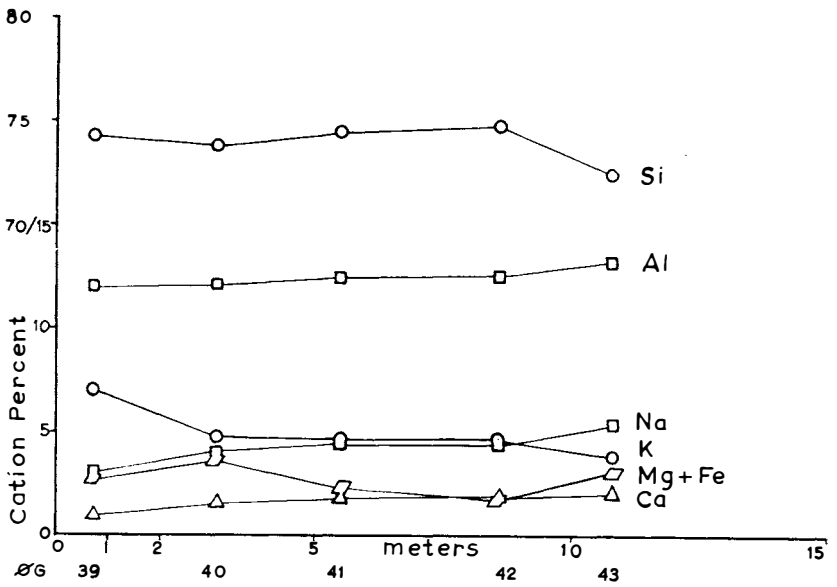


Fig. 10. Calculated cation percent composition of gneiss series ÖG39-43.

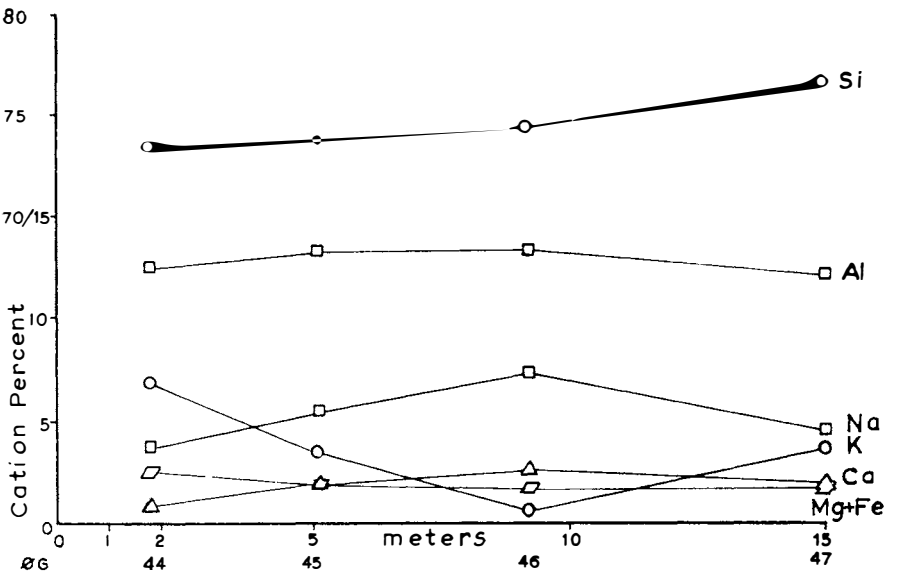


Fig. 11. Calculated cation percent composition of gneiss series ÖG44-47.

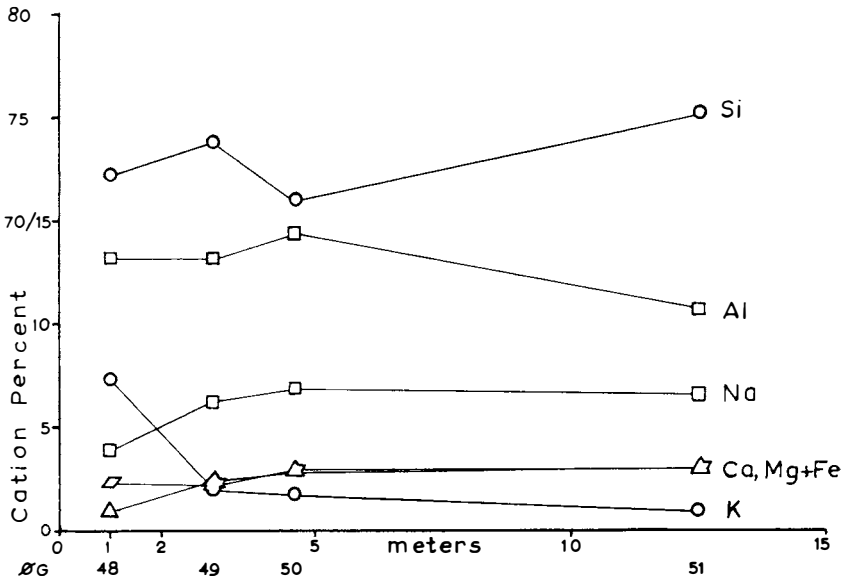


Fig. 12. Calculated cation percent composition of gneiss series ÖG48-51.

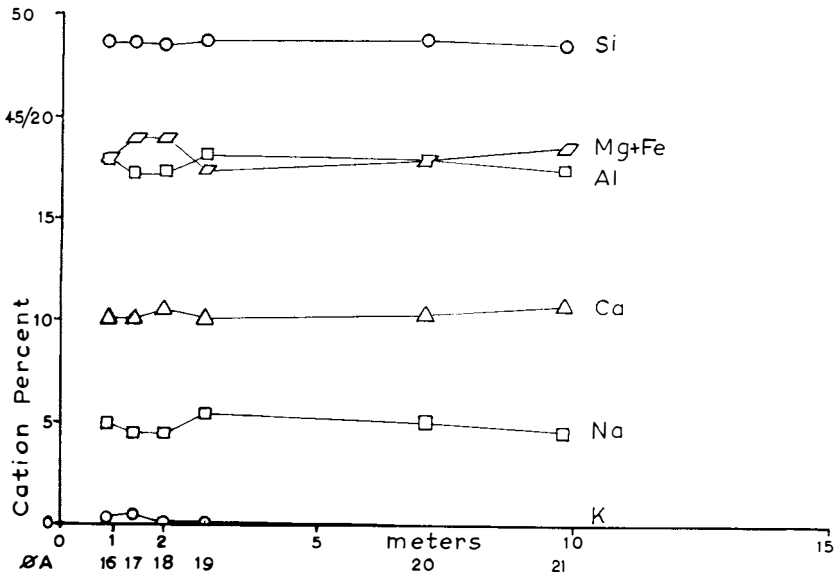


Fig. 13. Calculated cation percent composition of amphibolite series ÖA16-21.

Table 5
Comparison: samples closest pegmatite vs. others.

Sample Series		Si	Al	Mg Fe	Ca	Na	K
ÖG 27—33	28 } Max.	75.2	14.7	2.7	2.9	7.1	4.5
	to } Min.	71.5	12.2	1.1	1.7	4.7	1.2
	33 } Av.	73.6	13.3	2.0	2.3	5.8	2.8
	ÖG 27	74.8	11.4	3.0	0.6	2.4	7.8
ÖG 34—38	35 } Max.	74.9	13.7	2.5	3.1	8.0	1.2
	to } Min.	73.7	12.2	1.8	1.9	6.7	0.7
	38 } Av.	74.2	13.2	2.2	2.5	7.3	0.9
	ÖG 34	75.8	11.7	2.1	1.3	4.8	4.3
ÖG 39—43	40 } Max.	74.7	13.2	3.6	2.1	5.3	4.8
	to } Min.	72.5	12.1	1.8	1.6	4.1	3.8
	43 } Av.	73.8	12.6	2.7	1.8	4.6	4.4
	ÖG 39	74.3	12.0	2.7	1.0	3.0	7.0
ÖG 44—47	45 } Max.	76.3	13.3	2.0	2.7	7.3	3.6
	to } Min.	73.7	12.0	1.7	1.9	4.5	0.6
	47 } Av.	74.7	12.8	1.8	2.2	5.8	2.6
	ÖG 44	73.4	12.4	2.6	1.0	3.8	6.8
ÖG 48—51	49 } Max.	75.3	14.4	3.1	3.1	6.9	2.0
	to } Min.	71.0	10.8	2.3	2.4	6.3	1.0
	51 } Av.	73.4	12.6	2.6	2.6	6.6	1.6
	ÖG 48	72.2	13.2	2.4	1.0	3.9	7.3
ÖA 16—21	17 } Max.	48.8	18.2	19.0	10.7	5.4	0.6
	to } Min.	48.5	17.2	17.4	10.1	4.5	<0.1
	21 } Av.	48.6	17.6	18.4	10.4	4.8	0.2
	ÖA 16	48.6	17.9	18.0	10.1	5.0	0.4

of the rest of the series, but in three cases it is lower than or equal to the average and within the extreme values of the rest of the series. Al is in four cases lower and one case higher than the average, in three cases lower and in two cases within the extreme values of the rest of the series. Si is in three cases higher and in two cases lower than the average, in one case higher, another case lower, and in three cases within the extreme values of the rest of the series.

This indicates that there is a real increase in the percentage of K near the vein and a real decrease in the percentage of Na and Ca.

Table 6
Alkalis in Amphibolite

Sample no.	K ₂ O		Na ₂ O		Sericitization
	Calc. mol. %	Wt. %	Calc. mol. %	Wt. %	
ÖA 16	0.4	1.47	5.0	3.02	Generally strong
17	0.6	1.36	4.5	3.01	Patchy, moderate
18	0.2	1.86	4.5	2.93	Strong
19	0.2	1.68	5.4	2.94	Strong
20	—	1.63	5.1	2.59	Strong
21		1.58	4.6	3.64	Patchy, locally v.strong

Al may be slightly deficient nearest the vein as compared with the more distant samples, but the data are not absolutely conclusive. No consistant change of Si or Mg + Fe can be demonstrated.

The calculated cation percents of the samples from the amphibolite band yielded curves with little variation. It was considered possible that the rise of K within 2 m of the vein was real, being due to the increase of biotite near the vein. However, the irregular variation in the degree of sericitization, which was impossible to estimate quantitatively, made any conclusion hazardous. K₂O and Na₂O were therefore determined with the flame photometer. The weight percents determined and the cation percents which were calculated are compared in table 6. The agreement is not good and the changes determined are irregular, but all changes are very small — too small to be accorded any significance.

The change in the mineralogy and the chemistry of the surrounding rocks in the vicinity of the vein may have taken place with or without a change of volume of the rock. In order to determine this the volume change calculation which was introduced in a previous publication (REITAN, 13, p. 306) was used. In this calculation the relative volume occupied by a standard number of oxygen ions is determined after having determined the mol volumes of the minerals of the rocks (one mol of each mineral being defined on the basis of the formula containing 24 oxygen ions).

In the five gneiss series' and in the amphibolite series the sample nearest the vein was compared with the average of the rest of the series. The percent change in going from the average to the rock

Table 7
Calculated volume change

Sample no.	Volume no.	Difference	% change nearest vein
ÖG 27	29796.5	618.2	+ 2.12
Av. ÖG 28—33	29178.3		
ÖG 34	29301.9	407.9	+ 1.41
Av. ÖG 35—38	28894.0		
ÖG 39	29674.0	342.7	+ 1.17
Av. ÖG 40—43	29331.3		
ÖG 44	29781.6	708.1	+ 2.44
Av. ÖG 45—47	29073.5		
ÖG 48	29934.1	891.8	+ 3.06
Av. ÖG 49—51	29042.3		
ÖA 16.....	28851.3	96.7	+ 0.34
Av. ÖA 17—21.....	28754.6		

nearest the vein is shown in table 7. In all cases there was an increase of volume nearest the vein. The increase is much larger for the gneiss than for the amphibolite. The significance of this conclusion is more appropriately discussed in connection with the genesis of the pegmatite; further comment is deferred to p. 219.

Genesis of the pegmatite vein

So far virtually no mention has been made of the structure in the area. Little can be said. The pegmatite vein cross-cuts the parallel structure of the gneiss and the amphibolite bands. In almost all cases an amphibolite band which is cut off on one side can be found again on the other side of the vein. There has been no apparent off-set of the bands; dilation, if it occurred, must have been parallel to the strike. However, only one set of parallel structures crosses the pegmatite vein and therefore no conclusive answer to whether or not there has been dilation can be given on structural grounds.

The pegmatite cross-cuts the amphibolite bands and the parallel structure of the gneiss and amputates an inter-boudin pegmatite and

a white, plagioclase pegmatite vein filling in an amphibolite (cf. map, fig. 1). It must therefore be considered to be later than these rocks. As the white, plagioclase pegmatites (both the inter-boudin pegmatites and the vein pegmatites) are a product of the main dynamic metamorphism of the area, the pink pegmatite is later than the main deformation of the area.

To decide upon the mechanism by which the pegmatite formed, the following questions must be answered. Did the material which now constitutes the pegmatite come from the immediately surrounding rock or from elsewhere? Is the pegmatite a replacement pegmatite or did it form in a crack (dilation of the crack being parallel to the strike)?

The reason for taking the series' of samples and for doing the quantitative petrography was to be able to answer the first question. The curves obtained for the quantitative variations of the mineralogy of the rock surrounding the pegmatite, and even more clearly and strikingly the curves obtained when the calculated cation percents are plotted against distance from the vein, show that there is a relative increase of K and a relative decrease of Na, Ca, and possibly Al near the vein. The pegmatite vein consists predominantly of microcline with some quartz and plagioclase and a lesser amount of biotite and hornblende. This means that the cation which (relative to the average gneiss) is most enriched in the pegmatite vein is also most enriched in the immediately adjacent gneiss and diminishes with distance from the vein; those elements which (again relative to the average gneiss) are most deficient in the pegmatite (namely Na, Ca, and to a lesser extent Al) are deficient in the immediately adjacent gneiss and increase with distance from the vein.

This corresponds to the situation described graphically in fig. 14a and c. With respect to one cation (in this case K), enrichment in the vein and relative enrichment of that cation in the adjacent rock which diminishes with distance from the vein, implies diffusion of that element from its site of greatest enrichment (the vein) into the surroundings. With respect to another cation (Na, Ca) which is relatively deficient in the pegmatite and in the immediately surrounding rock but less deficient at some distance from the vein, movement of another cation into the surrounding rocks is implied such that the cation concerned is relatively depleted in the surrounding rocks. This

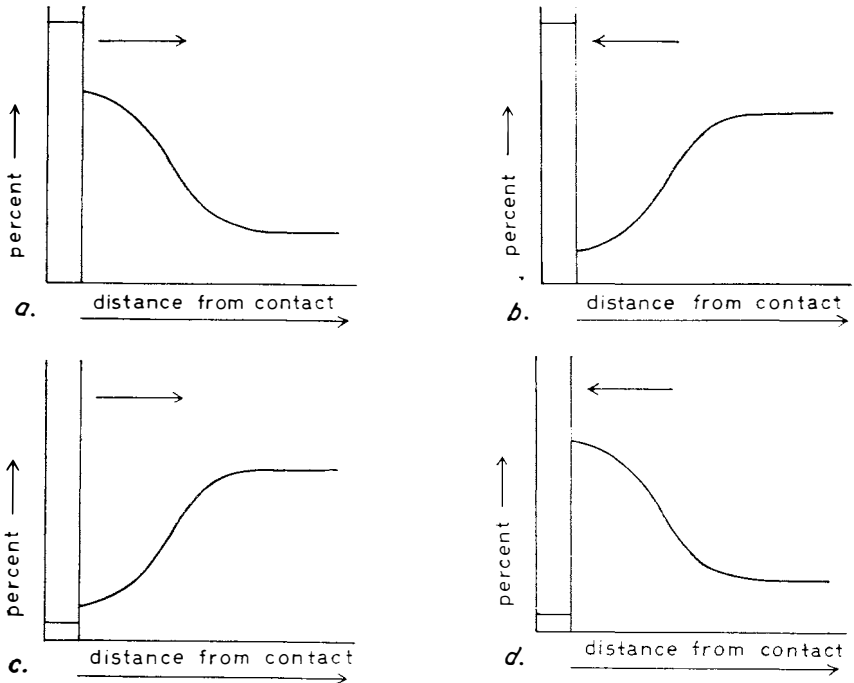


Fig. 14. Theoretical curves for the variation of a component in a pegmatite vein and with distance from the vein in the surrounding rock. a. Concentration high in the vein and diminishing with distance from the vein in the surrounding rock implies movement of the component from the vein into the surroundings. b. Concentration high in the vein and increasing with distance from the vein in the surrounding rock implies movement of the component from the surrounding rock into the vein, i.e., enrichment in the vein at the expense of the surroundings. c. Concentration low in the vein and increasing with distance from the vein in the surrounding rock — the complement of a. — implies movement of another (other) component(s) from the vein into the surroundings. d. Concentration low in the vein and decreasing with distance from the vein in the surrounding rock — the complement of b. — implies movement of another (other) component(s) from the surrounding rock into the vein; i.e., residual enrichment of the component near the vein.

is the complement of the former. Fig. 14b and d illustrate the case in which cations move from the surrounding rock into the vein. In the first case, a cation is «leached» from the surrounding rock and enriched in the vein. In the second case, a cation which does not move into the vein and is deficient there is residually enriched in the surrounding rock as another (other) cation(s) moves into the vein.

It is readily seen that the curves obtained for the gneiss at the western end of St. Hansholmen correspond to those shown in fig. 14, a and c. Therefore, material (primarily K) has moved from the vein into the surrounding rock.

This answers the first question. The material which now constitutes the vein did not come from the immediately surrounding rock. The material came from elsewhere and excess material moved out from the vein into the surrounding rocks.

One asks, from where did the material come?

The most obvious source and the most probable one is the group of granulite facies rocks, migmatites, banded gneiss etc., which according to the map of the facies series of the Arendal district (BUGGE, 3, fig. 26, p. 134) occur immediately to the southwest of St. Hansholmen. If the material of the rocks constituting St. Hansholmen, the mineral assemblage of which corresponds to the amphibolite facies, was, at the time of the formation of the pegmatite vein, not sufficiently mobile to move into the zone in which the pegmatite formed,¹ then the most likely place from which the material could have been derived is from the granulite facies area nearby, either below (?) or laterally.

It is therefore believed that a K-rich phase derived from the granulite facies rocks in the vicinity, constituted the material from which the pegmatite vein formed, and that some of this material also moved into the rocks surrounding the vein and led to the presently observable relative K enrichment and Na and Ca depletion.

There is no direct evidence as to whether the vein is a replacement vein or a dilation vein. However, the volume change calculations (p. 216) have shown that in every series of samples there has been a relative increase in volume of the rock close to the vein as compared with that more distant. This is of course to be expected if a crack had formed. The following sequence of events can be envisaged. A crack occurred in the banded gneiss. As a result the pressure in the surrounding rock was lowered in the direction perpendicular to the vein and while the crack was being filled by newly crystallized minerals from the phase introduced into the crack a small amount of ex-

¹ Note that as yet no standpoint has been taken as to the kind of medium from which the pegmatite formed or what form — magma, solution, suspension, or diffuse state — the material had which moved to the site now occupied by the pegmatite. This is not necessary at this point in the discussion.

pansion took place in the surrounding rock.¹ As the adjacent rock expanded after the release of pressure, material from the vein moved out into the surrounding rocks and there partly replaced the original minerals but also crystallized between the grains where the pressure was now low. Expansion in the surrounding rock would cease after the vein had been filled with crystalline material; diffusion of material from the vein into the surrounding rocks would stop as no new low pressure sites would be created. Note that the expansion in the amphibolite band was very little, while that in the gneiss was very much more. This is what would be expected on the basis of what is known about the relative rigidity of the rocks. The lack of chemical change in the amphibolite adjacent to the vein also indicates that it could not «blot up» material from the vein to the same extent as could the gneiss; there were very few low pressure sites in the amphibolite which were available to filling by material from the vein.

The lack of structural deformation associated with the cross-cutting vein would suggest that if it is a replacement vein it is most likely a volume-for-volume replacement vein. If this is the case, it is difficult to understand why the adjacent rocks have undergone a volume increase near the vein. The lack of deformation in the banded gneiss near the vein (which can be associated in time with this vein) hardly allows for the proposal that the vein is a replacement vein in a fold — or shear — determined low pressure zone crossing the banded gneiss.

It seems, therefore, most probable that the vein formed in a crack in the banded gneiss and that the material which filled the vein was derived from the rocks of the nearby granulite facies zone.

The final question to be answered in connection with the genesis of the pegmatite is: What was the nature of the pegmatite forming fluid?

Four possibilities must be considered. They are: 1) a concentrated fluid consisting primarily of the silicate components of which the pegmatite is now composed, in which a certain amount of water may have been dissolved, i.e. a magma; 2) a watery fluid in which the silicate

¹ The gneiss was apparently brittle enough to crack and sufficiently inert at the time of the formation of the pegmatite that it contributed no or extremely little material to the phase entering the crack — additional evidence that the vein formed quite late in the metamorphic history of the area.

materials now constituting the pegmatite were dissolved and which carried the dissolved components to the present site of the pegmatite where they precipitated, i.e. a hydrothermal solution; 3) a fluidized system, i.e. a gas-solid system consisting of a suspension of solid particles in a through-flowing gas (REYNOLDS, 11); and 4) a disperse phase consisting of the components of the pegmatite in ionic, molecular, or atomic form, accompanied by water also in disperse form, which diffused to the site of the pegmatite and there crystallized.

Possibility number two is discarded as quite unlikely for the following reasons. Large quantities of water would be necessary in order to dissolve and transport the material which now appears as the pegmatite vein. Calculations based on the solubilities which Friedman (4) arrived at in his study of the system $H_2O-Na_2O-SiO_2-Al_2O_3$ have led to the estimate that for every cm^3 of pegmatite material deposited, ca. $2 \times 10^2 cm^3$ of solution would have had to have passed the site of the pegmatite (REITAN, 12). SVERDRUP (15), basing his calculations on the solubilities of quartz and albite in superheated steam given by MOREY and HESSELGESSER (8), and assuming that *all* of the dissolved material precipitates at the site of the pegmatite, has arrived at approximately the same figure ($1.91 \times 10^2 cm^3$ of solution yielding $1 cm^3$ of pegmatite material).

However, the possibility that the pegmatite has been precipitated from a hydrothermal solution becomes even more unlikely when one attempts to calculate the amount of rock which would have to be «dehydrated» in order to provide the hydrothermal solution.

It has been suggested as most likely (p. 219) that the material which now constitutes the pegmatite vein was derived from the granulite facies rocks nearby. As no granite bodies are close to St. Hansholmen, the most reasonable source from which a hydrothermal solution could be derived is these granulite facies rocks. Such rocks are generally quite «dry», but it is just that water which has been expelled from them which could conceivably have constituted a hydrothermal solution which bore the material now constituting the vein to its present site.

If we assume that from $10^2 cm^3$ of the rock one derives $10 cm^3$ of solution¹ then, assuming the solubility previously arrived at (ca. $2 \times$

¹ None of the rocks in this area are particularly «wet», and as the formation of the vein occurred late in the main metamorphism of the area it seems unlikely that the rocks of the granulite facies would lose more than 1 % H_2O .

10^2 cm^3 of solution being capable of yielding 1 cm^3 of solid pegmatite material), ca. $2 \times 10^4 \text{ cm}^3$ of rock yield enough solution to form 1 cm^3 of pegmatite. If we assume that the vein on St. Hansholmen, which has a surface area of about 20 m^2 , was in all 500 m in vertical extent, then 0.4 km^3 of rock must have been «dehydrated» to yield solution sufficient to deposit this quantity of pegmatite. However, the vein exposed on St. Hansholmen is probably much longer than the exposure on the island. On the adjacent islands of Lille Stangholmen, Kaninholmen, and Engholmen, identical veins can be seen and these exposures all lie essentially in line with one another; they are undoubtedly parts of the same vein (personal observations, see map, fig. 3, p. 227 in REITAN, 12, for the location of these islands). If these are all parts of the same vein then the length of the vein is at least 500 m. If the width is assumed to be constant at 2 m and the vertical extent taken to be 500 m, then 10 km^3 of rock would have had to have been «dehydrated» in order to yield the quantity of hydrothermal solution necessary to form the vein.

That the pegmatite vein has crystallized from a fluidized gas-solid system is a possibility, but none of the characteristic features of veins for which REYNOLDS (11) has suggested such an explanation are to be seen in the pegmatite vein on St. Hansholmen. The explanation has its appeal in that it could explain the vein as the result of minimal or no dilation while yet allowing for some expansion of the surrounding rocks. However, as positive evidence in its favor is completely lacking it will not be advocated in this case.

To decide between the two remaining possibilities is difficult. Temperature determinations using Barth's feldspar thermometer (2) have been made, taking co-existing feldspars both from samples of the gneiss and of the pegmatite. The results are shown in table 8. The temperature of the pegmatite is considerably higher than that of the gneiss. The differences between the temperatures determined at three points in the pegmatite are so small that no importance can be attached to them. (For example, if the plagioclase in ÖP17 is Ab_{74} instead of Ab_{73} as determined, and that in ÖP18 is Ab_{68} instead of Ab_{69} , the temperature determined would be the same.) However, the difference between the pegmatite vein and the gneiss is significant, being about 100° C .

The temperatures determined in the gneiss are irregularly variable,

Table 8
Temperatures indicated by co-existing feldspars

Sample no.	ÖG27	ÖG30	ÖG31	ÖG32	ÖG33	ÖG39	ÖG40	ÖG41	ÖG42	ÖG43	ÖG44	ÖG45	ÖG47	ÖG48	ÖP17	ÖP18	ÖP19
Microcline																	
Na ₂ O	1.24	1.30	1.64	1.32	1.32	0.98	0.84	1.10	0.94	1.01	1.07	1.25	1.08	1.24	2.40	2.50	2.09
K ₂ O	14.36	13.44	14.24	13.88	14.75	15.45	15.42	15.08	15.25	15.00	15.00	14.57	14.63	14.85	12.96	13.50	13.27
Mol. prop.																	
ab	11.6	12.8	14.9	12.0	8.8	8.8	7.7	10.8	8.6	9.3	9.8	11.5	10.2	11.3	22.0	20.2	19.3
or	88.4	87.2	85.1	88.0	91.2	92.3	92.3	90.0	91.4	90.7	90.2	88.5	89.8	88.7	78.0	79.8	80.7
Ab-content of associated plagioclase .	80	70	76	70	70	75	72	71	70	71	80	72	71	80	73	69	69
k	0.14	0.18	0.20	0.21	0.17	0.12	0.11	0.14	0.12	0.13	0.12	0.16	0.14	0.14	0.30	0.29	0.28
Temperature	410	460	480	490	450	390	380	410	390	400	390	430	410	410	570	560	555

tending to be lower near the vein. This is probably because equilibrium was not established. The textures displayed by the microcline in the gneiss indicate that this is the case; had the plagioclase and microcline been in equilibrium one would not expect that the microcline would be present as intergranular stringers. If equilibrium was not established the tendency towards lower determined temperatures near the vein is easily explained.

A K-rich phase was introduced into the vein and this phase became more Na-rich as crystallization in the vein proceeded (cf. the change of composition of the feldspars in the vein, p. 200). Consequently the early metasomatism of the surrounding gneiss was very predominantly a K-metasomatism. Naturally the first material introduced into the gneiss crystallized at the first suitable low pressure sites arrived at, i.e. closest to the vein. Thus the mol fraction of albite in the alkali feldspar (the term which appears in the numerator of the distribution equation) is much lower than would be the case were equilibrium achieved. Material which enters into the gneiss later would be more Na-rich, but would be forced to penetrate further into the gneiss as suitable low pressure sites near the vein would have been already occupied (at least the percentage of late material would be higher further from the vein). Still another factor tending in the same direction is that the proportion of second generation microcline is highest nearest the vein. First generation microcline is probably in equilibrium with the coexisting plagioclase, and where this predominates the temperatures are higher and probably more nearly correct; the temperature determined for the gneiss at the opposite end of the island is 460° C. However, as equilibrium was not attained near the vein the temperatures determined in the gneiss near the vein have no significance and inconsistent and irregular variations are only to be expected.

The thin, more acidic (?) rims frequent on plagioclase adjacent to microcline also indicate that equilibrium was not achieved. They might be taken to indicate that the feldspars began to react such that a more acidic plagioclase began to be formed; the reaction which would take place with lowering of temperature. That this reaction was only initiated near the vein could be because only there were there sufficient volatiles to facilitate the reaction. If these rims are the result of limited reaction at lower temperature they indicate that

the surrounding rock was not appreciably heated near the vein at the time of its formation, and support the contention that the vein is late in the metamorphic history of the area.

Neither are the triclinicity measurements of any help. The triclinicity of the microcline in the pegmatite is higher than that in the gneiss (see table 2, p. 208), but this may be accounted for by the cooling history of the microcline at the two places and the probable abundance of interstitial fluids which would assist in the diffusion necessary to accomplish the reconstructive transformation which occurs in the ordering of microcline. The microcline in the gneiss was largely derived from the same phase as that in the pegmatite. However, the microcline in the gneiss crystallized at points where the surroundings were cooler than the vein. As equilibrium between the microcline and plagioclase was not achieved in the gneiss, one must assume that the minerals in the gneiss were rather passive at the time and since the microcline formed, this passivity probably being due to relatively low temperature. Thus, microcline formed in the gneiss, probably originally quite poorly ordered (GOLDSMITH, 5; GOLDSMITH and LAVES, 6), would have had less opportunity to achieve order than would the microcline in the pegmatite which cooled more slowly.

The possibility that the H_2O pressure was higher in the vein is also good in that the material which constitutes the vein must have been accompanied by considerable H_2O , no matter what the nature of the pegmatite forming fluid. If the fluid was a magma it must have been under rather high H_2O pressure in order to be mobile at a temperature below $600^\circ C$, and, as H_2O is among the most fugitive components of rocks, a disperse phase must also have contained considerable H_2O . The presence of H_2O (and other gases?) would assist in the diffusion necessary to order the Si and Al in the microcline.

The changes in the composition of the feldspars from the vein boundaries and towards the center are those which would be expected had the pegmatite crystallized from a magma. Both feldspars become more rich in Na towards the center of the vein, which is assumed to be latest.

If the vein crystallized from a disperse phase which migrated from the granulite facies rocks through the crack in which the pegmatite formed, this change of composition of the plagioclase may or may not follow naturally. It would appear that Na diffuses more rapidly

towards the zones of low pressure than Ca (RAMBERG, 10; REITAN, 12, 13, and 14). One should, therefore, predict that the plagioclase formed first would be richer in Na than that which formed later, as was the case in the veins in the olivine gabbro near Risør (REITAN, 13). This is not the case. However, at high temperatures, K metasomatism is much more predominant than Na metasomatism (RAMBERG, 9, p. 206), and might imply higher mobility of K than of Na at the temperature of formation of the vein on St. Hansholmen. If such is the case one would predict a more K-rich alkali feldspar first, followed by more Na-rich alkali feldspar. This is the case. But if the distribution of Na between the two feldspars is controlled by the temperature of their formation and the temperature is essentially constant from the first to the last, the feldspars produced will be a function of the limiting quantities of the various components. Thus, if the quantity of Na in the environment is the limiting factor, the composition of the feldspars will be controlled by its distribution. If the primary change in the environment from which the feldspars crystallized was an increase in Na, such that the alkali feldspars crystallizing out through time were forced to include more Na, then, at constant temperature, the plagioclase formed must also contain more Na if equilibrium is to be maintained (BARTH, 2). In other words, the composition of feldspars produced will be a function of the temperature and bulk composition of the phase from which they form. If formed from a magma the liquid must become more Na-rich through time and both feldspars become more Na-rich. If formed from a diffuse phase they may become richer or poorer in Na, depending on whether the controlling change in the composition of the environment is of Na or Ca or K.

The temperature at which the pegmatite formed — ca. 560°-570° C — is apparently not too low for the existence of certain magmas (i.e., molten silicate material). JAHNS and BURNHAM (7) report that the beginning of melting of the Harding, New Mexico, pegmatite under 2000 bars H₂O pressure occurred at 555 ± 5° C. The experimental work of TUTTLE and BOWEN (16) on the Quincy granite, Western granite, and the «ternary» (Ab-Or-SiO₂) minimum has shown that the beginning of melting curve at various water-vapor pressures approaches 650° C asymptotically as the pressure increases, at least up to 4000 kg/cm² pressure. However, further studies, with the proportion of alkalis in excess of the alkali-alumina ratio in alkali feld-

spar, have indicated that liquids rich in alkali silicates (and also water) can exist at lower temperatures. It is therefore impossible to dismiss a magma from consideration on the basis of the temperature determined for the crystallization of the pegmatite.

Tuttle and Bowen have also arrived at the conclusion that «at least some of the amphiboles may well be unstable in the presence of a moderate or high water-vapor pressure». (TUTTLE and BOWEN, 16, p. 92).

If the presence of hornblende in the pegmatite on St. Hansholmen requires the assumption that the water-vapor pressure was low, then the possibility that the pegmatite vein crystallized from a magma is reduced. At least moderate (ca. 1000 atm.) and probably higher water-vapor pressure must certainly be necessary (even if other volatiles are present) to allow the existence of a magma derived from ordinary rocks at temperatures of 650° C or below. (It is assumed here that a possible magma derived from the granulite facies rocks late in the metamorphic history of the region would have been a palinogenetic magma resulting from differential melting of these rocks and «sweating out» of the molten material).

In conclusion it must be said that a definite answer to the final question — what was the nature of the pegmatite forming fluid? — cannot be given. There have been found neither features which decisively prove what the nature of the fluid was nor features which are fatal to all but one conceivable possibility. The question must remain unanswered.

Only two possibilities seem to exist. Either the material now constituting the vein crystallized from a magma which was injected into a crack formed in the banded gneiss, or it crystallized from a disperse phase composed of high energy particles (ions, molecules, atoms) which diffused (and in a sense also were injected) into a crack formed in the banded gneiss. Most readers will probably prefer to believe in one or the other, but the author is aware of no evidence which justifies a conclusion.

Acknowledgements

Dr. H. Bjørlykke, director of the Geological Survey of Norway, has kindly allowed the publication of this paper and has allowed me to engage in this study while in the employ of the Geological Survey.

He has also made available to me the facilities of the Geological Survey of Norway. Thanks are also due to Miss K. Haugen who has performed almost all of the alkali determinations. The staff of the Geological Survey and the Mineralogisk-Geologisk Museum, University of Oslo, have at all times willingly given their assistance when it was needed. Dr. K. Heier has often discussed the problems of this study and related subjects with me, and for his time and interest I extend my thanks. For making available the facilities of the Mineralogisk-Geologisk Museum, and for very valuable criticism and advice and his unfailing interest and encouragement I wish especially to thank Prof. T. F. W. Barth.

Errata

In Pegmatite Veins and the Surrounding Rocks: I. Petrography and Structure : Norsk Geologisk Tidsskrift, Bind 36, Hefte 3, pp. 213—239, 1956, the composition of the plagioclase in sample ÖP17 was incorrectly reported. The following changes should be made.

p. 221 (in two places) — for An_{35} read An_{27} .

This change results in a change in the determined temperature of the pegmatite vein.

p. 235 — for 610° C read 570° C.

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Manuscript received May 5, 1959.

Printed September 1959.