THE RAPAKIVI OF HEAD HARBOR ISLAND, MAINE

Ruth D. Terzaghi, *Harvard University, Cambridge, Mass.*

Abstract

The granite of Head Harbor Island, Maine, a facies of the normal granite of Jonesboro, has the textural peculiarities of a typical rapakivi, including coarse grain and large rounded potash feldspar phenocrysts mantled by oligoclase. The occurrence and microscopic appearance of the rock suggest that it is of magmatic origin and not a product of granitization.

An examination of the normative feldspar content of 34 analyzed rapakivis and genetically related rocks indicates that these are, with few exceptions, represented by points lying in the plagioclase field of Bowen's equilibrium diagram for the system *or-ab-an,* in contrast to many granitized sediments whose projection points lie in the orthoclase field. This fact is believed to support the hypothesis that most rapakivis are of magmatic origin. The peculiar rapakivi texture occurs most commonly in rocks whose projection points lie on or near the boundary between the two fields, a circumstance to which the large size of the phenocrysts is thought to be related.

Although some of the older hypotheses concerning the origin of the oligoclase mantles are not discarded, it is suggested that these mantles may be due to a change in the position of the orthoclase-plagioclase field boundary.

Definitions

Among the earliest descriptions of rapakivi is that published by Sederholm in 1891. In 1928 the same writer defined the rock as a granite containing large rounded phenocrysts, or ovoids as he called them, of potash feldspar mantled by sodic plagioclase. Wahl (1925) has applied the term *pyterlite* to rapakivi-like rocks in which the ovoids are not mantled. These are so closely related to rapakivi in general appearance and in mineralogical composition that they may be considered as a variety of this species. While several investigators have applied the term rapakivi to rocks associated with, related to, or in some respect similar to the rapakivi in the narrower sense, the term will be applied in this article only to rocks actually containing conspicuous large rounded crystals of potash feldspar mantled by sodic plagioclase.

Description

On Head Harbor Island, near Jonesport, mapped in part on the Columbia Falls sheet and in part on the Great Wass Island sheet of the U. S. Geological Survey, is a rapakivi whose general appearance and mineralogical composition are so similar to that of the granite of Jonesboro which outcrops farther north in the same quadrangle and on nearby islands, that it seems to be unquestionably a facies of this rock.

The typical granite of Jonesboro, an older analysis of which is given below, consists essentially of perthitic orthoclase, oligoclase, quartz and biotite. With the exception of a few idiomorphic, apparently partially resorbed oligoclase phenocrysts 5 to 10 mm. long, the individuals of the various minerals are generally all about the same size, and have a diameter of several millimeters in typical specimens. Perthite occasionally exhibits idiomorphism, and in some outcrops is commonly, although not invariably, mantled by orthoclase. Neither the typical granite of Jonesboro nor its rapakivi facies show notable evidence of having undergone a tectonic disturbance, and they were probably intruded after the folding of the Silurian volcanics and sediments which outcrop in the area. Two of the lower members of this series, a quartz latite and a rhyolite, contain large amounts of secondary quartz, possibly a metamorphic effect of the granite, but the intercalated and overlying shales show no obvious effects of metamorphism.

The Head Harbor Island rapakivi differs from the typical granite of Jonesboro in that it is coarser grained and contains the large rounded phenocrysts (ovoids) of potash feldspar mantled by oligoclase which are typical of rapakivi. Professor Sederholm, who very kindly examined the writer's specimens in 1930, stated that they were similar to certain Finnish rapakivis. The Maine occurrence differs from the classical rapakivis of Finland in that the ovoids are less abundant and do not exceed about 2 cm. in length, whereas those of many Finnish rapakivis have a length of 8 cm. or more, 4 cm. being an average length. In the composition of the plagioclase mantles ($ab_{78}an_{19}or_{3}$), the Head Harbor Island rapakivi conforms closely to the Finnish type, except that the former contain somewhat less potash than those of Finnish rapakivis for which analyses are available. The potash feldspar ovoids of the Head Harbor Island rock are richer in soda than many of those of the Finnish rapakivi. Analyses of the perthite and of the oligoclase are given in Table 1. Like the normal granite of Jonesboro, the rapakivi facies contains a few large partially resorbed individuals of oligoclase which are smaller than the perthite ovoids but larger than minerals of the groundmass which are generally several millimeters in diameter. The groundmass consists of perthite, oligoclase and biotite.

Within the perthite phenocrysts, in a zone just beneath the surface, are a number of very small idiomorphic crystals of oligoclase, many of which have at least approximately the same orientation. As may be seen in Fig. 1, the (010) plane of these is roughly perpendicular to those of the mantle oligoclase and of the orthoclase of the ovoids. Small oligoclase individuals within the ovoids have also been observed in a few of the Finnish rapakivi (Backlund 1938b). The deposition of the oligoclase mantles was preceded or accompanied by some resorption of the orthoclase ovoids, as may be seen in Fig. 1. These mantles are composed of a

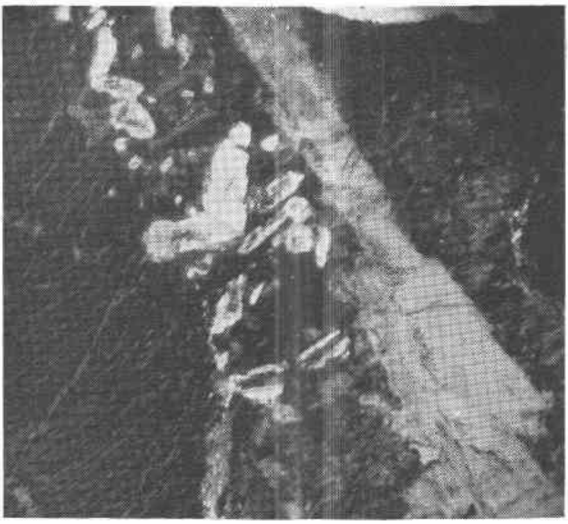

Fig. 1

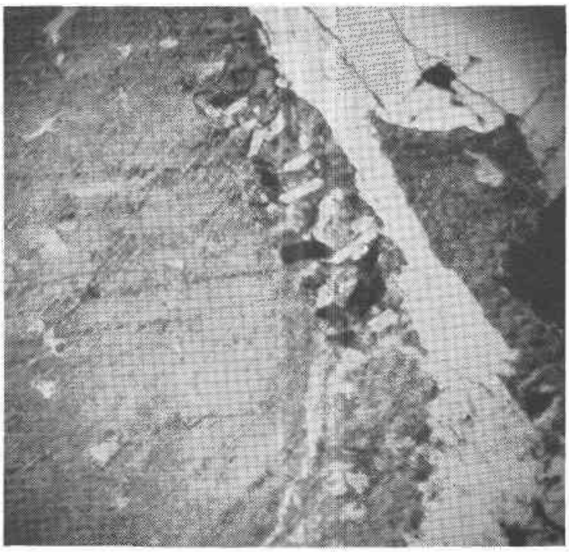

Fig. 2

Fig. 1. A portion of a perthitic ovoid with mantle and inclusions of oligoclase. The section is approximately parallel to the (100) plane of the orthoclase. The trace of the twinning lamellae of the mantle oligoclase is approximately parallel to that of the composition plane of the Carlsbad twins of the orthoclase. Crossed Nicols. ×22.

Fig. 2. The same ovoid. Quartz veinlets and inclusions appear as white spots within the feldspar. A small part of the Carlsbad composition plane appears indistinctly in the lower left-hand corner. Ordinary light. ×14.

number of sub-parallel individuals through which the twinning lamellae are not continuous. In this feature, the Maine rapakivi is similar to certain of the Finnish ones, according to a description published by Popoff in 1928. At one corner of the section shown in Fig. 1 may be seen a portion of an outer rim of perthite which does not however completely mantle the phenocryst. While numerous successive oscillations of this sort are common in some of the Finnish rapakivi, they are rather rare in that of Head Harbor Island and are never well developed.

Scattered throughout the phenocrysts, chiefly in the potash feldspar core but also to some extent in the oligoclase mantles, are small masses of

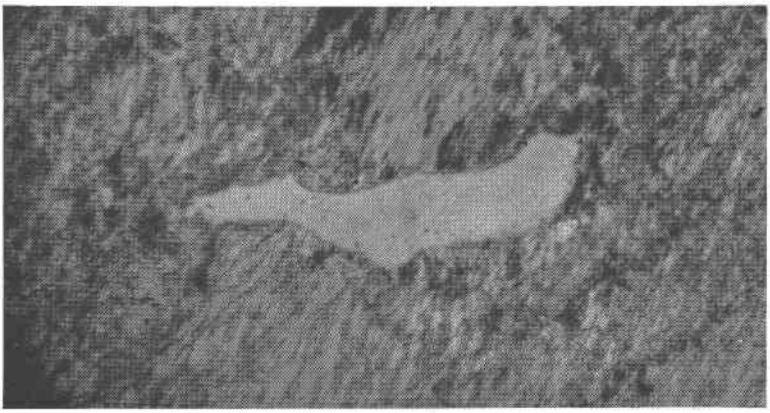

FIG. 3. Quartz veinlet in a perthite ovoid. Ordinary light. ×74.

quartz comprising roughly 2 per cent of the volume of the feldspar. Most of these are elongated and have irregular, in part concave, surfaces. They are generally less than 0.5 mm. long, the largest having a length of about 1 mm. A number of them appear as small white spots in Fig. 2 and one is shown highly magnified in Fig. 3. They appear to be replacement veinlets. Popoff (1928) described similar veinlets which he considered eutectic intergrowths with the feldspar. Rounded quartz grains having a diameter of 0.01 mm. or less are present in a zone 0.02 to 0.05 mm. wide, located within the potash feldspar ovoid approximately 0.7 mm. from its periphery, to which the zone is roughly parallel. (Figs. 1 and 2.) These appear to be inclusions which were partially resorbed before inclusion occurred. The parallelism between this zone and the surface of the ovoids indicates that the rounded form of the ovoids was acquired before the growth was complete, and that it is not merely a result of partial resorption at a final stage in their development.

Zircon and apatite are rare accessories in the normal granite as well as in the rapakivi.

TABLE 1. CHEMICAL ANALYSES

	1	2	3
SiO_2	72.97	65.38	63.08
TiO_2	n.d.	none	none
Al_2O_3	14.63	18.96	22.90
Fe_2O_3	n.d.	0.48	0.46
FeO	1.73	none	n.d.
CaO	1.48	0.18	3.80
SrO	n.d.	none	n.d.
MgO	0.27	0.12	trace
MnO	0.10	none	none
K_2O	5.18	10.74	0.56
Na_2O	3.28	3.64	8.80
BaO	n.d.	0.06	n.d.
S	0.03	n.d.	n.d.
CO_2	none	n.d.	n.d.
H_2O	n.d.	0.44	0.32
	99.67	100.00	99.92

Norms

	Marsh-field granite	Rapakivi Hd. Harb. Is. (est.)
qu	28.72	27
or	31.18	28
ab	27.75	36
an	7.33*	6
C	0.80	
hy	3.85	3
or:ab:an=	47:42:11	40:52:8

Optical Data

	$\beta(\pm 0.003)$	Max. ext. $\perp 010$	Est. *an* %†
orthoclase	1.525	—	—
perthitic albite	1.532	13°	5
oligoclase	1.540	3°	16

1. Marshfield granite, Booth Bros. Jonesboro Quarry, quoted from T. N. Dale (1907). Analysts, Ricketts and Banks.
2. Perthite ovoids from rapakivi of Head Harbor Island. Analyst, F. A. Gonyer.
3. Oligoclase of rapakivi of Head Harbor Island. Since the oligoclase of the ground mass and of the mantles had the same optical properties, no effort was made to separate them. Analyst, F. A. Gonyer.

* This value may be too high, since P_2O_5 and F were not determined.

† Corresponding to the optical data as given in Goranson's tables (1926).

In column (1) below, are given the mineral components of the perthite ovoids, in (2) those of the oligoclase, in (3) the estimated total minerals of the rapakivi, in (4) the estimated total minerals of the analyzed Marshfield granite, as calculated on the basis of the analysis and the minerals invariably present in the Marshfield granite, and in (5) the essential minerals of a typical specimen of the Marshfield granite from the Booth Brothers' Jonesboro Quarry, as estimated from a thin section. All quantities are given in weight per cent.

	(1)	(2)	(3)	(4)
quartz			27	37
orthoclase	62.4	3.1	26	23
albite	36.0	78.4	36	27
anorthite	1.6	18.5	6	6
biotite			5	7

		(5)
quartz		35
perthite		40
plagioclase	albite	18
	anorthite	2
biotite+chlorite		5

COMPOSITION AND ORIGIN OF THE RAPAKIVI GROUP

Until recently the rapakivi granites of Finland, the classical land of granitization, have been considered true igneous rocks. In 1938(b)

Backlund published for the first time in English the hypothesis that they have originated by the granitization of sandstones. The enunciation of this hypothesis has stimulated a lively controversy (Eckermann 1937, Backlund 1938a) which students of the problem may follow with profit and interest. So many convincing arguments are presented by both sides that the question immediately arises as to whether two or more different processes may not be capable of producing the rapakivi texture, with the result that each individual case must be examined on its own merits. In the Head Harbor Island occurrence, the writer found no evidence that the rapakivi is not of normal igneous origin. There is, for instance, no transition whatsoever between the typical granite and the practically unaltered older shales and volcanic rocks of the area. Moreover, the different orientations of the oligoclase of the mantles and of the inclusions within the perthite ovoids suggest two different origins for the two forms, and are not readily reconciled with the hypothesis of granitization.

The chemical composition of the rapakivi group as a whole, including the related rocks, offers statistical evidence in favor of an igneous origin. Conversely, if the rapakivis are true igneous rocks, the chemical composition of the group throws an interesting light on the origin of their texture. In Fig. 4 are shown the normative feldspars, recalculated to 100 per cent, of 34 fresh rapakivis and related granites (Carstens 1925; Eskola 1928, 1930; Hackmann 1934; Kanerva 1928; Laitakari 1928; Wahl 1925) including those of the one known American occurrence and of the normal granite of which this rapakivi is a facies. (Although there are about fifty superior analyses of fresh so-called rapakivis and related rocks, some of these, like the excellent and complete analyses and descriptions published by v. Eckermann (1936) refer to groups of rocks which include no true rapakivi, and others are not accompanied by descriptions which permit their classification as true rapakivi or as merely related granites. Such analyses are not represented in the diagram.) The true rapakivis are indicated in the figure by dots, while the related rocks are shown by circles. The curve is a part of the Bowen (1928) field boundary for the system *or-ab-an*, the exact location being based on evidence described by the present writer (Doggett, 1929).

It is a striking fact that many points representing the composition of rapakivi and related rocks lie on the field boundary and in the plagioclase field, but almost none in the orthoclase field. This limited range of composition would probably be a necessary feature of a group of unaltered rocks of igneous origin, but there is no apparent reason why their composition should be thus limited if they are all the products of granitization of sediments, many such rocks, as well as an extremely large number of granites of unknown origin being represented by points in the orthoclase field (Terzaghi 1935).

Of the 14 points representing true rapakivis in Fig. 4, 8 lie on or very near the field boundary. Over half the points lying on or near this line represent true rapakivis, while less than one third of those lying well within the orthoclase field represent such rocks. Even among the large number of rocks whose analyses are given in Washington's tables (1917) there are almost none other than rapakivis, either among the coarse or

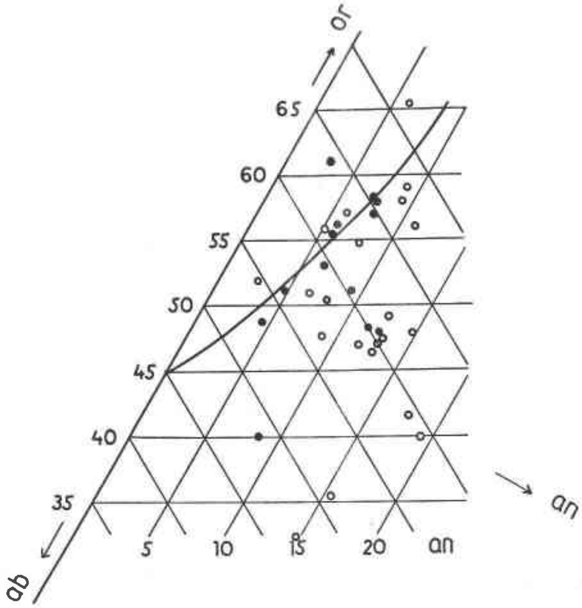

FIG. 4. The normative feldspar content of some rapakivis and related rocks plotted on a part of the hypothetical equilibrium diagram for the system *or-ab-an* (Bowen, 1928; Terzaghi 1929). Rapakivis and pyterlites are shown by dots, related rocks not having the rapakivi or pyterlite structure by circles.

the fine-grained rocks, whose composition corresponds to that of the rapakivis lying on the field boundary between points representing 54 and 58 *or*. Two interpretations of these facts occur to the writer. One is that the rapakivi composition is not attained by true magmas, and that the rapakivis are, therefore, as Backlund believes, of non-magmatic origin. On the other hand, if they are of magmatic origin, the rarity of rocks having the typical composition but not the texture of rapakivi suggest that this texture is a function of the composition. That composition is not the only factor involved is indicated by the fact that some rapakivis, including that of Head Harbor Island, do not have the typical rapakivi composition corresponding to points lying on the field boundary.

Among the many problems which arise in connection with the origin of the rapakivi texture, two are particularly interesting. The first of these involves the presence of potash feldspar phenocrysts in rocks whose bulk composition lies in the plagioclase field. Although there are many non-rapakivis which present this same problem, the consideration of these would transgress the limits of this article. However, much of the discussion of the origin of the rapakivi ovoids would apply equally well to the potash feldspar phenocrysts of other rocks. The second aspect of the problem is the origin of the mantle of sodic plagioclase surrounding the perthitic ovoids.

Many investigators have assumed that idiomorphism and large size of the individuals of any given mineral species indicate that that mineral was the first or among the first to crystallize from the magma. However, the course of differentiation—assuming an igneous origin—of several Finnish rapakivi series was such that the younger members of each series are richer in potash than the older members of the same series (Backlund 1938b). This indicates early separation not of orthoclase but of plagioclase, which is to be expected from the fact that the projection points of these rocks lie in the plagioclase field of the equilibrium diagram. It is therefore apparent that some cause, other than early crystallization, of the large size and idiomorphism of the potash feldspar individuals must be sought.

As will be shown in the following paragraphs, a consideration of the relative amounts of the two feldspars, and the relative rates at which the individual crystals probably grew, if they started to develop at the same time, indicates that a few large and probably idiomorphic potash feldspar individuals may develop simultaneously with a great number of smaller plagioclase crystals. Under certain conditions, it would appear that the potash feldspar individuals may develop a relatively large size even though they begin to crystallize later.

According to two sets of analyses given by Wahl (1925) the rapakivi whose projection points lie on the field boundary at about 55 *or* may contain potash feldspar ovoids consisting of 65 to 75 per cent orthoclase-molecule and 25 to 35 per cent highly sodic plagioclase, while the plagioclase individuals contain less than 9 per cent *or*. Assuming that the present bulk composition of the perthitic ovoids represents their original composition, there was 2.5 to 5 times as much potash feldspar substance ($or+ab$) in the magma as there was plagioclase. Hence a layer of liquid of infinitesimal thickness on each face of a crystal growing in such a magma contains 2.5 to 5 times as much potash feldspar substance as plagioclase, which must crystallize in response to the loss of a given heat quantity. If diffusion is able to keep pace with crystallization, the linear growth of the potash feldspar crystals may thus be 2.5 to 5 times as rapid as that of the plagioclase. While the potash feldspar crystals are growing rapidly and sweeping in the material from a relatively large volume of liquid, the plagioclase individuals grow slowly and derive their material from a correspondingly small volume. As a result, the liquid not immediately adjacent to plagioclase crystals is likely to become saturated with plagioclase, so that new centers of crystallization may be established. Thus the smaller quantity of plagioclase is divided among many crystals while the larger quantity of potash feldspar substance ($or+ab$) is divided among few crystals. If the ratio of their rates of lineal growth remains between 2.5 and 5 throughout the period of development, the ratio of their individual volumes will be between 15 and 125, assuming a roughly equidimensional habit. The large size and relatively rapid development (compared to the plagioclase) of the potash feldspar may account for the rounded outlines of typical ovoids of rapakivi.

If, on the other hand, the magma is rapidly cooled, a large number of crystals of both sorts may be developed, with the result that none of these can attain either relatively or absolutely great size. That slow cooling is, in fact, generally a necessary condition for the development of the rapakivi texture is indicated by the circumstance that this texture is very rare in fine-grained rocks and that the contact facies of some rapakivi masses lacks the rapakivi texture. (See for instance Laitakari's (1928) description of the Väkkära granite.)

According to this hypothesis of the origin of potash feldspar phenocrysts, a large amount of solid solution of plagioclase (chiefly albite) in the potash-feldspar solid phase, accompanied by little or no solid solution of orthoclase molecules in the plagioclase phase favors the development of potash feldspar phenocrysts. This offers a clue to the fact that the rapakivi texture is more likely to be present in rocks containing a moderately calcic plagioclase than in those containing a highly sodic one, since the potash feldspar molecule enters only slightly into solid solution with a plagioclase which is even moderately calcic, whereas it may be present in large amounts in an alkaline plagioclase (Mäkinen 1917). The soda content of orthoclase apparently does not necessarily vary greatly with the composition of the magma.

We may now consider the case of rapakivi texture in rocks whose feldspar content is represented by points not lying near the field boundary. Under normal conditions, the plagioclase crystals may have attained a considerable size before the potash feldspar begins to crystallize, with the result that the latter will not be able to overtake the former in size. If however, the magma is injected in such a way that the first stage of the cooling is accomplished rapidly, giving rise to many small plagioclase individuals, while the latter part of the cooling (after the orthoclase begins to crystallize), progresses slowly, the potash feldspar may be concentrated in a few large individuals. If the composition of the potash feldspar is very near that of the melt from which it is crystallizing, while that of the plagioclase is very different, the ratio of potash feldspar to plagioclase will be high and the development of large idiomorphic and possibly rounded potash feldspar individuals will of course be favored. Assuming that the composition of the Head Harbor Island rapakivi magma "arrived" at the field boundary at a point corresponding to about 52 *or*, the ratio of potash feldspar substance ($or+ab$) to plagioclase in the remaining melt would have been about 6.8, a high ratio which must have contributed to the development of the large size of the ovoids.

The second aspect of the problem of the rapakivi texture is concerned with the origin of the oligoclase mantles which alternate in some cases with perthite mantles. In 1928 Sederholm gave an excellent summary (pp. 88–89) of the various hypotheses concerning their origin which had been proposed at that time.

Among the most interesting of the older hypotheses is that of Vogt (1906) who suggested that the oligoclase and perthite mantles of the ovoids may be due to an oscillation of the composition of the magma about the "eutectic" (field boundary), first the oligoclase becoming supersaturated and then the potash feldspar. However, the development of a state of super-saturation in the entire magma with respect to components present in the crystalline state seems to call for a special explanation, and it appears to the writer more likely that the field boundary may have oscillated about the projection point of the magma than that the composition of the magma oscillated about that corresponding to the field boundary. A possible cause of such a change in the position of the field boundary will be discussed below.

A somewhat similar hypothesis proposed by Sederholm (1928) obviates the difficulty just mentioned. He postulated that a limited zone immediately surrounding the potash feldspar ovoids may have become supersaturated with the components of the plagioclase, with the result that this material was deposited in place of the potash feldspar as a mantle about the ovoids. If, as the present writer believes, the potash feldspar ovoids grew more rapidly than did the individual plagioclase crystals, this mode of origin of the mantles would appear to be among the most plausible suggested.

On the other hand, it may be that a shift of equilibrium between the feldspars was responsible for the plagioclase mantles. Certain facts suggest that the solubility of orthoclase in a magma may increase with increasing water content faster than that of sodic plagioclase (Terzaghi 1935). In other words, it appears that the field boundary may be shifted into the orthoclase field. If this is the case, an increase in the water content of the magma may cause the potash feldspar crystals to cease growing or even to be partially resorbed while oligoclase may be deposited in its place upon a further loss of heat. The quartz veinlets in the potash feldspar ovoids of the Maine rapakivi as well as in some others seem very clearly to represent replacement phenomena probably associated with a late stage of consolidation in which the remaining magma was rich in water, and they are thus in harmony with this hypothesis of the origin of the plagioclase shells.

Other things being equal, the upper limit set on the water content of a magma varies with the pressure on the gaseous phase with which the magma is more or less in equilibrium. If the cover is so pervious that the gas can escape readily, the water content of the magma may be reduced to a very low value. If the cover is impervious, the gas may develop a pressure equal to that exerted by the overlying column of rock, provided sufficient water is present in the magma. Thus very minor changes in the local conditions, such as the development or the closing of a few cracks in the overlying rocks, may be sufficient to cause variations in the water content of the magma. In this way, the position of the field boundary might be caused to oscillate, giving rise to the alternating deposition of plagioclase and of potash feldspar.

References

Backlund, H. G., The rapakivi puzzle. A reply: *Geol. För. i Stockholm, Förhandlingar*, **60**, 105–112 (1938a).

Backlund, H. G., The problem of the rapakivis: *Jour. Geology*, **46**, 339–396 (1938b).

Bowen, N. L., *The Evolution of the Igneous Rocks*, Princeton (1928).

Carstens, C. W., Rapakivigesteine an der Grenze des Trondhjemgebietes: *Norske Geol. Tidsskr.*, **8**, 81–92 (1925).

Dale, T. N., The Granites of Maine: *U. S. Geol. Surv., Bull.* **313** (1907).

Doggett, R. A., The orthoclase-plagioclase equilibrium diagram: *Jour. Geol.*, **37**, 712–716 (1929).

Eckermann, Harry v., The Loos-Hamra region: *Geol. För. i Stockholm, Förhandlingar*, **58**, 130–343 (1936).

Eckermann, Harry v., The genesis of the rapakivi granites: *Geol. För. i Stockholm, Förhandlingar*, **59**, 503–524 (1937).

Eskola, Pennti, On the disintegration of rapakivi: *Bull. Comm. Géol. Finlande, No.* **92**, (1930).

Goranson, Roy, The determination of the plagioclase feldspars: *Am. Mineral.*, **11**, 139–151 (1926).

Hackmann, Viktor, Das Rapakivigebiet der Gegend von Lapeeranta: *Bull. Comm. Géol. Finlande, No.* **106** (1934).

KANERVA, ILMARI, Das Rapakivigebiet von Vehmaa im südlichen Finland: *Fennia,* **50** No. 40 (1928).

LAITIKARI, AARNE, Palingenese am Kontakt des post-jotnische Olivindiabases: *Fennia,* **50,** No. 35 (1928).

LOKKA, LAURI, Neuere chemische Analysen von finnischen Gesteinen: *Bull. Comm. Géol. Finlande,* No. **105** (1934).

MAEKINEN, EERO, Ueber die Alkalifeldspate: *Geol. För. i Stockholm Förh.,* **39,** 149 (1917).

POPOFF, BORIS, Mikroskopische Studien am Rapakivi: *Fennia,* **50,** No. 34 (1928).

SEDERHOLM, J. J., Ueber die finnländischen Rapakivigesteine: *Tschermak's Min. u. Petr. Mitt.,* **12,** 1–31 (1891).

SEDERHOLM, J. J., On orbicular granites and on the rapakivi texture: *Bull. Comm. Géol. Finlande,* No. **83** (1928).

TERZAGHI, R. D., The origin of the potash-rich rocks: *Am. Jour. Sci.,* 369–380 (1935).

TERZAGHI, R. D., Geology and Petrology of the Columbia Falls Quadrangle, Maine: In press (1940).

VOGT, J. H. L., Physikalische Gesetze der Kristallizationsfolge in Eruptivgesteine: *Tschermak's Min. u. Petr. Mitt.,* **25,** 361–412 (1906).

WAHL, WALTER, Die Gesteine des Wiborger Rapakivigebietes: *Fennia,* **45,** No. 20 (1925).

WASHINGTON, H. S., Chemical analyses of igneous rocks: *U. S. Geol. Surv., Prof. Paper* **99** (1917).