

SIGNIFICANCE OF THE ORTHOCLASE-ALBITE-
ANORTHITE, AND THE NaAlSiO_4 - KAlSiO_4 - SiO_2
EQUILIBRIUM DIAGRAMS IN IGNEOUS
PETROGENY

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ABSTRACT

High temperature studies of silicate systems indicate that rocks which form at the latest stages of the differentiation of a basaltic magma should have salic normative proportions which lie in the low temperature region of the NaAlSiO_4 - KAlSiO_4 - SiO_2 equilibrium diagram. Their normative feldspar content should lie approximately on the cotectic curve of the Or-Ab-An equilibrium diagram. The chemical compositions of some potash- and soda-rich acidic rocks do not harmonize with these requirements. It is suggested, therefore, that such rocks are sometimes enriched in potash or soda through metasomatic processes, in other cases they are derived from the crystallization of potash-rich granitic or soda-rich spilitic magmas respectively, which form by differential remelting of the crust.

INTRODUCTION

The potash-rich rocks have normative feldspar contents corresponding to points in the orthoclase field of the Or-Ab-An equilibrium diagram (Bowen, 1928, p. 231). The salic normative constituents other than anorthite of most of these rocks exceed 80 per cent. The plot of the proportions of the salic normative constituents exclusive of anorthite of such potash-rich acidic rocks lies outside the region of low temperature representing the residual magma in the system NaAlSiO_4 - KAlSiO_4 - SiO_2 (Schairer & Bowen, 1935; and Bowen, 1937, p. 12). High temperature studies, on the other hand, indicate that rocks formed as products of the latest stages of primary crystallization of a basaltic magma should not have normative feldspar contents which lie in the orthoclase field, and they should have salic normative constituents placing them in the low temperature "valley" in the system NaAlSiO_4 - KAlSiO_4 - SiO_2 equilibrium diagram.

The discrepancy between the results of the above-mentioned equilibrium diagrams and the composition of the potash-rich acidic rocks with regard to their magmatic mode of origin needs discussion.

SOME EXAMPLES OF POTASH-RICH ROCKS

Noble (1948) gave chemical analyses of some potash-rich rhyolites from the Homestake Mine, Lead, South Dakota. He classified these rhyolites into two divisions; namely, high potash and low potash types. Soda and potash of the high potash type ranges from 0.23 to 0.59 per

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cent and 9.17 to 13.16 per cent, respectively. The potash: soda ratio in these rocks ranges from 15.5:1 to 48.8:1. He mentions that Washington (1917, p. 107) has listed ten other rocks which have chemical compositions similar to those of Lead, South Dakota. They are rhyolites,

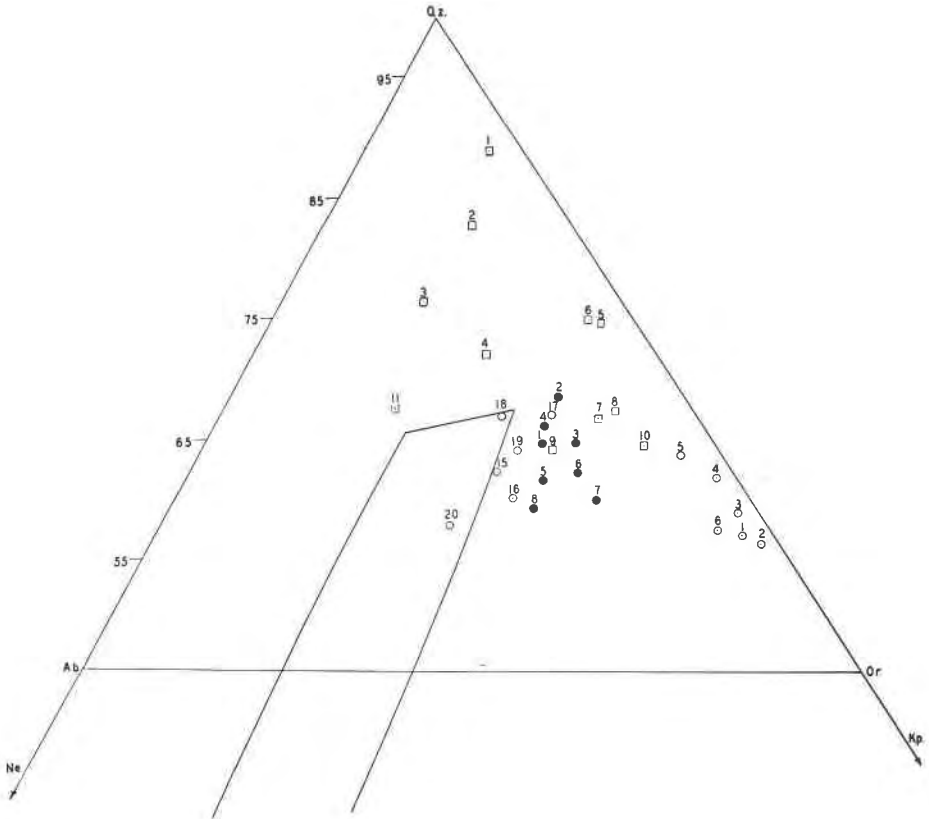


FIG. 1. Squares 1 to 11=1 to 11 (Terzaghi, 1948, p. 21). Circles 1 to 6=1 to 6 (Noble, 1948, p. 932, high-potash type). Circles 15 to 20=15 to 20 (Noble, 1948, p. 932, low-potash type). Solid circles 1 to 8=averages of rhyolite, rhyolite family 116, sodaclase rhyolite, leuco-rhyolite, all aplites, alkali aplite, rumite, and sodaclase granite respectively (Johannsen, 1931, pp. 509-513).

granites, and quartz porphyries. The normative feldspar contents of the rocks studied by Noble (1948, p. 933) as well as those given by the author (Higazy, 1949, Fig. 4) lie in the orthoclase field of the Or-Ab-An equilibrium diagram. In addition to these rocks, there are two rocks (Washington, 1917, p. 79), namely, a porphyry and a pitchstone which have identical chemical character to the high-potash rhyolites studied

by Noble. The porphyry has a potash:soda ratio of 28.5:1 and the pitchstone has a higher ratio since it possesses 6.75 per cent of K_2O and traces of Na_2O .

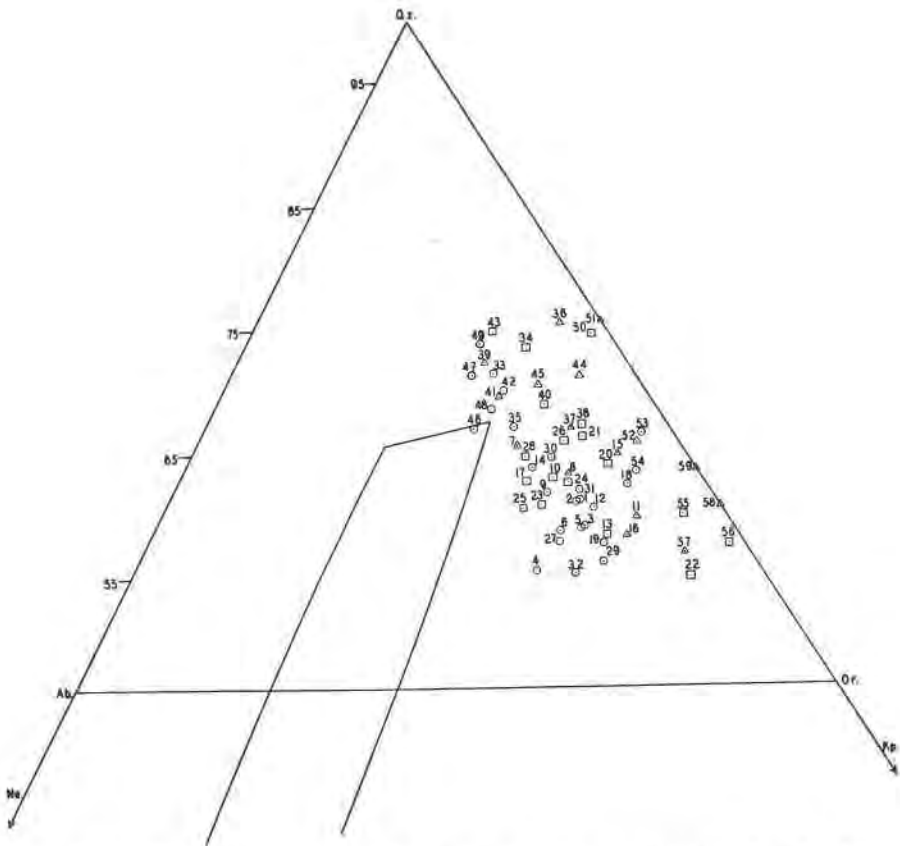


FIG. 2. Circle = deep-seated rocks, triangle = volcanic rocks, square = hypabyssal rocks. 1 to 5 and 6 to 32 = 1 to 5 and 7 to 33. Order quarzofelic britannare. Subrang dopotassic omeose (Washington, 1917, p. 109), 33 to 45 = 1, 2, 3, 11, 12, 13, 15, 18, 22, 25, 27, 30, and 31. Order quarfelic columbare. Subrang dopotassic magdeburgose (Washington, 1917, p. 57), 46 to 49 = 10, 31, 32, and 60. Order quarfelic columbare. Subrang sodipotassic alaskose (Washington, 1917, p. 61), 50 and 51 = 1 and 2. Order quarfelic columbare. Subrang perpotassic (Washington, 1917, p. 79), 52 to 59 = 4, 5, 7, 8, 9, 10, 11, and 12. Order quarzofelic britannare. Subrang perpotassic lebachose (Washington, 1917, p. 107).

The low-potash rhyolites of the Homestake Mine have soda and potash ranging from 1.84 to 4.48 per cent and 5.11 to 7.50 per cent, respectively. The potash:soda ratio in this type varies from 1.2:1 to 3.3:1. Examples of such rocks given by the author (Higazy, 1949, Fig. 4) are more abun-

dant than those of the high-potash type. They are granites, aplites, and pegmatites; quartz and granite porphyries; rhyolites, pitchstones, obsidians, and comendites—that is, rocks which are supposed to crystallize at the latest stages of the differentiation of the basaltic magma. The normative feldspar contents of the low-potash rhyolites of Lead, South Dakota (Noble, 1948, Fig. 1B), as well as those of the above mentioned examples (Higazy, 1949, Fig. 4), also lie in the orthoclase field. The salic normative proportions, excluding anorthite, of all the cited rocks lie outside the low temperature region of the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagram, close to its Or point as illustrated in Figs. 1 and 2.

Terzaghi (1948) gave chemical analyses of some potash-rich rhyolites from the Esterel region, France. In these rocks soda and potash ranges from 0.54 to 3.95 per cent and 2.45 to 8.71 per cent, respectively. The potash:soda ratio ranges from 0.8:1 to 11.6:1. It is 0.8:1 in a vitric rhyolite and 0.9:1 in a spherulitic rhyolite. Both of these rocks have normative feldspar content lying outside the orthoclase field of the Or-Ab-An diagram (Terzaghi, 1948, Fig. 1). The potash:soda ratio in the other nine rhyolites studied by Terzaghi ranges from 1.9:1 to 11.6:1. In four rocks the ratio lies within the range of the low-potash type of Noble. The plot of the salic normative constituents excluding anorthite of the Esterel region rocks falls outside the low temperature “valley” of the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagram, closer to its Q (SiO_2) point as shown in Fig. 1.

Johannsen (1931) gave average chemical compositions of rhyolites, sodaclase rhyolites, leuco-rhyolites, all aplites, alkali aplites, runite, and sodaclase granites. The normative salic constituents of these averages excluding anorthite form more than 80 per cent of the rock composition. The proportions of these constituents are plotted on the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagram (Fig. 1). They lie outside the “valley” of the residual liquids.

ORIGIN OF THE POTASH-RICH ROCKS

The potash-rich rocks may be explained as originating in two ways; namely, (a) crystallization differentiation and (b) metasomatic alterations.

Crystallization differentiation

The formation of a potash-rich liquor at the latest stages of magmatic crystallization has first been shown to be possible by Bowen (1928, p. 231). He postulated a reaction relation between anorthite and orthoclase enabling liquids to cross the cotectic curve of the Or-Ab-An system during the end of the magmatic crystallization history. This supposition

was considered by Noble (1948) to be true and accordingly he favored the differentiation theory to account for the genesis of the rhyolites he studied. However, the reaction relation has recently been found by Schairer and Bowen (1947) to be non-existent so that this hypothesis can no longer hold. Terzaghi (1935) thought that the presence of the normative feldspar content of the potash-rich rocks in the orthoclase field might be due to pressure. However, pressure should have but a negligible effect in the case of the rhyolites since they are extrusive types. Moreover, the author (Higazy, 1949) has shown that pressure does not seem to be responsible for the presence in the orthoclase field of the normative feldspar content of the deep-seated potash-rich rocks of granitic compositions derived from the differential crystallization of a purely basaltic magma. It might be argued that the volatiles affect the course of the crystallization, but the presence of other rocks supposed to form at the latest stages of crystallization whose normative feldspar contents do not lie in the orthoclase field and whose salic normative constituents lie in the low temperature region of the $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 diagram leads to the belief that the influence of the fugitive components cannot be the reason that compositions of the potash-rich rocks fail to conform to the crystallization differentiation theory as expressed by the feldspar and the $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 equilibrium diagrams. Nockolds (1946) studied some granitic rocks and found that their normative feldspar contents lie approximately on the cotectic curve of the Or-Ab-An equilibrium diagram. These rocks studied by Nockolds could be the result of the latest stages of crystallization of the basaltic magma. This, of course, would only be true in the case that the cotectic curve of the Or-Ab-An diagram is accepted to represent compositions which form at the latest stages of magmatic differentiation.

It may be true that the potash-rich rhyolites of the Lead region (Noble, 1948) are of a truly magmatic origin and have been derived from the differential crystallization of a basaltic magma, but neither the Or-Ab-An nor the $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 equilibrium diagram can satisfactorily account for their compositions. If such were the case, it would not be reasonable for petrologists to use the presence of the normative compositions of the different rocks types in certain portions of the equilibrium diagrams as proof or disproof of their derivation from the differentiation of a basaltic magma. If, however, we assume these diagrams to be valid in every case we must seek some other explanation for the origin of these rocks that do not conform to them.

One possible mode of origin of the potash-rich rhyolites is their formation from a primordial rhyolitic magma. Fenner (1948) believes in the presence of two immiscible liquids at high temperature, a rhyolitic one

and a basaltic one; these two liquids re-unite to form a single liquid before crystallization starts unless the two liquids have become separated from each others influence. The potash-rich rhyolites might on this assumption be the result of the crystallization of a rhyolitic magma originally rich in potash. The rhyolites of the Gardiner River area in Yellowstone Park impregnating the basalts of an earlier flow have been shown by Fenner (1948) to support his view. If this were true, one would not expect to find that the compositions of the rhyolites formed in this way follow the rules expressed by both the feldspar and the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagrams since these apply only in the case of crystallization differentiation of a purely basaltic magma. Under this assumption we can have two types of rhyolites. One type forms as the latest product of the differentiation of a purely basaltic magma, or a re-united mixture of both basaltic and rhyolitic magmas, the rhyolite magma being subordinate in amount. The other type is the product of the crystallization of a purely rhyolitic magma or a re-united mixture of both rhyolitic and basaltic magmas, the basaltic magma being subordinate in amount. The former category of rhyolites would have normative compositions which are in harmony with the phase equilibrium diagrams; examples of these rocks may be those selected by Bowen from the Eastern African lavas (Bowen, 1937). The rhyolites of the latter category would not necessarily have normative compositions which conform to the demands of the differentiation theory because they form substantially from an originally rhyolitic magma.

There are also soda-rich rhyolites. The normative salic constituents of this type also lie outside the field of the low temperature in the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagram close to its Ab point. Examples of this type are some aplites, microgranite, albite pegmatite, granite porphyry, granophyre, felsite, quartz keratophyre, and soda rhyolites (Washington, 1917, p. 77). Potash in these rocks varies from 0.00 to 0.99 per cent, while soda ranges from 4.53 to 6.89 per cent; the normative orthoclase and albite range from 0.00 to 6.12 and 37.73 to 58.16 per cent, respectively. Hatch (1889, p. 72) gives the chemical composition of a soda felsite from Brittas Bridge, Co. Wicklow, Ireland, which has 0.16 per cent potash and 7.60 per cent of soda. Thomas (1911), in his study of the Skomer volcanic rocks (Pembrokeshire) among which a soda rhyolite possessing 0.38 per cent of potash and 6.40 per cent of soda and whose orthoclase and albite normative percentages are 2.22 and 53.97 respectively, considered the chief mineralogical and chemical peculiarities of the Skomer rocks to be primary and he regarded the series in part as being rich in original soda and as having pantellerian affinities (Thomas, 1911, p. 210). Bowen (1945) in his studies of the

equilibrium relations in portions of the quaternary system, $\text{Na}_2\text{O}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$, shows that fractional crystallization in these compositions could give rise to differentiates analogous to tephrites, phonolites, and alkali rhyolites (soda-rich). The system studied by Bowen (1945) does not contain any potash. It seems probable that if K_2O were added to this system instead of Na_2O , similar differentiates could develop; namely, leucitites, leucite basalts, leucite bearing phonolites, and alkali rhyolites (potash-rich). There are no studies concerning the presence of both Na_2O and K_2O in a system containing CaO , Al_2O_3 , and SiO_2 and the prediction of the actual situation in such a quintuple system would indeed be difficult. The studies of the system $\text{NaAlSi}_3\text{O}_8-\text{KAlSi}_3\text{O}_8-\text{SiO}_2$ where potash and soda are equally represented indicate, however, that the latest products of differentiation will be restricted to those which have normative salic constituents which lie in the low temperature region of that system. Compositions which are relatively rich in either potash or soda cannot be explained. It seems, therefore, on the basis of what we know from the dry equilibrium phase diagrams, that the soda-rich and the potash-rich rhyolites could develop as the latest differentiates of two separate magmas, a soda-rich and a potash-rich liquor, respectively. This assumption cannot hold if we consider a primordial basaltic magma as the original material since there is no evident way at present of separating potassium- and sodium- aluminosilicates in the differential crystallization of a basaltic magma.

In the pegmatite phase, we may get replacing solutions composed essentially of albitic materials with negligible amounts of potash. In other cases, however, the replacing hydrothermal solutions may be composed substantially of microclinc materials with no or negligible amounts of soda. The question now is; are the albitic or soda-rich material and the microclinc or potash-rich material derived from the same original source? If they came from one source, then it can be assumed that there had been immiscibility between the sodium and the potassium aluminosilicates in the hydrothermal stages and this immiscibility might have been assisted by the enrichment in water in the hydrothermal stage. If immiscibility between the sodium and the potassium aluminosilicates is effective in the hydrothermal stage, has it also any influence at higher temperatures at which the rhyolites form? Experiments supporting the immiscibility between the alkali aluminosilicates at relatively high temperatures are not available. In the absence of such experiments, it is doubtful that this process occurs; it is more reasonable to assume that the albitic soda-rich and the microclinc potash-rich materials have been derived from two different sources.

Wahl (1949) states that during geosynclinal orogenies at least four

different kinds of parental magmas are formed by differential remelting of the crust; (1) spilitic and picrospilitic magmas, (2) granodioritic and dacitic-andesitic magmas, (3) basaltic magma, and (4) granitic magma. Furthermore, under cratogenic conditions other magmas are obtained. One of these magmas is a granitic one which differentiates into potash granite and gabbro-norite-anorthosite. The occurrence of such a granitic magma which is analogous in composition to rhyolitic compositions would solve the problem of the potash-rich acidic rocks. The soda-rich rocks, however, seem to be related to the spilitic and picrospilitic magmas, whereas the normal subalkalic rocks are apparently the differentiates of either a dacitic-andesitic magma or a basaltic magma or both.

Metasomatic alterations

Potash enrichment has been ascribed by some authors to secondary processes. Fenner (1936) has shown that thermal waters containing alkali halides and bicarbonates are still in the process of altering the rhyolite of the Yellowstone Park region. Terzaghi (1948) attributed the enrichment in potash of the rhyolites of the Esterel region, France, to alteration processes. Terzaghi arrived at that conclusion after some field evidences and the investigation of the textures of the studied rhyolites. The presence of the normative feldspar proportions of these rocks in the orthoclase field of the Or-Ab-An equilibrium diagram and the existence of the salic proportions outside the region of low temperature in the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagram is believed due to the secondary enrichment in potash. The vitric rhyolite studied by Terzaghi possesses a normative feldspar content which lies outside the orthoclase field and close to the cotectic curve of the feldspar equilibrium diagram. This might indicate that the rhyolite before devitrification and alteration was formed as an end stage of the differentiation of a basaltic magma. The formation of some potash-rich pegmatites of the Black Hills, South Dakota, has been shown by the author (Higazy, 1949) to be due to metasomatic processes. This conclusion has been drawn from the study of the chemical compositions and the textural features of the investigated rocks. Examples of secondary soda enrichment are numerous in the literature and need not be cited here. It may then be true that the other potash- and soda-rich rocks are altered by metasomatic processes but this conclusion cannot be arrived at except from field evidences and through investigation of the textural features of every individual occurrence of these rocks. Until we have such studies and more information about every individual case of the potash- and soda-rich rocks it should be stated that it is possible for these rocks to form directly by magmatic crystallization with no alteration. However, the possibility of these rocks

forming from the differentiation of a basaltic magma is very remote, if not altogether non-existent, unless the equilibrium systems which are discussed in this paper are changed in one way or the other in order to harmonize with the extreme compositions which we get in the case of the potash- and soda-rich rocks. The complications and the changes in these systems which are supposed to be due to pressure, water, volatile components, or even the combination of all these factors do not seem to affect the principal results derived from these equilibrium systems. It might possibly be proved that by means of some mechanism or relationship between the different components unknown at the present, that these factors have a significant influence in modifying the principles of crystallization in the studied equilibrium diagrams. Available data and experiments, on the other hand, do not point in that direction. The assumption of the presence of potash- and soda-rich magmas seems to solve the problem of the magmatic derivation of the potash- and soda-rich rocks respectively. Metasomatic processes by flowing pore solutions or diffusion of individual particles (Ramberg, 1944) may also be significant.

CONCLUSIONS

The Or-Ab-An and the $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$ equilibrium diagrams fail at present to account for the derivation of the potash- and the soda-rich rocks from the differentiation of a basaltic magma. Until a reasonable mechanism for their formation from such a magma is known it is assumed that they are in some cases the differentiates of potash-rich rhyolitic and soda-rich spilitic magmas respectively. In other cases, they are probably metasomatic rocks formed from the alteration of other subalkalic rocks. The field and textural features for every individual occurrence must be known to establish their metasomatic derivation.

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REFERENCES

- BOWEN, N. L. (1928), The evolution of the igneous rocks, Princeton.
 ——— (1937), Recent high-temperature research on silicates and its significance in igneous geology: *Am. Jour. Sci.*, **33**, 1-21.
 ——— (1945), Phase equilibria bearing on the origin and differentiation of alkaline rocks: *Am. Jour. Sci.*, **243-A**, 75-89.
 FENNER, C. (1936), Yellowstone Park borehole investigations: *Jour. Geol.*, **44**, 226-315.
 ——— (1948), Immiscibility of igneous magmas: *Am. Jour. Sci.*, **246**, 465-502.

- HATCH, F. H. (1889), On the occurrence of soda-felsites (keratophyres) in Co. Wicklow, Ireland: *Geological Mag.*, **6**, 70-83.
- HIGAZY, R. A. (1949), Petrogenesis of perthite pegmatites in the Black Hills, South Dakota: *Jour. Geol.*, **57**, 555-581.
- JOHANNSEN, A. (1931), The average chemical compositions of various rock-types: Sonder Abdruck aus dem neuen *Jahrbuch f. Mineralogie, etc., Beilage-Band 64*, Abt. A. (Brauns Festband), 505-516.
- NOBLE, J. A. (1948), High potash dikes in the Homestake Mine, Lead, South Dakota: *Bull. Geological Soc. Am.*, **59**, 927-940.
- NOCKOLDS, S. R. (1946), The order of crystallization of the minerals in some Caledonian plutonic and hypabyssal rocks: *Geological Mag.*, **83**, 215.
- RAMBERG, H. (1944), The thermodynamics of the earth's crust I. Preliminary survey of the principal forces and reactions in the solid crust: *Norsk. Geologisk Tidsskrift*, **24**, 104.
- SCHAIRES, J. F., AND BOWEN, N. L. (1935), Preliminary report on equilibrium-relations between feldspathoids, alkali-feldspars, and silica: *Trans. Am. Geophys. Union*, 16th Ann. Meeting, 325-328.
- AND — (1947), The system anorthite-leucite-silica: *Bull. de la Comm. Geologique de Finlande*, **140**, 67-87.
- TERZAGHI, R. (1935), The origin of the potash-rich rocks: *Am. Jour. Sci.*, **30**, 141-142.
- (1948), Potash-rich rocks from the Esterel, France: *Am. Mineral.*, **33**, 18-30.
- THOMAS, H. H. (1911), The Skomer volcanic series (Pembrokeshire): *Quart. Jour. Geological Soc. London*, **67**, 210.
- WAHL, W. (1949), Isostasy and origin of sial and sima and of parental rock magmas: *Am. Jour. Sci.*, **247**, 145-167.
- WASHINGTON, H. S. (1917), Chemical analyses of igneous rocks: *U. S. Geological Surv., Prof. Paper 99*.