

FELDSPAR EQUILIBRIA AND THEIR IMPLICATION I

BY

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WITH 4 FIGURES IN THE TEXT

In the present paper synthetic melts and natural rocks have been compared in order to find the laws governing the interrelation between the individual feldspar phases met with in rocks. Some of the preliminary results have been published elsewhere more than three years ago (Naturen 1934, pp. 190-192). By comparing the results of recent synthetic studies with new data obtained from natural rocks through several years of gathering, some conclusions now seem so definite as to justify publication, although many questions still await their explanation.

For the present study I have received material from: The late Dr. H. S. Washington; rocks from Mte. Amiata, Italy.

Dr. W. F. Foshag, National Museum, Washington, D. C.; rocks from Siebenbirge, Germany and from Gunnison Co., Colo.

Dr. C. A. Anderson, University of California; rocks from the Clear Lake Area, California.

Dr. C. Bugge, Director, Norges Geologiske Undersøkelse, rocks from southern Norway collected by Olaf Andersen.

The present paper falls in three parts.

- I. The Feldspar Minerals Arranged as Reaction Series.
- II. The Mixed Crystals.
- III. The Feldspar Geologic Thermometer.

The Feldspar Minerals Arranged as Reaction Series.

A. Feldspar in Artificial Melts.

The composition of the rock-making feldspars can be expressed in terms of the mineral molecules Or (KAlSi_3O_8), Ab ($\text{NaAlSi}_3\text{O}_8$), and An ($\text{CaAl}_2\text{Si}_2\text{O}_8$). But the physico-chemical system formed by these three components is not a true ternary system under ordinary pressure, but due to the incongruent melting of Or with separation of leucite it is actually quaternary.

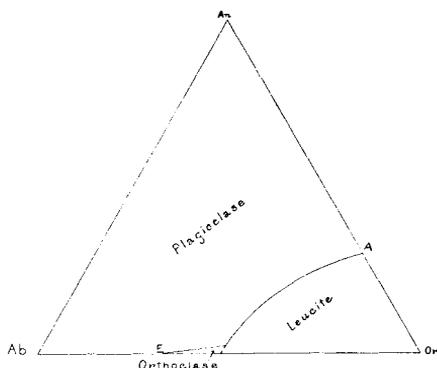


Fig. 1. Schematic equilibrium diagram of the system Orthoclase-Albite-Anorthite, being part of the quaternary system Silica-Leucite-Albite-Anorthite.

Although no quaternary silicate system has been completely studied in the laboratory the all-important equilibrium studies by Bowen and Schairer have now given so much information about the fusion relations of feldspar, that the application to igneous geology has become obvious.

In Fig. 1 a triangular diagram has been used to show the equilibrium relations in the quaternary system Or Ab An, the presentation is therefore by necessity inadequate, but nevertheless good enough for an approximate survey of the conditions. It has been constructed from various data published by Bowen and Schairer.¹

At the Or-corner leucite is the primary phase. The liquidus point is at about 1530° and the lowest temperature on the join Or An is approximately 1375° (A in Fig. 1, but this is not a true eutectic, these parts of the diagram actually being governed by quaternary equilibria). Only in a very small field is orthoclase solid solution a primary phase. In the whole remaining area of the diagram plagioclase is the primary phase (including here soda-rich anorthoclase which physico-chemically represents the same phase). The lowest point on the fusion surface towards which all residual liquids will trend is at 33 Or, 67 Ab with a temperature of 1076° (E in Fig. 1).

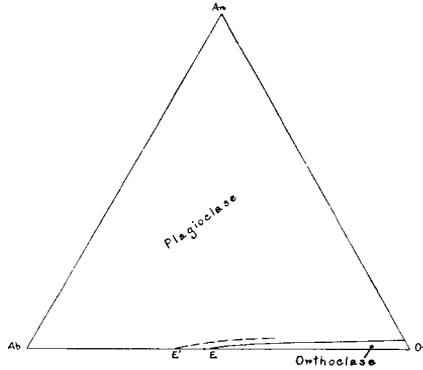
¹ N. L. Bowen, The Melting Phenomena of Plagioclases, *Am. Jour. Sci.* 33, 551, 1912.

J. F. Schairer and N. L. Bowen, Equilibrium Relations between Feldspatoids, Alkali Feldspars, and Silica, *Trans. Am. Geophys. Union* 16. Ann. Meeting 1935, p. 325.

N. L. Bowen, Recent High-Temperature Research on Silicates and Its Significance in Igneous Geology. *Am. Jour. Sci.* 33, 1, 1937.

Fig. 2. *Full line* illustrates schematically the equilibrium conditions on a section with 30 % silica in the system Silica-Orthoclase-Albite-Anorthite.

Stippled line refers to the equilibrium diagram of the truly ternary system Or-Ab-An under approximately 1000 Atmospheres.



In natural magma these relations will be somewhat modified, partly by presence of other substances, partly by hightened pressure. Substances of modifying influence are for instance water and other mineralizers. But at present it is hardly possible to say much about the character of their effect, no pertinent laboratory data being available. The effect of excess silica, however, has been shown by Bowen and Schairer to involve interesting consequences in igneous geology: Addition of silica causes the leucite field to shrink until it eventually disappears at about 30 % excess silica. The equilibrium conditions in a feldspar melt with 30 % excess silica are schematically and graphically shown in Fig. 2. Of course, this system is not ternary, and the triangle diagram of Fig. 2 cannot, therefore, give full information of the various equilibria. Schematically it shows, however, that no leucite field is present, and that the plagioclase field has encroached still further on the domain of Or-solid solutions, which now is restricted to a narrow zone in the lower right hand part of the diagram. The lowest point on the fusion surface is now at 48 Or, 52 Ab (+ 30 % excess SiO₂) where the temperature is around 1000° (E in Fig. 2).

The effect of pressure on feldspar melts is not known in detail, but can be estimated by applying the well-known thermodynamical equation of Clausius-Clapeyron giving the variation of the melting point, T, with pressure, P:

$$\frac{dT}{dP} = \frac{T \Delta v}{Q},$$

where Δv is the increase of volume attending the melting, and Q the heat absorbed.

The calculated rise of the melting point, $\Delta T/1000 \text{ Atm.}$, for Or, Ab, and An amounts to 10° , 25° , and 4° respectively.¹ But still another effect is produced by the pressure: it wipes out the leucite field. The mode of occurrence of leucite and its small density had long been taken as indicative of a reduced stability field at higher pressures, and recently Goranson² has succeeded in demonstrating experimentally, that under sufficient pressure orthoclase melts congruently. The consequence is that at such pressures the system Or Ab An becomes truly ternary. Just what the necessary pressure is, has not been stated, but this figure is of minor importance for the present discussion. Using the values given above for the increase of the melting points with pressure, and remembering Goranson's experimental finding, we now can form an opinion of the equilibrium conditions under a pressure of, say 1000 Atm. The field boundary between the plagioclases and the orthoclase solid solutions will be approximately as shown by the stippled line in Fig. 2.

In certain respects the equilibrium conditions are rather similar to those obtained under ordinary pressure with 30% excess silica. Again the lowest point on the fusion surface is on the Or Ab join (at approximately 38 Or, 62 Ab and 1095° i. e. at E' in Fig. 2) and the field of the orthoclase solid solutions is reduced to a narrow strip in the lower right hand part of the diagram.

All information thus far obtained from experiments and from theoretical considerations serve to elucidate the crystallization process of rock magmas. Depending upon the chemical composition a magma may correspond to a point in the plagioclase field or in the orthoclase field of the present system.³ Accordingly either plagioclase or orthoclase will crystallize first, the composition of the residual liquid thereby in any case being pushed towards the boundary line. When

¹ For the values of the constants T, Δv , and Q, see R. Doggett Terzaghi, *Am. Jour. Sci.* 29, 1935 p. 374, where references to the original literature are given.

² R. W. Goranson, *Silicate-Water Systems*, *Trans. Am. Geophys. Union*, 17. Ann Meeting, 1936, p. 259.

³ If one recalculates the normative feldspar content of a rock to 100 per cent, $or' + ab' + an' = 100$, the composition of the normative feldspar can be plotted in Fig. 2, and thus its position in respect to the boundary curve shown. Since the curve is determined by two coordinates, for example ab' and an' , the equation of the boundary curve can be given as follows:

$$(an')^2 + 2ab' = 120 \text{ (approximately).}$$

the boundary line is reached a simultaneous crystallization of plagioclase and orthoclase solid solution begins, and thenceforth continues, until the lowest point on the fusion surface is reached. The position of this point is always on the Or—Ab join (no An present). Under surface conditions it corresponds to 33 Or, 67 Ab; but both increasing pressure and excess silica will tend to push it towards the Or-corner. Thus it would seem that all natural rest magmas should be enriched in an alkali feldspar containing about 40% of the orthoclase molecule.

B. *Feldspar from Igneous Rocks.*

Now it remains to compare these results with observations on feldspars from igneous rocks. To this end rocks have been investigated containing as products of a simultaneous crystallization two feldspar phases; viz. plagioclase, and orthoclase solid solution. The feldspar phases were separated and analyzed individually. Thus the composition of the two phases which during the crystallization were in equilibrium with each other could be determined.

1) Feldspars from Mte. Amiata, Italy. These interesting rocks have been carefully described and analyzed by Williams.¹ For all details the reader is referred to his paper; suffice it here to state that the rocks consist of a more or less fine-grained ground-mass in which are distributed rather large phenocrysts of both plagioclase and sanidine. Several of the phenocrysts have been analyzed by Williams, but his analyses, which are now 50 years old, do not all come up to modern standards. Particularly doubtful are his alkali determinations which were made according to the old Berzelius method, which is inferior to the Smith method that is now universally

From this it follows that if the composition of the feldspars of a magma is such as to satisfy the equation, a simultaneous precipitation of plagioclase and orthoclase will take place in the magma. If the sum is larger than 120 the magma would precipitate only plagioclase. If less than 120 the magma would precipitate only orthoclase solid solutions; but this last condition, according to Ruth Doggett Terzaghi (op. cit.) does not obtain in primary magma. If therefore the composition of the feldspars of a rock meets the following condition:

$$(an')^2 + 2ab' < 120,$$

it would seem to indicate a replacement mode of origin of the rock.

¹ J. F. Williams, Monte Amiata und seine Gesteine, Neues Jahrb. Beil. Bd. 5, 1887—1888, p. 381.

Table 1.
Sanidine, Mte. Amiata, Barth analyst.

SiO ₂	63.66
TiO ₂	0.08
Al ₂ O ₃	20.29
Fe ₂ O ₃	0.13
MgO	trace
BaO	trace
CaO	0.51
Na ₂ O	2.48
K ₂ O	12.59
H ₂ O	0.32
<hr/>	
Sum.	100.06
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Or	74.5
Ab	21.0
An	2.5
Balance	2.0

adopted. It would seem that in most of the analyses by Williams the alkali determinations are too high. Due to this error an apparent deficiency of silica will appear in the feldspars, a circumstance responsible for the old assumption that the Mte. Amiata feldspars were chemically anomalous. A new analysis by me on typical sanidine phenocrysts shows them to be normal in all respects. The analysis is quoted in Tab. 1. Occurring together with sanidine are plagioclase crystals which also have been analyzed by Williams. Careful measurements on a Fedorov stage show them to be labradorite of composition 62 An, in good agreement with Williams' analysis. The mode of occurrence of these two feldspars as phenocrysts in the same rock, often in direct contact with each other leaves no doubt as to their simultaneous crystallization from a common magma with which both of them were in equilibrium.

2) Feldspars from oligoclase trachyte, Ölberg.

3) Feldspars from oligoclase trachyte, Perlenhardt, Siebengebirge. These rocks have been described by various authors¹ as more or less fine-grained with large phenocrysts of oligoclase and sanidine. New determinations of the chemical composition of the oligoclases

¹ P. Grosser, Trachyte des Siebengebirges, *Tschermak Min. Petr. Mit.* 13, 39. vom Rath, Trachyt von Perlenhardt, *Zeit. deutsch Geol. Ges.* 27, 1875, 329. Zirkel, *Petrographie II*, p. 381.

Rosenbusch, *Massige Gesteine II*, p. 594.

were made optically with a Fedorow stage (plotted in Fig. 3), and new alkali determinations were made on the sanidines. The results are entered in Tab. 2. It may be added that the position and the shape of the optical indicatrix of the oligoclases are quite normal, indicating that the feldspars strictly belong to the plagioclase series (potash-free). The analyses of the sanidines show the maximum content of the An-molecule to be 6–8%; it probably is much less since

Table 2.

	I	II
Na ₂ O.....	4.22	4.46
K ₂ O.....	9.89	9.27
Or	58.4	54.7
Ab	35.5	37.7

I. Sanidine from Oligoclase Trachyte, Ölberg, Barth analyst.

II. Sanidine from Oligoclase Trachyte, Perlenhardt, Siebengebirge, Barth analyst.

the analyzed material could not be obtained absolutely pure, but most likely contained small amounts of water and other impurities.

4) Feldspars from trachyandesite, Ragged Mt., Gunnison Co., Colorado. This rock has been described by Cross.¹ It contains very large phenocrysts of alkali feldspar, frequently 5–8 cm long. Large crystals of plagioclase are also present. Although it is probable that the two feldspars are simultaneous, the sequence of crystallization in this rock cannot be deduced with certainty from its structural features. Measurements with the Fedorov stage showed the plagioclase to contain 40 An. A chemical analysis of the alkali feldspar has been made by Spencer.² New alkali determinations were made by me. The results are entered in Tab. 3.

5) Feldspars from biotite-hornblende rhyodacite, Mt. Konati, California. The rock has been described and an analysis published by

¹ W. Cross, Lacolithic Mountain Groups in Colorado etc. U. S. Geol. Survey Ann. Rep. 14₂, 1892–93, p. 165.

² E. Spencer, A contribution to the study of moonstone from Ceylon and other areas, and of stability relation of alkali feldspar. Min. Mag. 22, 334, 1930.

Table 3.

	I	II
Na ₂ O	2.78	2.74
K ₂ O	11.38	11.74
Or		72.9
Ab		24.1
An		3.0

I. Alkali feldspar from trachyandesite, Ragged Mt., Gunnison Co., Colorado, Barth analyst.

II. Alkali feldspar, E. Spencer analyst. (Spencer has given a complete analysis of the feldspar; in this table only the alkali determinations have been quoted.)

Anderson.¹ The rock shows phenocrysts of quartz, sanidine, oligoclase partly intergrown with augite, basaltic hornblende, and biotite. The groundmass consists of feldspar microliths and cryptocrystalline or glassy matrix. The phenocrysts being too small for hand-picking had to be separated by heavy liquids. Two fractions were obtained: One fraction containing sanidine, another containing oligoclase plus quartz. Chemical analyses were made of the two fractions. The results are presented in Tab. 4.

Table 4.

	I	II
CaO	n. d.	5.24
Na ₂ O	4.28	8.10
K ₂ O	8.72	0.98
Or	51.7	5.6
Ab	36.2	68.4
An	-	25.9

I. Sanidine from biotite-hornblende rhyodacite, Mt. Konati, California, Bruun analyst.

II. Plagioclase from the same rock, Bruun analyst.

¹ C. A. Anderson, Volcanic history of the Clear Lake Area, California. Bull. Geol. Soc. Am. 47, 629. 1936.

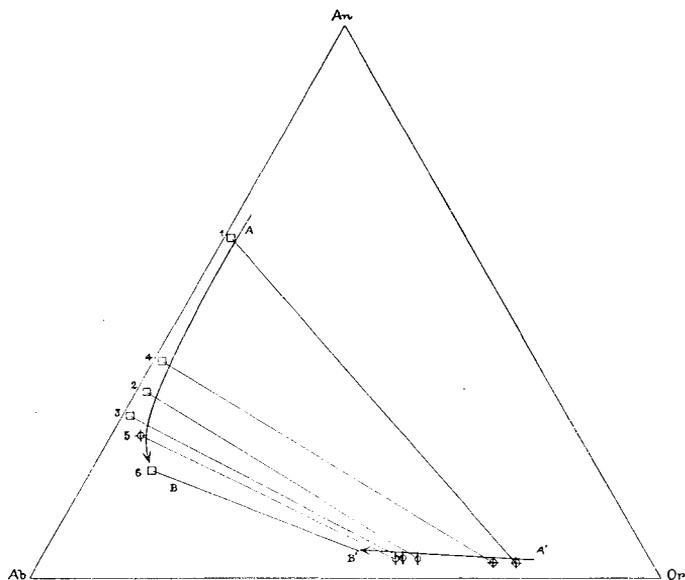


Fig. 3. Composition of various feldspars from volcanic rocks. Feldspars from the same rock, and thus in mutual equilibrium during crystallization, are connected with lines.

- 1 Feldspars from Mte. Amiata.
- 2 " " Ölberg, Siebengebirge.
- 3 = " " Perlenhardt, Siebengebirge.
- 4 " " Ragged Mountain.
- 5 = " " Mt. Konati.
- 6 = " " Marquesas Islands.

⊕ designates complete chemical analysis, ⊖ incomplete analysis, · designates that composition is calculated from rock analysis, and □ from optical analysis.

6) Feldspar from trachyte, Marquesas Islands. This rock has previously been described by me.¹ The amount of dark minerals is extremely small, only about 5 0/0. The composition of the feldspar phases can therefore be calculated with rather great accuracy from the rock analysis. Oligoclase contains about 20 An, and Fedorov measurements indicate that some but not much potash is present in solid solution. The alkali feldspar is a soda orthoclase of the following composition:



A graphical survey of all the feldspar determinations so far communicated is given by the diagram, Fig. 3.

¹ T. F. W. Barth, Mineralogical Petrography of Pacific Lavas, Am. Jour. Sci. 21. 523. 1931.

In this diagram feldspars from the same rock and thus presumably in equilibrium with each other at the time of crystallization are connected with lines. The diagram clearly demonstrates that calcic plagioclase is in equilibrium with potassic sanidine, and sodic plagioclase with sodic sanidine. It thus follows from the diagram that the alkali feldspars form a reaction series from potassic to sodic analogous to the reaction series of the plagioclases from calcic to sodic (the series from A' to B' parallels the series A to B), and that the residual liquids will trend towards a point on the Or-Ab join, the composition of which may be somewhat different for the different rocks depending on composition and geological environment, but which generally speaking must be in the neighbourhood of an alkali feldspar containing about 40% of the Or-molecule.

In this connection certain studies on Pacific lavas by myself may be mentioned (op. cit. p. 398). It was demonstrated that in all these lavas the residual liquids produced by fractional crystallization tended toward a composition of about 50 Or, 50 Ab (\pm SiO₂), after which a last precipitation of a homogeneous mix-crystal of feldspar of that composition took place.

The exact shape of the fusion surface of the field of the orthoclase solid solutions has not yet been fully determined in artificial melts. In an earlier paper Bowen¹ discusses the possibilities of a reaction relation between orthoclase and anorthite vs. a eutectic relation. The results of the above petrographic studies, which essentially verify and supplement those by Terzaghi² seem to indicate a eutectic relation.

All feldspars thus far considered have been taken from unaltered volcanic rocks, and no reasonable objection can be raised to the assumption that the pristine chemical composition has been preserved. Feldspars from deep-seated rocks are different, however. Here the perthites are universally met with, and it is a well-known fact that for certain kinds of perthitic lamellæ a replacement origin must be considered. Using the criteria discussed by Andersen³ it is theoretic-

¹ N. L. Bowen, *Evolution of Igneous Rocks*, p. 230.

² Ruth Doggett, The orthoclase-plagioclase equilibrium diagram, *Jour. Geol.* 37, 712, 1929.

Ruth Doggett Terzaghi, Origin of the potash rich rocks, *Am. Jour. Sci.* 29, 359, 1935.

³ Olaf Andersen, The genesis of some types of feldspar from granite pegmatites, *Norsk Geol. Tidsskr.* 10, 116, 1928.

tically possible by microscope studies to determine the composition and amount of the lamellæ of replacement origin, and by application of this correction calculate the pristine composition of the feldspar. Actually this is not so easy. Partly because of gradation of different types of lamellæ into one another, partly because of an uneven distribution, the results are rarely quantitatively reproduceable. It can be shown, however, that the corrections to be applied to the feldspars to be mentioned in the sequel are insignificant. In the following discussion the data of the chemical analyses are therefore directly used. This means that the original composition of the microcline perthites might have been slightly more albitic than given in Fig. 4.

Several feldspars of granitic pegmatites and coarse granites were selected for studies.

1) Feldspars from pegmatite, Frøyna. This pegmatite has been studied by Olaf Andersen (op. cit. and Norges Geol. Undersøkelse No. 128 b, 1931). The dike consists of quartz, microcline-perthite, andesine and mica. The composition of the feldspar phases are entered in Fig. 4.

Table 5.

	I	II
SiO ₂	57.35	65.55
Al ₂ O ₃ *	28.02	18.98
MgO	0.11	0.03
CaO	7.09	0.13
Na ₂ O	6.02	2.20
K ₂ O	1.10	13.11
H ₂ O at 105	0.09	-
H ₂ O	0.70	0.07
	100.48	100.07
Or	6.5	80.1
Ab	50.9	19.2
An	35.1	0.7
Balance	7.5	-

* Including FeO = 0.18

- I. Plagioclase from pegmatite, Berø, Bruun analyst.
- II. Microcline from pegmatite, Berø, Quoted after O. Andersen, Op. cit.

2) Feldspars from pegmatite, Berø. An analysis of the pegmatite is given by Olaf Andersen (op. cit.) who also has studied the accompanying minerals. A new analysis of the plagioclase is entered in Tab. 5. The composition of the feldspar phases is given graphically in Fig. 4.

3) Feldspars from pegmatitic granite, Stjernøy. Like the preceding rock this represents a pegmatitic facies of the South Norwegian gneiss formation. It contains quartz, microcline-perthite, and plagioclase. New chemical analyses of the microcline-perthite and of the plagioclase are quoted in Tab. 6, and graphically presented in Fig. 4.

Table 6.

	I	II
SiO ₂	63.18	64.07
Al ₂ O ₃	24.00*	20.68
MgO	0.03	0.13
CaO	3.12	0.30
Na ₂ O	8.77	2.66
K ₂ O	0.87	12.49
Los on ign.	0.16	n. d.
	100.13	100.33
Or	5.1	73.7
Ab	74.0	22.5
An	15.5	1.5
Balance	5.4	2.3

* Including FeO = 0.26.

I. Plagioclase from Stjernøy, Bruun analyst.

II. Microcline from Stjernøy, Bruun analyst.

4) Feldspars from pegmatite, Risøen. This rock has been studied by Olaf Andersen (op. cit.). The predominant minerals are plagioclase and quartz; in addition microcline-perthite, green pyroxene, and biotite occur. Chemical analyses have been published of both feldspar phases. The compositions are graphically plotted in Fig. 4.

Fig. 4 gives a graphical survey of the feldspar determinations; feldspars from the same rock are connected with lines. Fig. 4 resembles Fig. 3. It is again seen that the more calcic the plagioclase the more potassic the orthoclase solid solution with which it is in

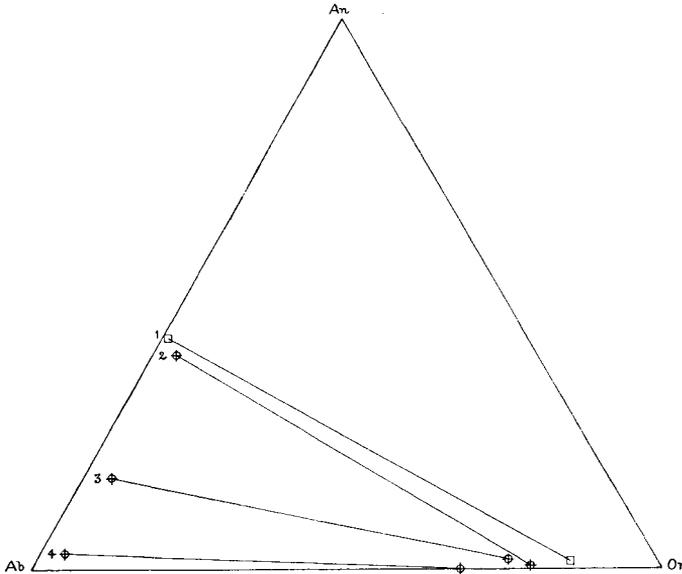


Fig. 4. *Composition of various feldspars from pegmatitic rocks.*
 Feldspars from the same rock and thus in mutual equilibrium during crystallization are connected with lines.

- 1 = Feldspars from Frøyna.
- 2 = " " Berø.
- 3 = " " Stjernøy.
- 4 = " " Risøen.

Symbols as in Fig. 3.

equilibrium. The conclusions from p. 186 are thus verified: In deep-seated rocks also orthoclase solid solutions form a reaction series from potassic to sodic keeping pace with the plagioclase reaction series.

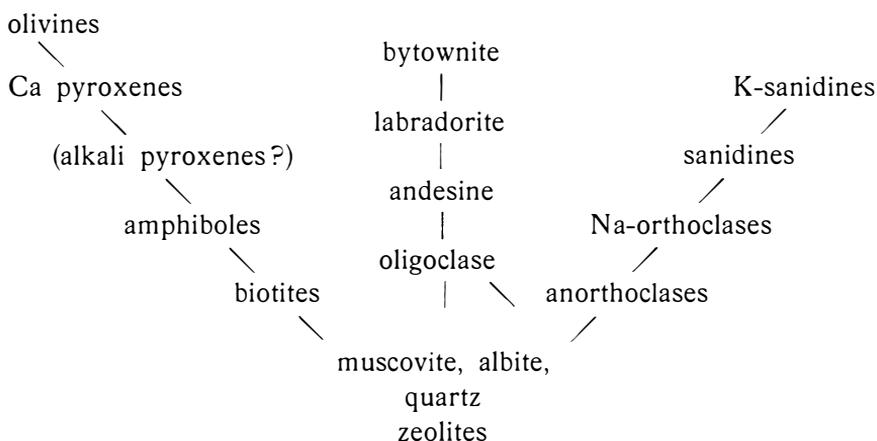
C. Conclusions.

It is the merit of Bowen¹ to have demonstrated and pointed out the fundamental importance of reaction series in petrology. He has arranged the minerals of the ordinary sub-alkaline rocks as reaction series consisting of two branches converging upon potash feldspar.

The results of the present investigation indicate that in certain rock magmas the reaction series of the alkali feldspars should be recognized in addition to that of the plagioclases.

¹ N. L. Bowen, The reaction principle in petrogenesis, Jour. Geol. 30, 177, 1922.

This is graphically indicated below:



In a recent paper Bowen (op. cit.) has pointed out that in fractional crystallization of silicate melts resembling "average" magmas the bulk of the plagioclase and ferromagnesian minerals will separate before the alkali feldspars start to crystallize. Under such conditions no great importance can be attached to the series of the alkali feldspars. However, sanidines are early crystallization products in some specialized potash-rich magmas, as demonstrated by the present observations, and in such magmas the reaction series of the alkali feldspars becomes of great consequence for the further magmatic development. With special reference to such rocks it would seem justified to place the beginning of this reaction series on level with that of the plagioclases.

*Mineralogisk institutt Oslo,
September 1937.*