

PEGMATITE VEINS AND THE SURROUNDING ROCKS

II. Changes in the olivine gabbro surrounding three pegmatite veins, Risør, Norway.

BY
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Abstract: A detailed study was made of the changes in the olivine gabbro surrounding three pegmatite veins at Risør, Norway.

The pegmatite veins and the surrounding rocks are briefly described petrographically. From the modal analyses of twenty samples the changes in the chemical composition of the surrounding rock as a function of distance from the veins were calculated. These calculations show that near each of the veins there exist zones of markedly increased basicity. A discussion of the distribution of pressure near a break in a competent rock (e. g. olivine gabbro) surrounded by a rock flowing plastically (e. g. gneiss) during the dynamic regional metamorphism leads to the conclusion that pressure differences would be created such that thermodynamic gradients would necessitate the migration of material from zones of relatively high pressure to zones of relatively low pressure, minerals of low mol volume being preferred in the zones of high pressure, while minerals of large mol volume would be preferentially formed in the zones of

low pressure. The pegmatite veins and the nearby zones of increased basicity are therefore interpreted as the result of a process of metamorphic segregation during the dynamic metamorphism of the area.

Calculations of the density of cations per unit number of oxygen ions according to Barth's standard cell method (2, 3), and calculations of the changes in the volume occupied by a unit number of oxygen ions, based on a method taking into account the mol volumes and the modal percentages of the constituent minerals, verify the validity of the mode of formation proposed for the pegmatite veins and the nearby depleted zones of increased basicity.

Introduction

This paper is the result of a detailed investigation of the changes found in a normally very homogeneous country rock in the vicinity of three pegmatite veins. The country rock surrounding the veins is an olivine gabbro. In the near vicinity of the veins the surrounding rock is completely recrystallized and metamorphosed to amphibolite.

A series of samples was collected in a road cut in an olivine gabbro body near the town of Risør on the south coast of Norway. Figure 1 is a diagrammatic sketch of the road cut showing the relative positions of the veins and the locations of the samples.

The olivine gabbro occurs as an elongate body about 120 m wide and 1 km long before it disappears into the sea. It is surrounded by gneiss (gneissic migmatite and banded gneiss) and is elongate parallel to the main strike direction which, locally, is about N55E. The dips in this area are near perpendicular.

BUGGE's (8) studies of the Kongsberg-Bamble formation and my detailed study of the island St. Hansholmen (23) indicate that the regional metamorphic facies reached in the Risør area was the amphibolite facies.

The gabbroic rocks which occur along the south coast of Norway have been very thoroughly studied and described by BROGGER (7). The reader is referred to his paper for general information about these rocks, the variations in them, and their special characteristics. In this paper only those features which occur within the small area studied will be considered.

The paper is divided into two parts. The first part, in which interpretation has been avoided, is descriptive, presenting the data on which the second and interpretive part is based.

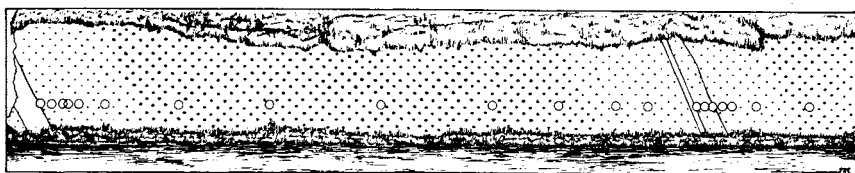


Fig. 1. Diagrammatic sketch of the roadcut from which samples were taken. The pegmatite veins are shown in white, the olivine gabbro is stippled, and the relative positions of the samples are shown by open circles. Vein number 1, at the left, is just over 1 meter broad. The horizontal distance between vein number 1 and vein number 2 is just over 25 meters. The sample farthest from the veins was taken at a point out of the sketch to the right, 15 m horizontally from vein number 2.

Petrography

PEGMATITE VEINS

The pegmatite veins consist primarily of plagioclase and quartz. A modal analysis was performed on an 80 cm² polished surface of vein number 1, the results of which appear in table 2. In vein number 1, the largest vein, there is an ill defined zoning; quartz and plagioclase being graphically intergrown near the boundaries and occurring as separate masses towards the center. Dark minerals are rare throughout; plates of biotite and very small flecks of opaque minerals having been seen. Vein number 2 also consists primarily of plagioclase and quartz, is slightly finer grained than vein number 1, is not visibly zoned, but contains a slightly higher percentage of dark minerals; biotite, hornblende, and garnet having been identified here. The two cm broad veinlet, vein number 3, is slightly finer grained than vein number 2, also consists primarily of plagioclase and quartz, with a small amount of hornblende and a very little biotite.

The An content of the plagioclase at three different points in vein number 1 was determined by means of the index of refraction. As can be seen from figure 2 the plagioclase in the vein is less calcic than that in the surrounding rock but becomes more calcic towards the center of the vein than it is near the vein boundaries. In figure 2 one can also see that the plagioclase of vein number 2 is less calcic than that of the surrounding rock.

OLIVINE GABBRO

The rock which surrounds the pegmatite veins consists of plagioclase, olivine, and clinopyroxene as essential minerals, apatite and opaque minerals as accessories, and biotite, orthopyroxene, brown amphibole, and symplectitic green amphibole and spinel in corona structures (see table 2, sample R2PC9 for the modal analysis of the least metamorphosed sample). According to the system of classification proposed by JOHANNSEN (17) the rock receives the symbol 2312P; the appropriate petrographic name therefore being olivine gabbro.¹

The micro-texture of the least metamorphosed olivine gabbro is medium grained, consisting of lath shaped plagioclase, equidimensional olivine, and sub-ophitic clinopyroxene. Coronas occur around the dark minerals. Biotite occurs in the coronas around the opaque minerals. A thin corona of brown amphibole occurs around clinopyroxene. Around the grains of olivine there occurs a double corona consisting of an inner corona of orthopyroxene and an outer corona of symplectitic light green amphibole needles² and dark green spinel blebs. These coronas are of types described by BRØGGER (7), SEDERHOLM (24), and others, and are in no way unusual.

¹ Hyperite is the name which scandinavian geologists have generally used for the gabbroic bodies which occur in the Kongsberg-Bamle formation and for the similar bodies which occur in southwestern Sweden. BRØGGER (7), BUGGE (8), HØGBOM (14), TØRNEBOHM (25), and others have used the name hyperite. For reasons pointed out by GJELSVIK (12, pp. 116, 117) and from HJELMQUIST's (13) review of the term hyperite, the author thinks that hyperite is an unnecessary petrographic term, and because of the difference in the meaning of the term, as defined by scandinavian geologists and by widely used petrography textbooks (HOLMES (15), JOHANNSEN (17), TRØGER (26)), it is a term subject to misunderstanding. Hyperite may be a useful geologic term if limited in application to those bodies of gabbroic rock occurring in southern Norway and southwestern Sweden. Used in this way the term includes normal gabbros, olivine gabbros, and gabbros transitional into norites. As this report is not a general report on the hyperites of the region but rather a report on the detailed changes in the rock within a very small area, the author prefers to use the petrographic term which accords with the world-wide petrographic nomenclature for the type of rock under consideration — that is, olivine gabbro.

² JØSANG (18) has identified diopside as the light green mineral in the outer corona around olivine from the Modum area. Therefore a tiny piece of the outer corona around olivine was separated and by means of an x-ray powder photo was identified as amphibole.

Within ca. 2.5 m of the pegmatite veins the olivine gabbro is completely recrystallized and metamorphosed to amphibolite. From the samples furthest removed from the veins to the zone of amphibolite nearest the veins, certain changes in the corona structures can be followed.

From the samples furthest removed from the pegmatite veins up to within about 4.5 m from the pegmatites the coronas increase in size. This is especially marked for the double coronas around olivine. Only the sample most distant from the veins contains appreciable amounts of olivine.

It appears to be the case that after the inner corona of orthopyroxene has, by growing inwards, completely replaced the original grain of olivine, the outer amphibole-spinel corona continues to grow at the expense of plagioclase and the inner corona of orthopyroxene until, at a distance of about 4.5 m from the veins, the orthopyroxene is completely replaced and only a cluster of small amphibole grains remains.

In the samples furthest removed from the veins the corona of brown amphibole around the ophitic clinopyroxene is quite thin. The corona becomes only slightly thicker upon approaching the veins until, quite abruptly within a small interval about 3.5 to 4.5 m from the veins, the clinopyroxene is completely replaced by amphibole.

At a distance of about 3 m from the veins there can therefore be seen two types of amphibole; the clusters of small grains derived from the original olivine and the large ophitic grains derived from clinopyroxene.

The coronas of biotite around the opaque grains are never very large and disappear completely when the rock becomes completely recrystallized.

Changes in the plagioclase can also be followed on approaching the veins. In the samples furthest removed from the veins the plagioclase occurs as lath shaped grains which are densely clouded by very fine inclusions. The inclusions impart to the plagioclase a quite dark brownish-violet color. Examination of a polished section in reflected light at 1000 times magnification revealed that the inclusions for the most part are approximately rectangular in shape and lie in the size range between 0.001 mm and 0.0001 mm. There were no detectable changes in the magnetic properties of the plagioclase with change in

density of the inclusions insofar as this could be determined with the Franz Magnetic Separator. A quantitative spectrographic determination for Fe and Ti was performed on hand picked pure plagioclase from sample R1PC9, the results of which are shown in table 1. From the above information it seems most likely that the inclusions are primarily hematite. For other discussions on clouded plagioclase see POLDERVAART and GILKEY (19) and CARSTENS (9).

Table 1.
Partial spectrographic analysis of clouded plagioclase.

Sample R1PC9		
Fe ₂ O ₃ (total Fe)	= 0.25 wt. %	Analyst: B. Dirdal
TiO ₂	= 0.05 " "	Sentralinstitutt for industriell forskning.

At a distance of about three meters from the veins the plagioclase occurs as corroded laths and the density of the inclusions is reduced. Within 2.5 m from the veins the plagioclase occurs as clear, unclouded, irregularly shaped grains.

Within 2.5 m distance from the veins the rock surrounding the veins is a completely recrystallized amphibolite. The amphibolite consists of medium sized, interlocking, irregularly shaped grains of plagioclase and green to greenish-brown amphibole with accessory apatite, opaque minerals, and biotite.

Besides the textural and qualitative mineralogical changes in the rock surrounding the pegmatite veins there are quantitative changes which are also clearly related to the veins.

There is a distinct variation in the composition of the plagioclase in the surrounding rock as a function of distance from the veins. This variation is shown in table 2 and diagrammatically, along with the change in composition of the plagioclase within vein number 1, in figure 2. The An content in the plagioclase from the various sample was determined by means of the index of refraction.

Spectrographic analyses of plagioclase for Sr showed that the Sr content in the plagioclase from the veins is lower than in the plagioclase from the surrounding rock. Plagioclase taken near the boundary of vein number 1 contained ca. 100 ppm Sr while that taken near the center contained ca. 200 ppm. In the surrounding rock the Sr content

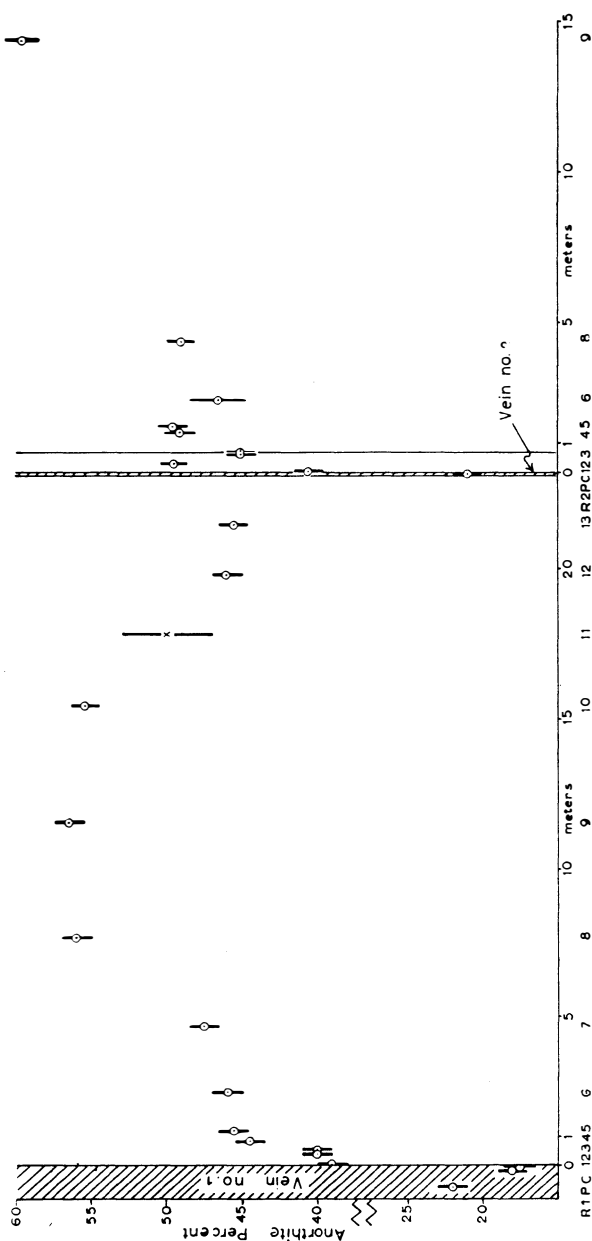


Fig. 2. The change of An content in the plagioclase shown as a function of distance. An content along the ordinate; distance along the abscissa.

in the plagioclase is quite constant at ca. 500 ppm except for samples R1PC4, R1PC5, R1PC13, R2PC2, and R2PC5 in which the Sr content is ca. 800 ppm. (Only one run was made of each sample and the amount of Sr was determined by visually estimating the relative density of the faintest step of the Sr line which could be seen on the spectrographic plate. Consequently no high degree of accuracy can be claimed for the figures given.)

Garnet occurs sporadically in tiny grains and in small clusters throughout the olivine gabbro. In one case it was observed as a participant in the outer corona around olivine. Garnet was separated from one sample (R1PC12) and its composition was determined from the unit cell size (11.514\AA), index of refraction (1.775), and specific gravity (4.08). Its composition is therefore about 50 percent pyrope and 50 percent almandine. An x-ray powder diagram of garnet from pegmatite vein number 2 showed the same spacing as that of the garnet from the olivine gabbro.

Modal analyses were made of the thin sections of all the samples of the olivine gabbro except for sample R1PC2. This sample was omitted because the section was small and was dominated by three relatively large plagioclase grains. The thin section was evidently not representative of the rock at the point where the sample was taken. Modal analyses of 13 of the sections were made using the Hurlbut electric counter moving the slide at the rate of about 16 mm per minute. In those cases where the number of minerals to be counted exceeded the number of keys on the Hurlbut counter a point counter was used. 7 sections were counted with the point counter. The minimum number of counts was 1160 and the maximum was 1720. The results of the modal analyses are shown in table 2 and figures 3 and 4. In the diagrams showing the modal composition of the rocks the percentages of the various mineral types are plotted as a function of the distance from the veins.

As can be seen especially well from figures 3 and 4, there are quantitative mineralogical changes in the rock which surrounds the veins. It is to be noted that at a short distance from the veins there is a marked decrease in total plagioclase and a corresponding marked increase in total dark minerals. This change in the mineralogical composition is not strikingly evident in the field, partly, at least, being obscured by the change in color of the plagioclase.

Table 2.
Modal analyses of thin-sections.

Sample no.	Quartz	Plagioclase				Olivine	Clinopyroxene	Orthopyroxene	Amphibole	Biotite	Garnet	Opaque	Apatite	Σ Dark ²⁾
		An ¹⁾	Total	Albite	Anorthite									
R1PC1	—	39	65.4	39.9	25.5	—	—	—	28.7	0.7	3.2	1.7	0.3	31.9
3	—	40	56.2	33.8	22.5	—	—	—	37.1	5.8	—	0.4	0.4	37.1
4	—	44 1/2 ³⁾	44.7	24.8	19.9	—	—	—	52.6	0.1	—	2.2	0.3	52.6
5	—	46	47.1	25.4	21.7	—	—	—	49.9	2.1	—	0.8	0.1	49.9
6	—	46 ³⁾	56.4	30.4	25.9	—	—	—	41.7	0.1	—	1.5	0.5	41.7
7	—	47 1/2	62.6	32.9	29.7	1.9	6.1	9.4	18.5	—	—	1.3	0.2	35.9
8	—	56	62.1	27.3	34.8	—	1.2	9.7	17.5	1.2	6.5	1.8	—	34.9
9	—	56 1/2	66.0	28.7	37.3	—	2.7	10.2	18.2	1.5	—	1.2	0.1	31.1
10	—	55 1/2	61.3	27.3	34.3	—	0.9	11.6	24.1	—	—	1.8	0.3	36.6
11	—	50	61.8	30.9	30.9	1.0	11.6	5.3	16.6	—	—	3.5	0.2	34.5
12	—	46	37.7	20.4	17.6	—	—	7.4	43.5	—	10.0	1.0	0.3	60.9
13	—	45 1/2	57.2	31.2	26.0	—	—	—	41.3	0.4	—	0.8	0.2	41.3
R2PC1	—	40 1/2	39.2	23.3	15.9	—	—	—	43.3	16.6	—	0.6	0.2	43.3
2	—	49 1/2	28.2	14.2	14.0	—	—	—	71.4	0.2	—	0.1	0.1	71.4
3	—	45	41.7	22.9	18.7	—	—	—	56.3	0.3	—	—	1.6	56.3
4	—	49	49.8	25.4	24.4	—	—	—	48.5	1.4	—	—	0.2	48.5
5	—	49 1/2	27.5	13.9	13.6	—	—	—	72.1	0.1	—	0.3	0.1	72.1
6	—	46 1/2	40.2	21.5	18.7	—	—	—	59.3	0.1	—	0.3	0.1	59.3
8	—	49	58.0	29.6	28.4	0.2	8.2	10.0	22.1	—	—	1.2	0.1	40.6
9	—	59 1/2 ³⁾	59.1	23.9	35.2	12.0	8.8	5.3	13.5	0.1	—	0.9	0.3	39.6
R1P1 ⁴⁾	27.0	18	72.8	59.7	13.1	0.2								

¹⁾ An content of plagioclase determined by index of refraction except for R1PC11 for which the determination was by maximum-extinction angle in thin-section.

²⁾ The sum of olivine, pyroxenes, amphibole, and garnet.

³⁾ An content of plagioclase in these samples determined by the extinction angle in the plane \perp (001) and (010) and the maximum extinction angle in the zone II (010) using the 5-axis universal stage, showed that the determination by refractive index was too high by 2 to 3 An %.

⁴⁾ Modal analysis of a sample from pegmatite vein no. 1; performed on a polished surface 80 cm².

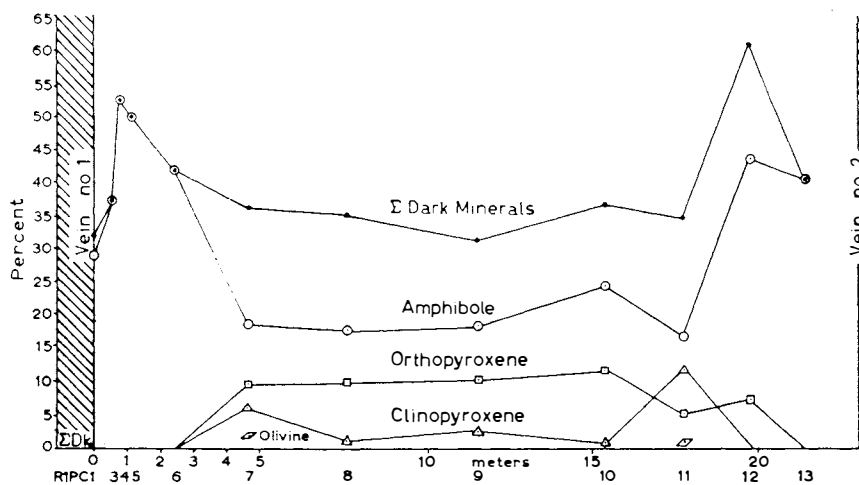
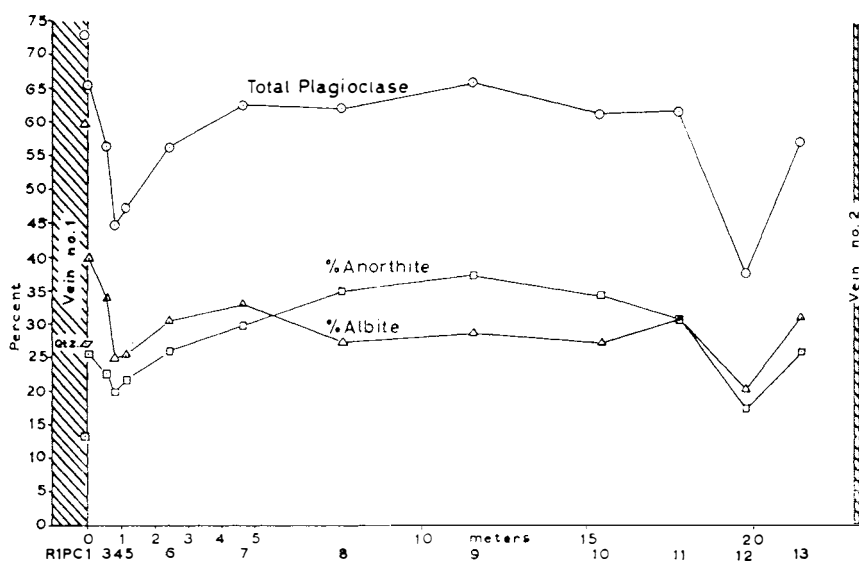


Fig. 3. Results of modal analyses. a. The variation in the percentage of plagioclase as a function of distance between vein number 1 and number 2. Total plagioclase is separated into anorthite and albite which is also shown. b. The variation of the dark minerals as function of distance between vein number 1 and number 2.

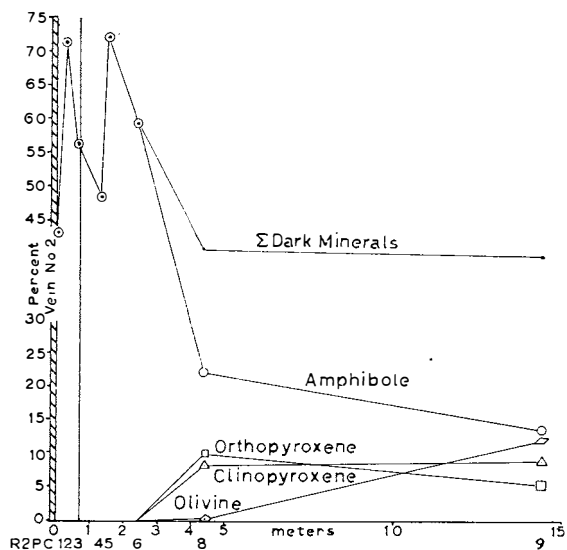
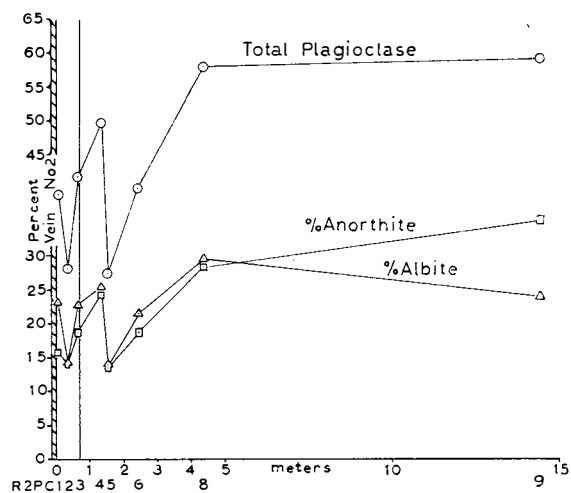


Fig. 4. Results of modal analyses. a. The variation in the percentage of total plagioclase, anorthite, and albite, as a function of distance from vein number 2. b. The variation of the dark minerals as function of distance from vein number 2.

The relationship between the curve for total dark minerals, amphibole, and plagioclase is interesting in that it supports the interpretation based on textural evidence that amphibole grows at the expense of plagioclase and the pyroxenes. It has been proposed (7) that this mineralogical reaction is possible with little or no change in the total chemistry of the rock.

Because this change may be possible without any change in bulk chemical composition and because the total content of the albite molecule in the rock (see figure 3) does not vary with the distance from the veins in the same way as the composition of the plagioclase varies (figure 2), interpretation and theorising concerning the genesis of the pegmatite veins on the basis of the data so far presented is hazardous. This is so because inspection of the data does not make the chemical changes in the rock evident.

Petrochemical calculations

Because a discussion of the genesis of the veins ought to take into consideration the changes in the chemistry of the rock surrounding the veins as a function of the distance from the veins, the chemical composition of the rock at the points where samples were taken was calculated from the modal analyses.

To do this the chemical compositions of the minerals had to be known. As mentioned previously, the composition of the plagioclase and the garnet was determined from physical properties. The composition of the amphibole could be determined with reasonable accuracy from the chemical analyses¹ of two samples of amphibolite. The remaining minerals occurred intimately intergrown in corona structures and were impossible to separate. Therefore the compositions of the individual mineral types could not be determined. However, by using the chemical analysis of the least metamorphosed olivine gabbro and subtracting the amounts necessary for plagioclase, amphibole, and accessories, the distribution of Si, Al, Fe, Mg, and Ca in olivine and the pyroxenes could be assumed. In addition a number of pub-

¹ Chemical analyses of three samples (R1PC4, R1PC6, and R2PC9) were performed in the analytical laboratory of the Geological Survey of Norway.

Table 3.

 Mineral formulas used in petrochemical calculations¹

Olivine	Mg ₆ Fe ₆ Si ₆ O ₂₄
Orthopyroxene	Mg _{4.9} Fe _{2.7} Al _{0.8} Si _{7.6} O ₂₄
Clinopyroxene	Ca _{3.0} Mg _{3.0} Fe _{0.75} Al _{1.5} Si _{7.5} O ₂₄
Amphibole	Na _{0.6} Ca _{1.8} Mg _{2.7} Fe _{1.35} Al _{2.3} Si _{6.7} O ₂₂ (OH) ₂
Biotite	K _{1.8} Mg _{2.5} Fe _{2.5} Al _{3.0} Si _{5.8} O ₂₀ (OH) ₄
Garnet	Mg ₃ Fe ₃ Al ₄ Si ₆ O ₂₄
Anorthite	Ca ₃ Al ₆ Si ₆ O ₂₄
Albite.....	Na ₃ Al ₃ Si ₉ O ₂₄

¹ Several of the formulas used do not agree exactly with the ideal formulas for the minerals. Real variations from ideality were taken into account.

Table 4.

Calculated compositions in cation %.

Sample	Si	Al	Fe	Mg	Ca	Na	K
R1PC1	49.1	23.9	3.2	5.8	8.6	9.3	
3	47.9	22.6	4.2	7.5	8.9	8.3	0.7
4 ¹	46.9	21.3	4.7	9.4	10.4	7.2	
5	46.8	21.8	4.7	9.1	10.2	7.1	0.2
6 ¹	47.6	23.1	3.7	7.4	10.2	7.9	
7	48.4	22.6	4.2	8.0	9.4	7.4	
8	46.8	24.9	4.7	7.8	9.4	6.2	0.1
9	47.4	24.8	3.7	7.2	10.2	6.5	0.2
10	47.5	23.8	4.2	8.0	10.0	6.5	
11	48.3	23.2	3.4	7.4	10.7	7.1	
12	45.9	20.7	7.0	11.9	8.7	5.8	
13	47.8	23.1	3.7	7.3	10.2	8.0	
R2PC1	45.7	20.9	6.5	10.3	8.3	6.4	1.9
2	45.3	19.2	6.3	12.5	11.2	5.6	
3	46.6	20.9	5.0	10.1	10.5	6.9	
4	46.7	22.4	4.5	8.7	10.6	7.0	0.2
5	45.2	19.0	6.3	12.6	11.2	5.6	
6	46.4	20.5	5.3	10.5	10.6	6.7	
8	48.2	22.2	4.1	8.7	10.0	6.9	
9 ¹	45.7	22.2	6.5	9.7	10.3	5.5	

¹ The calculated values of Si, Al, Ca, and Na are slightly changed if the An %'s determined with the universal stage are used. Si changes by a maximum of 0.4 %, Al by a maximum of 0.7 %, Ca by a maximum of 0.5 %, and Na by a maximum of 0.3 %.

Table 5.
Chemical Analyses.

	R1PC4				R1PC6				R2PC9						
	Wt %	Cat-ion Prop.	Cat-ion %	Sub-tr. ¹⁾ for acc.	Cat-ion ²⁾ % rec. to 100 %	Wt %	Cat-ion Prop.	Cat-ion %	Sub-tr. ¹⁾ for acc.	Cat-ion ²⁾ % rec. to 100 %	Wt %	Cat-ion Prop.	Cat-ion %	Sub-tr. ¹⁾ for acc.	Cat-ion ²⁾ % rec. to 100 %
SiO ₂	47.66	7 943	44.41		46.53	48.15	8 025	44.95		47.15	47.83	7 972	43.87		45.16
TiO ₂	1.84	230	1.28	1.28		1.32	165	0.92			1.00	125	0.69	0.69	
Al ₂ O ₃	20.58	4 035	22.56		23.63	20.98	4 114	23.04		24.17	20.09	3 939	21.68		22.32
Fe ₂ O ₃	1.02	128	0.72	0.72		1.51	189	1.06	1.06		0.67	84	0.46	0.46	
FeO	8.90	1 236	6.91	1.28 0.36	5.67	7.65	1 062	5.95	0.92 0.53	4.87	9.65	1 340	7.37	0.69 0.23	6.77
MnO	0.18	25	0.14			0.18	25	0.14			0.17	24	0.13		
MgO	5.45	1 362	7.62		7.98	5.13	1 282	7.18		7.53	7.85	1 963	10.80		11.12
CaO	9.25	1 632	9.24	0.28	9.39	9.00	1 607	9.00	0.40	9.02	8.80	1 571	8.64	0.27	8.62
Na ₂ O	3.60	1 161	6.49		6.80	3.83	1 235	6.92		7.26	3.29	1 061	5.84		6.01
K ₂ O	0.38	81	0.46	0.46		0.50	106	0.59	0.59		0.26	55	0.30	0.30	
H ₂ O-	0.10					0.90					0.11				
H ₂ O+	0.65					0.71					0.34				
CO ₂	—					—					—				
P ₂ O ₅	0.22	31	0.17	0.17		0.30	42	0.24	0.24		0.21	29	0.16	0.16	
S	0.28					0.60									
Total	100.11		100.00	4.55	100.00	99.95		100.00	4.66	100.00			100.00	2.80	100.00
O=S	0.07					0.14									
Total	100.04					99.81					100.27				

Analyst: Liv Bolkesjø, NGU Laboratory.

¹⁾ In order to make comparison with the calculated values possible, TiO₂, Fe₂O₃, P₂O₅ and the necessary FeO and CaO were subtracted, being attributable to accessory Ilmenite, Magnetite and Apatite.

²⁾ After subtraction of the cations necessary to make the accessory minerals the cations remaining were recalculated to 100 % because all calculated compositions were calculated to add up to 100 %.

Table 6.

Comparison between chemical analyses and calculated values.

Sample No.	Si	Al	Fe	Mg	Ca	Na
R1PC4 ¹			5.67	7.98		
Chem. analysis	46.53	23.63	13.65		9.39	6.80
R1PC4			4.7	9.4		
Calculated values	46.9	21.3	14.1		10.4	7.2
R1PC6			4.87	7.53		
Chem. analysis	47.15	24.17	12.40		9.02	7.26
R1PC6			3.7	7.4		
Calculated values	47.6	23.1	11.1		10.2	7.9
R2PC9			6.77	11.12		
Chem. analysis	45.16	22.32	17.89		8.62	6.01
R2PC9			6.5	9.7		
Calculated values	45.7	22.2	16.2		10.3	5.5

¹ The values given for the chemical analyses are in cation % recalculated to 100 % after subtraction of the cations which form accessory minerals. Accessories were not included in the calculated values.

lished analyses² of the minerals concerned were examined. The mineral formulas which were used in the calculations are shown in table 3.

The method used to make these calculations starts with the modal analyses and the formulas assigned to the minerals present. The calculation follows the reverse path of a norm calculation, stopping at the cation percent. Accessory minerals were ignored in the calculations.

The results of these calculations are shown in table 4 and diagrammatically in figure 5. The comparisons between the chemical analyses,

² The chief sources were HOWIE (16), DE VORE (10, 11), and RAMBERG and DE VORE (22). Analyses of 32 biotites, 30 hornblendes, 20 clinopyroxenes, 17 orthopyroxenes, and 2 olivines plus the study by RAMBERG and DE VORE (22) of co-existing olivines and orthopyroxenes were used to help in determining the mineral compositions to be used in the calculations.

R21P ⁹	43.9	0.7	21.7	0.5	7.4	0.1	10.8	8.6	5.8	0.3	0.2	23.9 (26.6) ¹
Albite	16.4		5.5						5.3	0.2	27.4	35.2 (32.5) ¹
Anorthite	11.3		11.4					5.7			28.4	12.0
Olivine	4.0				4.0		4.1				12.1	8.8
Clinopyroxene	3.7		1.5		0.4		1.8	1.4			8.8	5.3
Orthopyroxene	3.4		0.5		0.8		2.8				7.5	13.5
Amphibole	5.1		2.8		1.2	0.1	2.1	1.2	0.5	0.1	13.1	0.1
Biotite	—		—		—		—			—	—	0.9
Opaque		0.7		0.5	1.0						2.2	0.3
Apatite								0.3			0.2	

Yields Olivine formula: $Mg_{6.0} Fe_{6.0} Si_{6.0} O_{24}$
 Clinopyroxene « : $Ca_{2.5} Mg_{3.2} Fe_{0.7} Al_{2.7} Si_{6.8} O_{24}$
 Orthopyroxene « : $Mg_{5.9} Fe_{1.7} Al_{1.1} Si_{7.4} O_{24}$
 Amphibole « : $K_{0.1} Na_{0.6} Ca_{1.5} Mg_{2.5} Mn_{0.1} Fe_{1.5} Al_{3.3} Si_{6.1} O_{22} (OH)_2$

¹ The values shown in parentheses are those obtained if the An values determined by use of the universal stage are used.

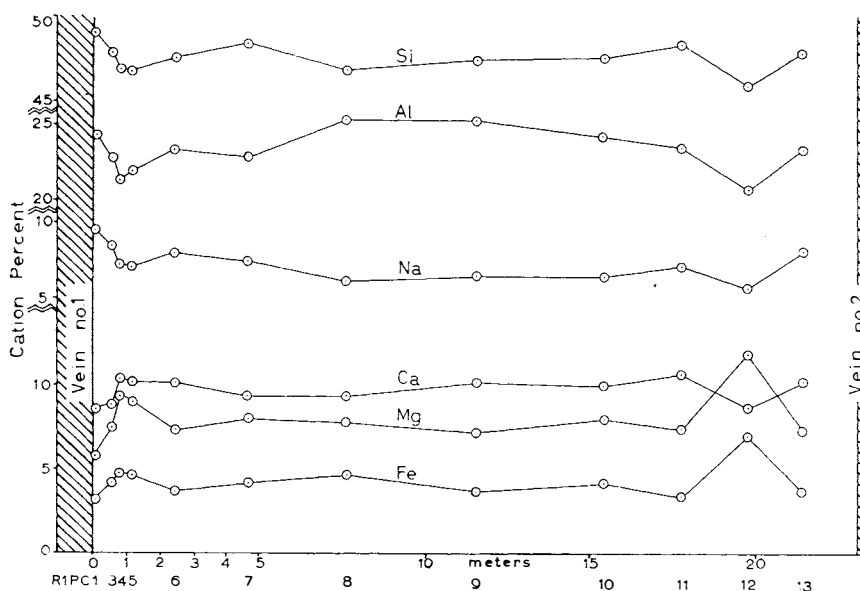


Fig. 5 a. Results of the calculated chemical compositions as a function of distance between vein number 1 and vein number 2.

shown in table 5, (recalculated to cation percents and again recalculated to 100 percent after the subtraction of TiO_2 , Fe_2O_3 , P_2O_5 , and the necessary FeO and CaO to form the accessories) and the calculated compositions are shown in table 6. From the chemical analyses the modes were also calculated in the manner shown by BARTH (5) (see table 7).

On the diagram showing the variations in the calculated composition of the rock surrounding the veins the reader is asked to note especially the shape of the curves for Si, Al, and Na in contrast to the curves for Mg, Fe, and Ca. Strikingly borne out by these curves is the fact that near the veins there exists a zone of markedly increased basicity of the surrounding rock. It is clear that those elements which are enriched in the veins are depleted in the basified zones near the veins, while those elements which occur in only minimal amounts in the veins are enriched in the nearby zones. Ca follows the curves of Mg and Fe more closely than those of Si, Al, and Na, but occupies an

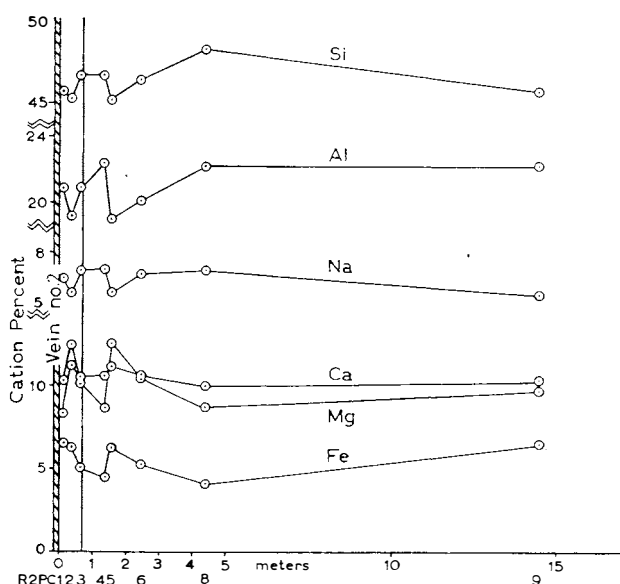


Fig. 5 b. Results of the calculated chemical compositions as a function of distance from vein number 2.

intermediate position. This is not surprising as Ca occurs in appreciable amounts both in the plagioclase and in the dark minerals, hornblende and clinopyroxene.

Having come this far it seems that one has enough data to begin the discussion of the genesis of the pegmatite veins.

Genesis of the Pegmatites

The explanation of the zones of increased basicity, their location near the pegmatite veins, and the cause of the formation of the pegmatite veins, is to be found in the physical properties of the rocks and the resulting distribution of pressure in them during the dynamic metamorphism of the area.

The olivine gabbro is surrounded by gneiss which deformed plastically during the dynamic metamorphism of the area (8, 23). The olivine gabbro must be reckoned as a very competent rock which would

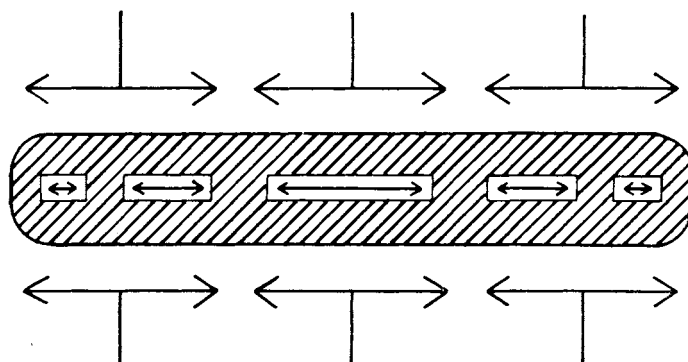


Fig. 6. A boudin in which the arrows show the magnitude of the tensile stress caused by the plastic flow of the surrounding gneiss.

be capable of only very little plastic deformation (see ANDERSEN, 1 and RAMBERG, 21).

In order to understand what happens within the competent olivine gabbro in response to the plastic deformation of the surrounding gneiss, let us first consider the distribution of tensile stress within a boudin surrounded by plastically flowing gneiss, the whole being under compression.

The friction along the surface between the competent boudin and the plastically flowing gneiss which surrounds it gives rise to tensile stress within the boudin. The tensile stress at any point within the boudin will be a function of the distance of that point from the nearest end of the boudin, such that the tension increases as the distance from the end increases (see figure 6 and RAMBERG, 21, figure 2, p. 516). If the boudin is not capable of sufficient plastic deformation it will break when the tensile stress becomes sufficiently great. In a homogeneous boudin the break must occur near the middle of the boudin — not at the ends where the tension is least. Any zone of weakness will, of course, be a favorable site for fracture if it is in a part of the boudin which is under sufficient tensile stress.

What is seen to be the case within the boudin is applicable to the olivine gabbro body. It is a very competent and homogeneous body surrounded by gneiss which flowed plastically.

Within the part of the olivine gabbro under consideration one can assume that at first quite uniformly distributed tensile stress was

developed. At a zone of weakness (due e. g. to slight inhomogeneity or previous tectonic disturbance) there occurred a break (which would be essentially perpendicular to the direction of tensile stress) in which the pressure would be exceptionally low, and across which the tensile stress could not be transmitted. After the break has occurred its sides are directly comparable to the ends of the boudin, except that the pressure in the break would be less than the pressure in the plastic gneiss which surrounded the boudin. (It is most unlikely that the gneiss would have flowed plastically into the break where the pegmatite vein now exists. The roadcut from which the samples were taken is fully 40 m from the nearest gneiss. The largest vein is only 1 m broad. The break was undoubtedly much less than 1 m across when it was first formed and therefore the viscosity of the gneiss would have been too great to allow it to flow into the break. See p. 304 for further discussion of the development of the break.) The tensile stress in the olivine gabbro, caused by the plastic flow of the surrounding gneiss, will therefore be at a minimum adjacent to the break and will increase as the distance from the break increases (figure 7, b).

As the tensile stress can be thought of as tending to pull the mineral grains apart from one another in the direction of the stress, thus reducing the pressure on the grains in that direction, it follows that the mineral grains in the olivine gabbro are under anisotropic pressure (see figure 7, a and b) because of the tensile stress caused by the plastic flow of the surrounding gneiss. The degree of anisotropy of the pressure at any point will be directly proportional to the tensile stress at that point. Therefore, as the tensile stress caused by the plastic flow of the gneiss increases with distance from the break, the anisotropy of pressure due to this effect will increase with distance from the break (figure 7, c). However, there is another factor which, near the break, will cause anisotropic pressure on the grains.

In the break the pressure is exceptionally low. Because the pressure in the break is very low the mineral grains in the olivine gabbro immediately adjacent to the break will be under strongly anisotropic pressure (low pressure in the direction perpendicular to the break). This effect will decrease with increasing distance from the break (figure 7, d). The effect on the mineral grains is similar to that due to the tensile stress caused by the plastic flow of the gneiss, but its change of magnitude relative to the distance from the break is oppo-

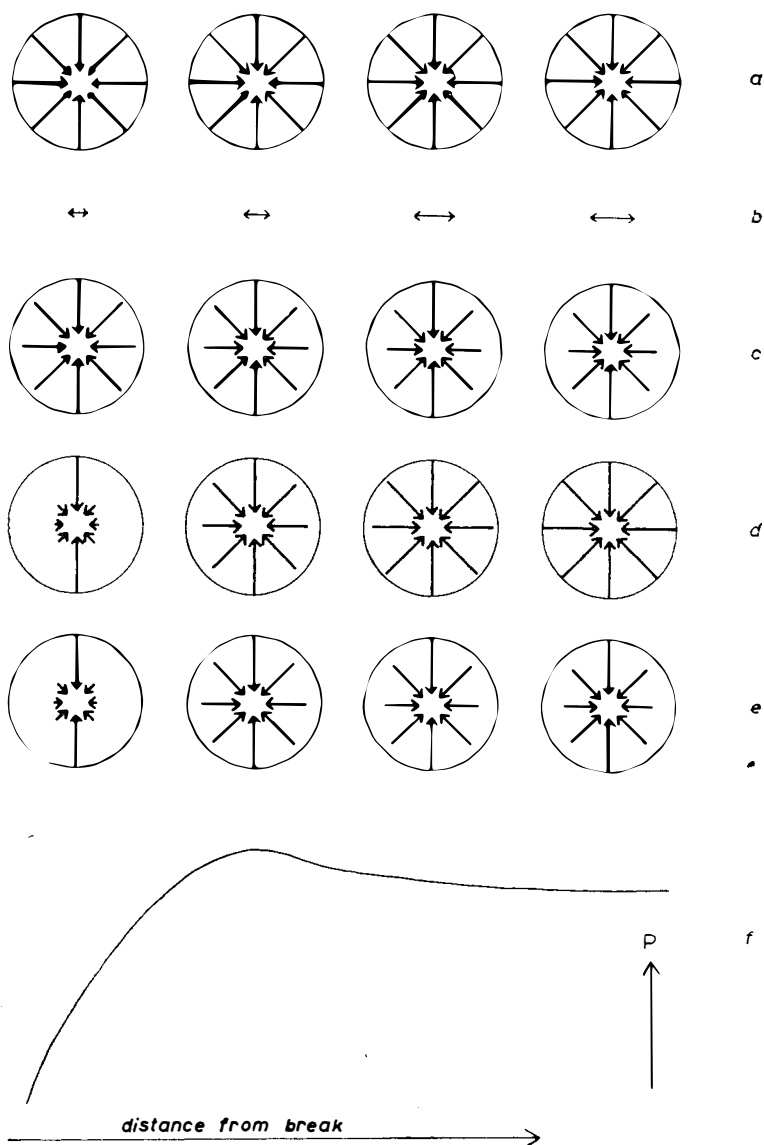


Fig. 7. In the diagram the break is at the left hand side. Distance from the break increases towards the right.

site. That is to say, the reduction of pressure in the direction perpendicular to the break because of the tensile stress caused by the plastic flow of the gneiss will be directly proportional to the distance from the break, whereas the reduction of pressure in the direction perpendicular to the break because of the very low pressure in the break will be inversely proportional to the distance from the break.

If these two effects are superimposed one is able to draw pressure rosettes for several points in the olivine gabbro showing the relative amount by which the pressure in the direction perpendicular to the break is reduced (figure 7, e). The curve showing the variation of pressure (in the direction perpendicular to the break) with distance from the break which results from this superimposition is shown in figure 7, f. The exact shape of this curve will depend on the competence of the rock in which the break occurs. A more competent rock would be able to support a steeper pressure gradient adjacent to the break. The effect of differences in the competence of the rock in which a break occurs is shown in figure 8. Only in a competent rock could one expect a marked pressure maximum to have been maintained.

The development of the distribution of pressure postulated above causes a thermodynamically unstable situation. From a system previously under homogeneous pressure a system with low pressure

Fig. 7. Continued.

a. Pressure rosette for isotropic pressure due to hydrostatic pressure before deformation begins. Arrows represent the direction and magnitude of the pressure.

b. The arrows show the variation in magnitude of the tensile stress (due to the plastic flow of the gneiss) with distance from the break.

c. Pressure rosettes showing the change in anisotropy of pressure (due to the plastic flow of the gneiss) with distance from the break. Note that the reduction in pressure in the direction perpendicular to the break is *directly* proportional to the distance from the break.

d. Pressure rosettes showing the change in anisotropy of pressure (due to the very low pressure in the break) with distance from the break. Note that the reduction in pressure in the direction perpendicular to the break is *inversely* proportional to the distance from the break.

e. Pressure rosettes showing the change in anisotropy of pressure when the two effects which cause reduction in pressure in the direction perpendicular to the break are superimposed.

f. Curve showing the change in pressure in the direction perpendicular to the break with distance from the break.

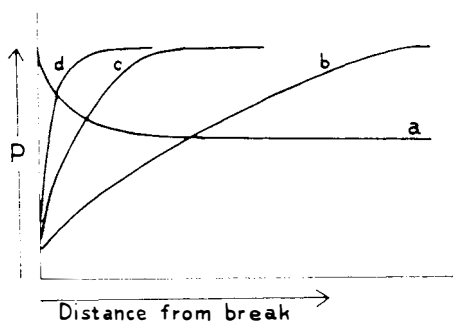


Fig. 8. Pressure curves in the direction perpendicular to the break. Curve a. shows the pressure in this direction caused by the plastic flow of the gneiss. Curves b., c., and d. show possible pressure gradients adjacent to the low pressure in the break for increasingly competent rocks. In very competent rocks a pressure maximum occurs near the break, being nearer the break the more competent the rock

zones and varying stress has been created. The result will be that the system will shift in such a way as to neutralize the effect of this change (the principle of Le Châtelier).

The creation of a low pressure zone in the break gives rise to mechanical pressure gradients (figure 7, d) which cause chemical activity gradients such that the material in the area of relatively high pressure (where the activity is high) will migrate towards the zone of low pressure (where the activity is lower). That the activity gradients parallel the pressure gradients is shown by the following equations which state the relationship between pressure, P , free energy, F , and the activity, a :

$$\left(\frac{\partial F}{\partial P}\right)_{T,X} = V$$

where V is the molal volume and T , the absolute temperature, and X , the bulk chemical composition of the system, are kept constant, and

$$F_i = RT \ln a_i + F_i^0$$

where R is the gas constant, the subscript i indicates the chemical species i , and F_i^0 is the free energy in the standard state.

The activity gradients necessitate the transport of material into the low pressure zone. Consequently the minerals in the higher pressure areas will begin to disintegrate and the constituents will migrate towards the low pressure zone where new minerals will form from the disperse phase which is introduced. Those minerals which will be most favored in the low pressure zone are minerals of high mol volume

(e. g., feldspar and quartz). On the other hand, minerals of low mol volume (e. g., amphiboles and pyroxenes) — those which most efficiently concentrate cations — will be favored in the area of higher pressure. This transport of material tends to equalize the pressure differences by reducing the amount of material in the areas of high pressure, thereby relieving the pressure, while increasing the amount of material in the low pressure zone. (For other and more detailed discussions of this process the reader is referred to Barth, 4, pp. 317, 318, and Ramberg, 20, pp. 215—220.)

This process leads primarily to the formation of feldspars (plagioclase if the environment is poor in K) and quartz in the zone of low pressure, the exact composition of the newly crystallized mineral assemblage being dependent on the composition of the disperse phase from which the minerals grew. The surrounding rock is depleted in the constituents which predominate in the newly crystallized minerals, i. e., primarily Si, Al, and Na.

From the discussion of the distribution of pressure in the olivine gabbro in the vicinity of the break it was seen that the anisotropy of the pressure on the mineral grains varied with distance in the direction perpendicular to the break. The stress on the minerals will, of course, cause recrystallization in order to relieve the stress, as indicated by Riecke's principle. However, it is to be remembered that at a short distance from the veins there exists a zone of maximum pressure in the direction perpendicular to the veins in which the anisotropy of pressure is least. In this zone the tendency for the constituents in the disperse phase to crystallize in local low pressure zones adjacent to the stressed grains is less than in any other part of the olivine gabbro, because the local pressure differences are less. However, the pressure difference between this zone and the low pressure zone in the break is greater than the difference between any other part of the olivine gabbro and the break. Therefore, it is from this zone of relatively little anisotropy of pressure that the greatest percentage of the material in the newly crystallized mineral assemblage in the break will be derived. This zone will suffer the maximum depletion of those constituents which are enriched in the low pressure zone, Si, Al, and Na, and the maximum relative enrichment of the remaining constituents, Mg, Fe, and Ca.

The deformation of the olivine gabbro caused by the plastic flow

of the gneiss is continuous throughout a period of time. The break slowly but steadily opens and is equally steadily filled by the crystallization of new minerals. The pressure differences are relieved by recrystallization (according to Riecke's principle) and by the loss of material to the low pressure zone, but are simultaneously constantly built up anew by the steady deformation. Consequently the degree of depletion in the relatively high pressure zone in the olivine gabbro can be considerable, the extent of the depletion being a function of the length of time of the deformation. The process of transfer of material will stop as soon as the pressure differences have been equalized after the deformation stops. Because the process is a response to the deformation one can expect to see no distortion adjacent to the low or the high pressure areas.

A discussion of this process which is in many respects similar to the one above, though with reference to a somewhat larger scale and with more exhaustive thermodynamic justification, has been published by Bennington (6).

The proposals above seem to constitute the most satisfactory explanation for the genesis of the pegmatite veins and the nearby zones of markedly increased basicity. Any explanation, whether it be magmatic, hydrothermal, or metasomatic, which requires that the material now present in the pegmatite veins was introduced exclusively from outside of the olivine gabbro body is unable to explain the changes in the chemistry of the rock surrounding the veins. Yet the regular repetition of the zones of increased basicity near the veins requires that both these zones and the veins be explained by one and the same process.

Two calculations have been made which serve to support the suggestions made above.

Assuming that the composition of the sample R1PC9 (taken approximately midway between veins number 1 and number 2) represents essentially unaltered olivine gabbro one can, by means of Barth's standard cell calculation (2, 3), determine the changes in the cations per 160 oxygen ions which occur during the rearrangement of material proposed above. The change in going from R1PC9 to the average of R1PC4 and R1PC5 (samples taken from the zone of increased basicity near vein number 1) and the change in going from R1PC9 to R1PC1 (the sample nearest vein number 1) were calculated. The results are

Table 8.
Standard Cell Calculations.

Sample No.	Si	Al	Fe	Mg	Ca	Na (+K)	Total
R1PC9 Cations per 160 O	48.3	25.3	3.8	7.3	10.4	6.8	101.9
R1PC1 Cations per 160 O	50.1	24.4	3.2	5.9	8.8	9.5	101.9
R1PC4 Cations per 160 O	48.8	22.2	4.9	9.8	10.8	7.5	104.0
R1PC5 Cations per 160 O	48.6	22.7	4.9	9.5	10.7	7.6	104.0
Average R1PC4 & R1PC5	48.7	22.4	4.9	9.7	10.7	7.6	104.0
R1PC9 to R1PC1	+1.8	-0.9	-2.0 -0.6	-1.4	-1.6	+2.7	
% change R1PC9 to R1PC1	+3.6	-3.6	-18.0 -14.7	-19.7	-15.1	+25.3	
R1PC9 to Av. R1PC4 & 5	+0.4	-2.9	+3.5 +1.1	+2.4	+0.3	+0.8	
% change R1PC9 to Av. R1PC4 & 5	+0.8	-11.2	+31.0 +29.1	+31.9	+3.0	+10.4	
Changes R1PC9 to R1PC1			Changes R1PC9 to Av. R1PC4 & R1PC5				
Adding		Subtracting		Adding		Subtracting	
1.8 ions Si 2.7 ions Na(K)		0.9 ions Al 0.6 ions Fe 1.4 ions Mg 1.6 ions Ca		0.4 ions Si 1.1 ions Fe 2.4 ions Mg 0.3 ions Ca 0.8 ions Na(K)		2.9 ions Al	
4.5 ions representing 9.9 valences		4.5 ions representing 9.9 valences		5.0 ions representing 10.0 valences		2.9 ions representing 8.7 valences	

Table 9.
Example of volume change calculation.

Mineral	Modal %	Recalculated to 100 %	Mol volume	Volume number
Albite.....	28.7	29.6	301	8909.6
Anorthite	37.3	38.4	302	11596.8
Clinopyroxene	2.7	2.8	242	677.6
Orthopyroxene	10.2	10.5	259	2719.5
Amphibole	18.2	18.7	278	5198.6
				29102.1

Calculated volume changes.

% Change	R1PC9 to Av. of R1PC4 and R1PC5	= -0.75
% «	R1PC9 « R1PC1	= +0.31
% «	R1PC9 « R1P1	= +0.69

shown in table 8. These calculations show that in the zone of increased basicity there is an increase in the total number of cations per 160 oxygen ions which is especially marked for Mg and Fe. However, this calculation assumes that the volume occupied by 160 oxygen ions remains constant and that the volume of rock in a given area remains essentially unchanged. That is, the method is designed to enable one to calculate the cation changes which take place during volume for volume replacement. But this is not what has been proposed above. It has been proposed that the volume (e. g., occupied by a given number of oxygen ions, for the sake of a reference standard) in the zone of increased basicity has been reduced. If this is so, then the increase in Mg and Fe per unit volume is even greater than that indicated by the «standard cell» calculation.

Consequently, a calculation was made which would show the change in volume of a fixed number of oxygen ions.

The mineral formulas presented earlier (table 3, p. 291) are all based on 24 oxygen ions per formula. This was taken as defining one mol of each mineral. The mol volumes of the various minerals concerned were then calculated. Then the modal percentages of the main minerals in samples R1PC9, R1PC5, R1PC4, R1PC1, and R1P1 (from pegmatite vein number 1) were recalculated to 100 % and these figures

were multiplied by the appropriate mol volumes. This yielded a number which is proportional to the volume occupied by the specific mineral in the sample concerned. The sum of these numbers for each sample gives a number proportional to the volume of 100 mols of the rock — the volume of rock containing the standard number of oxygen ions. A sample calculation (for R1PC9) is given in table 9. The percent changes in going from R1PC9 to the average of R1PC4 and R1PC5, to R1PC1, and to R1P1 are also shown in table 9.

These calculations verify the validity of the proposal that the zones of increased basicity are residual zones in which Mg and Fe have been relatively enriched while the volume occupied by the remaining rock has decreased. Simultaneously the volume of the rock adjacent to the veins and the rock now occupying the veins is greater than the original volume of the olivine gabbro. That the sum of the two volume increases is greater than the volume decrease is attributable to two factors. First, immediately after the break occurred there would be a certain amount of elastic recoil in the olivine gabbro such that the break would consist of an unfilled volume available to filling by high volume minerals without necessitating an exactly corresponding volume decrease in the olivine gabbro. Second, while the vein grows the two parts of the olivine gabbro are bodily moved apart from one another due to the plastic flow of the gneiss, such that the present system, vein plus surrounding rock, occupies a greater volume than did the olivine gabbro before the break occurred.

It may be suggested that the presence of hydrated minerals (primarily amphibole) in (roughly) decreasing quantity with increasing distance from the veins, indicates that the material now forming the veins was derived from a fluid rich phase which was introduced into the break in the olivine gabbro from some external source. The author does not believe this to be the case.

As is so elegantly explained by Ramberg:

«The opening will first be filled with the most mobile constituents of the host rock, that is, water, carbon dioxide, and other «fugitive» and mobile compounds existing throughout the rock. We concluded . . . that the pressure in these gaseous fillings in the beginning would not exceed the total vapor pressure of the rock's minerals with their intergranular adsorbed particles. . . . Such a hydrous liquid phase would also, in most cases, have a pressure less than the rock pressure.

After the first rather rapid filling of the opening with the most fugitive constituents, there will still be disequilibrium in the rock-fissure system because minerals existing in the fluid filled fissure have still less molal free energy than the corresponding minerals in the rock. . . . The tendency will necessarily be that minerals slowly disintegrate in the rock and the constituents diffuse towards the low-pressure place, where precipitation must take place. . . .

The growth of minerals along the wall of the crack and the plastic yield of the host rock make the fluid-filled volume of the opening decrease, followed by an increase of pressure of the fluid phase. If the wall was impermeable . . . , the pressure in the filling would gradually become equal to the pressure in the rock, and the situation would be mechanically stable. Since the walls are permeable, however, the fugitive constituents will start to diffuse from the fluid filling into the country rock, whereas the elements constituting the minerals in the fissure may continue to migrate into the fissure until the process comes to a stop when the fissure is closed either by plastic yield in the country rock and/or by the newly formed minerals.» (20, pp. 215, 216).

Some of the data concerning plagioclase are also easily explained on the basis of the mode of formation of the pegmatite veins suggested above.

The observations which must be explained are: the variation in the An content from the boundary towards the center of vein number 1; the abrupt change of the An content in the plagioclase on crossing from the veins into the surrounding rock; the gradual increase of the An content in the plagioclase with distance from the veins; the variation of Sr content in the plagioclase from the veins; and the variation of the Sr content in the plagioclase in the surrounding rock.

It has been shown how the creation of the pressure differences postulated requires the diffusion of material in the disperse phase towards the low pressure zones. It is probable that Na is much more mobile and diffuses more rapidly than Ca, but even if one does not accept this as probable, it is the case that the recrystallization of the olivine gabbro would require the local use and retention of Ca for the formation of the low mol volume minerals which are relatively preferred. Therefore, in the disperse phase which migrates towards the low pressure zones, Ca will lag behind and/or will be preferentially retained. Consequently, the disperse phase will become richer in Na on approaching the veins and, just after the break opens, be much richer in Na than was the mineral assemblage from which it was deri-

ved. Therefore, the plagioclase which grows in the break will grow from a relatively Na rich environment. The plagioclase which recrystallizes in the surrounding rock will also be in a more Na rich environment the closer it is to the vein, but here the sites of disintegration and recrystallization are so close that the environment will be richer in Ca throughout the surrounding rock than it is in the vein.

The environment in the break will become gradually enriched in Ca through time because the slower moving Ca catches up to the Na which reached and crystallized in the break first and/or because the environment in the surrounding rock becomes effectively satiated with respect to Ca and will no longer preferentially retain it. Therefore, the plagioclase growing in the vein will become steadily richer in Ca. The last formed plagioclase (in the center of the vein) must then be richer in Ca than that which formed first.

The variation of Sr in the plagioclase both in the veins and in the surrounding rock is rather similar to that of Ca, except that Sr is markedly increased in the zones of increased basicity. This would indicate that Sr is even less mobile than Ca and/or preferentially retained even more strongly than Ca. Consequently the variations of the Sr content are similar to but more pronounced than those of the Ca content in the plagioclase.

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Errata

In Pegmatite Veins and the Surrounding Rocks: I. Petrography and Structure: Norsk Geologisk Tidsskrift, Bind 36, Hefte 3, pp. 213—239, 1956, the following corrections should be made.

- | | |
|-------------------|--|
| p. 213 (Abstract) | — for An_{30} read An_{20} |
| | — for An_{23} read An_{28} |
| p. 231 | — for 244 cm^3 read 234 cm^3 |
| | — for $244,000\text{ cm}^3$ read $234,000\text{ cm}^3$ |

Attached map — the scale is given as 1 : 600. Because the map was reduced less than was anticipated when it was reproduced the scale is actually almost 1 : 400.

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