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## KERATOPHYRES OF EASTERN OREGON AND THE SPILITE PROBLEM.[1]


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### PART I.


ABSTRACT.

The Permian rocks of the Baker quadrangle and adjacent areas of eastern Oregon include considerable thicknesses of keratophyres, quartz keratophyres, spilites and allied pyroclastics, and albite diabases, mildly metamorphosed in part to albite-chlorite schists. They are associated with marine limestones in such a way as to suggest their submarine origin, and have been intruded by several varieties of plutonic rocks, among them albite granite.

Relics of more calcic plagioclases in the now dominantly albitic rocks, the mottling and inclusions of the feldspars, the direct correlation between the amount of chlorite and epidote among the mafic minerals and the proportion of albite in the feldspars, the ophitic texture of the albite diabases, the presence of albite veins and albite-filled vesicles and association with albite granites showing evidence of albitization, all point to the more albitic of the present feldspars being largely of metasomatic origin, especially in the less siliceous members.

The literature of the spilitic rocks is reviewed and the attempt made to evaluate the several theories advanced to explain their peculiarities. The conclusions reached are: that the spilitic rocks are derivatives of normal alkalicalcic magmas; that the oligoclase quartz keratophyres are probably normal magmatic products of a trondhjemitic differentiation series (a series tending toward oligoclase quartz-diorite) whose trend is probably conditioned by the absorption of water either from the wall rocks as postulated by Goldschmidt or by engulfment of wet sediments; that the spilites, albite diabases, and siliceous rocks richest in albite have all been metasomatically enriched in albite; that this enrichment was probably entirely subsequent to their consolidation and brought about either by resurgent water from the wet sediments as suggested by Daly, or by albitic solutions derived by deeper-seated differentiation along trondhjemitic lines. The common association of albite granites and spilitic rocks is explicable by this source of albitizing solutions. All these conclusions are quite consistent with the commonly geosynclinal locus of spilitic rocks, with the sporadic distribution of their mineral facies, and their frequent association with normal basalts. At the same time they suggest that availability of water rather than simply tectonic conditions governed the trend of differentiation. Anomalous local conditions may thus account for the local occurrence of keratophyric rocks in continental environments.


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GEOLOGIC SETTING.

The Wallowa and Blue mountains of eastern Oregon expose, in the midst of the Tertiary volcanic field, considerable areas of pre-Tertiary rocks. This pre-Tertiary terrane is composed dominantly of supracrustal rocks of Carboniferous to Triassic ages invaded by large plutonic bodies ranging in composition from gabbro to albite granite. Some of these plutonic rocks (gabbros, hornblende quartz diorites, trondhjemites, and albite granites) are strongly gneissic, but others (biotite quartz diorites) are massive. Their intrusions have been tentatively assigned to two cycles[2] the later of which at least is of Mesozoic, probably post-Jurassic, age. The earlier may be late Permian, Triassic, or even an early phase of the tentatively distinguished second cycle.

In connection with the keratophyres and spilites to be discussed in this paper, only one group of these plutonic rocks seems worthy of more than passing mention. This group, comprising the hornblende quartz diorite, trondhjemite, and albite granite, has been described in some detail and the conclusion reached that it comprises original diorite and quartz diorite of normal magmatic origin which have in part (and, indeed, in considerable volume) been altered by circulating soda-rich hydrothermal solutions to albite granite. The albite granite is regarded as of metasomatic origin.[3] It is possible that there is a genetic relation between these albitic intrusives and the keratophyric volcanics, although the intrusions are definitely younger than the supracrustal rocks and are probably separated from them by an orogenic period. This matter is discussed in a later section of the paper.

The pre-Tertiary supracrustal rocks of this region have been strongly deformed, probably more than once, in pre-Tertiary time. They are now exposed in closely appressed, in part isoclinal, folds of generally easterly trend, but even their larger structural and stratigraphic relations are still but little known. Tertiary (chiefly post-Miocene) deformation by both folding and faulting along northwesterly lines has been much

[2] Reed, J. C., and Gilluly, James: Heavy mineral assemblages of some of the plutonic rocks of eastern Oregon: American Min., vol. 17, pp. 201-220, 1932.

Gilluly, James: Geology and ore deposits of the Baker quadrangle, Oregon: U. S. Geol. Survey Bull. in preparation.

[3] Gilluly, James: Replacement origin of the albite granite near Sparta, Oregon: U. S. Geol. Survey Prof. Paper 175-C, pp. 65-81, 1933.

less intense than the pre-Tertiary, although it dominates the present topography of the region.

## PERMIAN GREENSTONE.

*Distribution.*—One of the most widespread formations of the pre-Tertiary terrane of northeast Oregon is a series of altered volcanic rocks with minor sedimentary members, which extends in a belt eastward from a point west of the town of North Powder, across the northern parts of the Baker and Pine quadrangles to the Snake River at Homestead, a distance of about 50 miles. Its farther extent east and west is not at present known, nor, indeed, is its outcrop continuous within this region for it is interrupted by igneous intrusions and by overlapping Tertiary rocks for considerable distances. The present paper is based upon studies of the formation within the Baker quadrangle and for a short distance to the east.

*Stratigraphy and Structure.*—This formation is so strongly deformed and its exposures are so discontinuous that it has so far proved impossible to decipher the details of stratigraphy. Presumably it overlies the argillite, of Carboniferous age, exposed in Elkhorn Ridge, but whether conformably or not is unknown. Neither have its relations to the known Triassic rocks of the region been determined, but the notably greater metamorphism to which it has been subjected suggests that there is an unconformity between them. From poorly preserved fossils contained in the limestones and associated tuffs, the formation is known to be of Permian age.[4]

Most of the formation is composed of quartz keratophyre flows and tuffs, keratophyre flows, meta-andesites, spilites, albite diabases, and keratophyre tuffs. Subordinate constituents are chert, conglomerate, argillite, and limestone. All these subordinate constituents occur in small, commonly lenticular bodies probably due to the shearing out, during orogenesis, of originally more continuous members.

Owing to strong deformation which the rocks have undergone, their thickness is uncertain within wide limits. Across the northern part of the Baker quadrangle the formation forms a belt, approximately 4 miles wide transverse to the strike, in which the dips are nearly vertical. Although it is probable that this great apparent thickness is due to repetition by iso-

[4] Girty, G. H.: personal communication, cited in full in U. S. Geol. Survey Bull. 830-A, p. 13, 1932.

clinal folding, the diverse lithology of the formation would seem to require at least 4,000 feet of stratigraphic thickness.

*Petrography.*—The dominant rocks of the greenstone are clearly effusive, and their association with fossiliferous sediments renders a submarine origin most probable, although no pillow structures—such as are common in subsiliceous lavas of this environment—have been detected even among the less siliceous members. Amygdaloids are commonly present but not conspicuous. Contacts between flows cannot ordinarily be recognized because of the widespread metamorphism. Most of the formation is highly sheared, with seams of chlorite dividing the rocks into lozenge-shaped blocks, and in places it is difficult to make the rock break on surfaces other than these shears.

The most abundant component of the formation is quartz keratophyre. These rocks are porphyritic, with sporadic rounded phenocrysts of plagioclase and dark quartz ranging between .5 mm. and 1 cm. in size, set in an aphanitic greenish-gray groundmass which varies from porcellanous to microcrystalline.

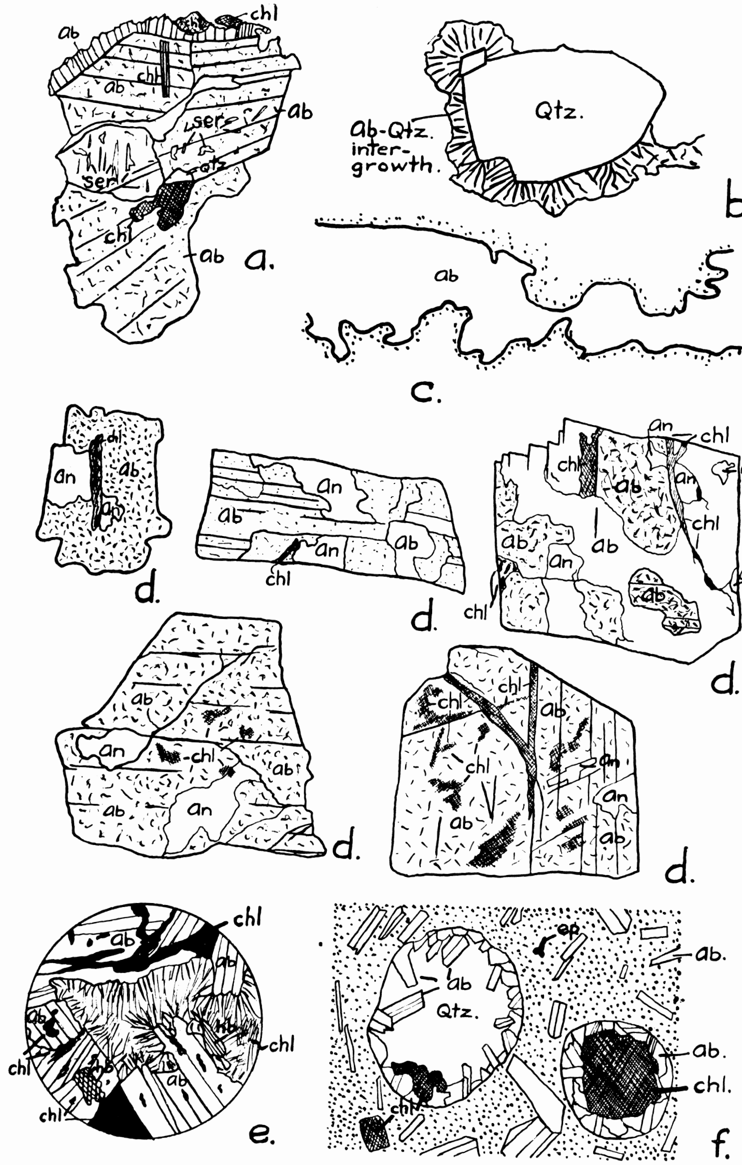
The microscope reveals quartz and cloudy albite set in a groundmass of quartz, albite, and chlorite. Orthoclase may be present in some specimens but was not detected and if present must be in small amount. Epidote, calcite, green hornblende, sericite, and biotite, occur in some specimens and titanite, magnetite, ilmenite, zircon, and apatite are accessory. Chlorite overwhelmingly predominates among the mafic minerals. Groundmass textures range from andesitic (felted) and trachytic through microspherulitic and microfelsitic (devitrified?) to granophyric. The phenocrysts are commonly broken by flow movements in the lava, but orogenic shearing is also evident in practically every thin section. Some of the rocks are wholly mylonitic.

The feldspars range from nearly pure albite to sodic oligoclase. Almost all have $\gamma$ less than 1.54, corresponding to compositions more sodic than $An_5$. One analyzed specimen, No. 1 in Table 1, carries only enough CaO to satisfy the $P_2O_5$ present for apatite. Only one feldspar is apparent in this specimen and since considerable $K_2O$ is present, the albitic feldspar may contain potassium feldspar in solid solution, although symmetrical extinction angles of 16° on sections normal to 010 and angles of 18° to 22° between $\alpha$ and 001 on sections normal to $\gamma$ correspond to accepted values for nearly pure albite.

Hence, if potassium feldspar is contained in solid solution it does not appreciably affect the optical properties. Some orthoclase is possibly present in the microcrystalline groundmass of this specimen, accounting for the $K_2O$ content, but several other specimens carry much less $K_2O$ so that their feldspars are, except for inclusions, nearly pure Ab. Although some of the feldspars are clear and appear fresh, most are cloudy, owing chiefly to very minute inclusions of chlorite and sericite. Commonly the feldspars are mottled because of the irregular distribution of the inclusions. A few specimens show rims formed by water-clear crystals of albite surrounding and radiating from mottled central crystals of albite. Several specimens have albite with radiate habit surrounding central crystals of either quartz or albite and so intergrown with quartz as to approach the granophyric texture; but it is probable that the texture in these rocks is due not to primary crystallization but to metasomatism, for it is found only in rocks cut by albitic veinlets. These structures are shown in the camera lucida drawings of Fig. 1-a and 1-b, and an albite veinlet with unmatched walls, suggesting a metasomatic origin, is shown in Fig. 1-c. Although the mottled appearance and inclusions in the feldspars suggest a secondary origin, epidote is sparingly present and zoisite practically absent, hence the albite of these rocks is not simply saussuritic, as might be expected from the shearing they have undergone. For these reasons, and because of demonstrable albitization in associated rocks, at least the most albitic of the feldspars are considered as probable products of albitization, although oligoclase, where present, may be primary.

Non-quartzose keratophyres are widespread among the greenstones. Most are finely porphyritic with phenocrysts of plagioclase and, in some, of hornblende, set in a dense, greenish-gray groundmass. Except that they lack quartz the rocks greatly resemble the quartz keratophyres. Locally flow structures can be made out in the field.

Albite (and rarely oligoclase-albite)—commonly of two crystal-sizes—chlorite, epidote, secondary quartz, a little sericite and accessory magnetite, titanite, and apatite, are found in all specimens. The textures are chiefly felted, with some trachytic and felsitic. A few rocks show unaltered augite, but in most this has altered to uralitic amphibole or has been pseudomorphically replaced by chlorite or epidote. Hornblende—pleochroic in green and brown—biotite, clinozoisite,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and calcite occur in some specimens. The epidote of these rocks is chiefly a replacement of augite or hornblende, although a minor part replaces the feldspar. Clinozoisite and epidote are contained in the feldspars of some of the rocks, although so little is present that their solution in the feldspar could hardly render the composition more calcic than sodic oligoclase. As in the quartz keratophyres, the feldspars of the non-quartzose keratophyres are cloudy owing to inclusions of chlorite and sericite. Many of the rocks are cut by albitic veins. The evidence that the feldspars are products of albitization of originally more calcic feldspars is much stronger than in the quartz keratophyres, for the textures of these rocks are those of typical andesites, and the partly albitized meta-andesites, next to be described, are found representing intermediate stages in the alteration.

The meta-andesites, although subordinate constituents of the formation, are especially illuminating in respect to the origin of the albitic rocks. They are dark green; some are porphyritic and some non-porphyritic. The phenocrysts—where present—are chiefly feldspar, with less abundant chlorite pseudomorphs after hornblende. The microscope shows felted textures, and the following minerals: labradorite-andesine (in some specimens albite), augite, green hornblende, chlorite, epidote, zoisite, sericite, calcite, secondary quartz, apatite, and ilmenite. Augite and hornblende are invariably partly altered to chlorite and epidote. Some specimens retain quite unaltered feldspars of intermediate composition, others show slight saussuritization, while still others have their original labradorite or andesine embayed and partly replaced by albite which is cloudy from chloritic inclusions and with blebs of chlorite scattered through it. The boundaries of this albite against

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Fig. 1. Camera lucida drawings of textures and minerals of the Permian greenstone of Eastern Oregon.

a. Cloudy and mottled albite rimmed by radiate clear albite, in quartz keratophyre.

b. Quartz crystal surrounded by radiating intergrowth of quartz and albite, in quartz keratophyre.

c. Albite vein in quartz keratophyre of b.

d. Albite crystals showing mottling by irregularly distributed inclusions of chlorite and sericite and with remnants of original andesine. Keratophyric meta-andesite.

e. Corroded crystals of albite mottled by chlorite inclusions, in meta-andesite.

f. Amygdule in spilite, lined with water-clear albite and filled with quartz; a second amygdule lined with clear albite and filled with chlorite. ab = albite, an = andesine, qtz. = quartz, chl. = chlorite, hb = hornblende, ser. = sericite.

the more calcic feldspar are far too irregular to be referred to zonal growth. In a few specimens this replacement has proceeded to the extent that only cores of the original more calcic feldspars remain, but in others it is incipient or even absent. Representative crystals showing advanced replacement are shown by camera lucida drawing in Fig. 1-d and 1-e.

These features suggest strongly that in the associated keratophyres the feldspars richest in albite are secondary, for the rock textures are identical and the only mineralogic differences between the two varieties are in their feldspar compositions and in the considerably greater ratio of chlorite to pyroxene and amphibole in the keratophyres as contrasted with the meta-andesites. There seems clearly to be a direct correlation between the amount of chlorite and epidote among the mafic minerals and the amount of albite among the feldspars in these rocks.

A few specimens best described as spilite were collected from the formation. Superficially these resemble the dense meta-andesites but the microscopic features: divergent granular textures and chlorite pseudomorphs after olivine, suggest an originally basaltic composition. Hornblende and augite are relatively common in these rocks though chlorite is probably the dominant mafic mineral. The feldspar is albite at least as sodic as $An_4$, much of it clear but other grains cloudy with epidote and sericite. Some specimens are amygdaloidal, with euhedral water-clear albite crystals lining the former vesicular cavities whose centers are now filled with quartz and chlorite. See Fig. 1-f. These rocks, accordingly, show albite of definitely hydrothermal origin as well as do the meta-andesites.

Albite diabase is a minor component of the greenstone. It is finely crystalline, dark greenish gray and with macroscopic feldspar and chlorite. The microscope reveals an ophitic texture with the original pyroxene altered to uralite and chlorite. The feldspar is albite ($An_2$—$An_4$), practically free from zoisite or epidote. Such epidote as occurs in the rock is in the chlorite pseudomorphs after augite, not in the feldspar. Ilmenite, leucoxene, and magnetite are accessory.

A large part of the greenstone series is composed of pyroclastic sediments—breccias and tuffs. Although they are not prominent in the part of the greenstone series exposed along the Eagle River, it seems likely that they constitute at least a fourth and perhaps nearly half of the entire formation in the Keating region.

The coarser breccia members are composed of angular and subrounded fragments of volcanic rock a foot or even more in maximum length, set in a fine-grained chloritic groundmass. In many localities it is difficult to decide whether the somewhat sheared, fragmental-appearing blocks composing a given member of the greenstone series are volcanic bombs and boulders, or originally blocky lava (aa), or whether they are portions of an originally massive flow that have been sheared, rounded in part, and separated by chloritic zones formed during the later deformation of the series. The commonest varieties recognized in such fragmented beds are keratophyres, chiefly non-quartzose, although quartz keratophyre, normal andesite, albite diabase, and locally a few limestone fragments are also represented.

Finer-grained tuffaceous sediments are rather common. Characteristically they are faintly banded rocks whose laminations are emphasized on weathered surfaces. They range in color from gray through buff, light green, dark green, and blue-green to nearly black. Some are dense rocks without megascopically recognizable granular structure or minerals; and others are clearly clastic rocks that contain recognizable feldspar, quartz, and chlorite, or small pellets of volcanic rocks. Many are highly silicified and break with a conchoidal fracture.

In thin section representative specimens of these rocks are seen to be composed chiefly of small angular fragments of rock with separate slivers of individual crystals. Most of the fragments are albitic volcanic rocks, either non-quartzose, with trachytoid or diabasic texture, or quartzose, with rhyolitic texture. Practically all the pyrogenic dark minerals have been altered to epidote-chlorite aggregates, with a little hornblende, although a few crystals of augite remain but slightly altered. Some of the albite is clear and glassy, but much of it contains considerable clinozoisite and epidote and is thus probably an alteration product of an originally more calcic feldspar. This origin is supported by the fact that a few fragments of andesitic rock retain their original andesine. The quartzose keratophyres exhibit marked magmatic corrosion of both quartz and plagioclase phenocrysts.

The crystal slivers common in these rocks plainly can not have been transported any considerable distances. Locally the rocks are cemented with calcite and even contain calcite nodules which are apparently clastic constituents; elsewhere they are silicified.

In addition to the fragmental texture visible both in hand specimens and in thin sections, these rocks have almost all undergone considerable shearing and brecciation at a much later date, so that they contain chlorite seams and are well impregnated with sericite and epidote. Some of these crystal tuffs are so fine grained that they resemble argillites very closely.

The chert and argillite beds are few, thin, and locally restricted; the conglomerate members are apparently discontinuous either by reason of deposition or later deformation and are probably intraformational as they contain, in a chloritic matrix, fairly well-rounded pebbles of volcanic rocks like those with which they are interbedded. Limestone and limestone breccia comprise much less than 1 per cent of the formation; and occur in discrete lenses or pod-shaped masses ranging in size from a few feet to about 2,000 feet long and from a few inches to 400 feet wide. Some of these lenses contain interspersed fragments of volcanic rock, which is probably pyroclastic; but most are rather pure blue-gray limestone that is only locally coarsely recrystallized to marble, although signs of flow are common. The limestones and associated limy pyroclastics carry sparse, poorly preserved fossils.

## Chemical Composition.

Specimens representative of several facies of the greenstone were selected and analyzed chemically, with the results shown in Table 1. For comparison some analyses of other "spilitic" rocks are included.

The similarity of the eastern Oregon rocks to the representative spilitic rocks of Dewey and Flett is obvious. No. 1, of the table page 235, differs in having more potassa than soda but even in this the molecular ratios are 3:2 in favor of soda, while in the others, as in the British spilitic rocks, this ratio is very much higher. In No. 1 there is only enough CaO to satisfy the $P_2O_5$ present for apatite, so that the feldspar contains no anorthite whatever. Rocks No. 2 and 3 have less than 1 per cent of normative anorthite.

## THE "SPILITIC SUITE."

Petrologic attention to the albite-rich lavas was much increased by the appearance, in 1911, of the classic paper by

TABLE 1.

Analyses of rocks from the Permian greenstone of eastern Oregon, and from other "spilitic" associations.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 72.31 | 75.04 | 81.33 | 66.05 | 79.64 | 53.30 | 59.84 | 53.15 | 51.31 | 51.22 | 46.01 |
| $Al_2O_3$ | 12.76 | 13.39 | 9.21 | 13.29 | 11.44 | 15.16 | 15.71 | 14.39 | 12.67 | 13.66 | 15.21 |
| $Fe_2O_3$ | 1.94 | 1.61 | 1.09 | 3.22 | .11 | 2.54 | 1.68 | 1.28 | .54 | 2.84 | 1.35 |
| FeO | 1.26 | .37 | .74 | 5.07 | .30 | 8.71 | 7.03 | 9.33 | 7.99 | 9.20 | 8.69 |
| MgO | 1.32 | .18 | .40 | 1.36 | .15 | 4.14 | 1.37 | 4.74 | 2.19 | 4.55 | 4.18 |
| CaO | .10 | .40 | .25 | .50 | .71 | 2.97 | 3.71 | 7.04 | 8.17 | 6.89 | 8.64 |
| $Na_2O$ | 3.69 | 6.36 | 3.25 | 6.67 | 6.40 | 5.55 | 6.52 | 4.58 | 5.21 | 4.93 | 4.97 |
| $K_2O$ | 3.82 | .83 | 1.66 | .87 | .38 | .32 | 2.76 | 1.01 | .54 | .75 | .34 |
| $H_2O+$ | 1.48 | 1.07 | 1.12 | 1.88 | .30 | 3.14 | .31 | 2.02 | 2.31 | 1.88 | 2.48 |
| $H_2O-$ | .26 | .24 | .15 | .96 | .16 | .18 | .14 | .19 | .04 | ... | ... |
| $TiO_2$ | .40 | .10 | .25 | .49 | .50 | 2.41 | .64 | 1.50 | 1.92 | 3.32 | 2.21 |
| $P_2O_5$ | .15 | .08 | .04 | .09 | .08 | .51 | .20 | .19 | .90 | .29 | .61 |
| MnO | .08 | .05 | .05 | ... | .08 | .28 | .12 | .14 | .45 | .25 | .33 |
| BaO | .09 | none | tr? | ... | ... | none | ... | none | nt. fd. | ... | ... |
| $FeS_2$ | none | none | none | ... | ... | .40 | [5].10 | tr? | .30 | ... | ... |
| $Fe_7S_8$ | ... | ... | ... | ... | ... | ... | ... | ... | .17 | ... | ... |
| $CO_2$ | tr. | .10 | .10 | ... | .02 | none | ... | .10 | 6.15 | .94 | 4.98 |
| Sum | 99.66 | 99.82 | 99.64 | 100.45 | 100.27 | 99.61 | 100.13 | 99.66 | 100.86 | 100.72 | 100.00 |

[5] S, not $FeS_2$.

1. Quartz keratophyre, west of Balm Creek, in NW. ¼, sec. 29, T. 7 S., R. 43 E., Oregon. J. G. Fairchild, analyst.
2. Quartz keratophyre, SW. ¼, sec. 21, T. 7 S., R. 41 E., Oregon. J. G. Fairchild, analyst.
3. Quartz keratophyre, silicified, SW. ¼, sec. 23, T. 7 S., R. 41 E., Oregon. J. G. Fairchild, analyst.
4. Keratophyre, Trevennen, Cornwall (No. II, p. 209, Dewey and Flett). W. Pollard, analyst.
5. Soda rhyolite, west side of Skomer Island, Wales. (No. III, p. 209, Dewey and Flett.) E. G. Radley, analyst.
6. Albite diabase, No. 2 level, Poorman mine, sec. 32, T. 7 S., R. 43 E., Oregon. J. G. Fairchild, analyst.
7. Albite diabase, Newlyn, Cornwall (No. I, p. 208, Dewey and Flett). W. Pollard, analyst.
8. Spilite, NE. ¼, sec. 35, T. 7 S., R. 42 E., Oregon. J. G. Fairchild, analyst.
9. Spilite, Tayvallich Peninsula, Argyll. (No. I, p. 206, Dewey and Flett.) E. G. Radley, analyst.
10. Average spilite, according to N. Sundius. Geol. Mag. vol. 67, p. 9, 1930.
11. Average spilite, according to A. K. Wells. Geol. Mag. vol. 60, p. 69, 1923.

Dewey and Flett,[6] in which it was pointed out that many of the submarine, usually basic, pillow-lavas are rich in soda and associated with other sodic rocks of a wide range in silica content. The suggestion was made that they are members of a natural family of igneous rocks, the "spilitic" suite, comparable in importance with the "Atlantic" and "Pacific" suites. As defined by them, the "spilitic" suite comprises picrite, albite diabase, minverite (hornblende albite diabase), quartz diabase, spilite, keratophyre, quartz keratophyre, soda-felsite, and albite granite. The essential characteristics of the suite are the abundance of soda feldspar and the common albitization of the rocks, especially of the less siliceous members. This albitization is believed to be a juvenile alteration of the rock masses caused by the same agents that produce the adinoles and cherts commonly associated with them. It is attributed to "pneumatolytic emanations" of uncertain composition but surely rich in water, soda, and silica, and probably in carbon dioxide. Some of the albite, especially of the more siliceous members, they regard as primary. The "spilitic" rocks occur in formations of many ages in the British Isles and elsewhere, and Dewey and Flett believe that they are characteristic of regions of dominant subsidence without important folding. They are the common submarine lavas.

The theory of widespread albitization put forth in the paper of Dewey and Flett was largely based upon, or at least cogently supported by the earlier work of Bailey and Grabham[7] on the alteration of Carboniferous lavas and Permo-Carboniferous intrusions in Scotland. In these rocks albite has replaced the earlier more calcic feldspars on a considerable scale, locally leaving kernels of the original feldspar veined and corroded by albite. The more calcic feldspars seemed especially susceptible to metasomatic albitization, indicating a notable introduction of soda. Though this is true within a given lava, as between distinct flows the more siliceous are the more altered, so that the conclusion was presented that the albitization is due to a kind of autometamorphism (autolysis), the lava "stewing in a concentrated solution of sodium carbonate" of internal derivation. The secondary albite is commonly sericitic or

[6] Dewey, H., and Flett, J. S.: Some British pillow-lavas and the rocks associated with them: Geol. Mag., Decade 5, vol. 8, pp. 202-209, 241-248, 1911.

[7] Bailey, E. B., and Grabham, G. W.: Albitization of basic plagioclase feldspars: Geol. Mag., Dec. 5, vol. 6, pp. 250-256, 1909.

chloritic, but may be water-clear. The intrusive quartz diabase sills carry very numerous albitic segregation veins, testifying to a high concentration of sodic siliceous solutions in these sills late in their consolidation period. The segregation material in the sills was regarded as analogous to the sodic solutions that permeated the lavas.

Benson[8] studied in great detail the "spilitic" rocks along the serpentine belt of New South Wales where spilites, diabases, keratophyres, quartz dolerites, variolites, and spilitic tuffs are associated with radiolarian chert, jasper, limestone, and shales, and gabbro and serpentine intrusives. Except in the quartz dolerites, which carry andesine, the feldspars are almost all albite or albite-oligoclase. The fresh variolites contain andesine but the altered have albitic feldspars. Some of the rocks carry fresh augite with the sodic feldspar. No adinole occurs at the sill contacts. Many of the rocks, however, show partial or complete albitization of originally more anorthitic feldspar with chloritization of the mafic minerals. The feldspars commonly have inclusions of sericite or paragonite and some are spongy; they are commonly untwinned or poorly twinned.

Despite these features, which suggest a secondary origin of the feldspars, Benson regarded them as primary because of their association in places with fresh augite. In the Tamworth district, however, he believed the keratophyre feldspars secondary, because the phenocrysts consist of albite-calcite masses and octagonal areas of albite appear to represent pseudomorphs of pyroxene. In the associated pyroclastic rocks, too, many albitic feldspars are "obviously" secondary.

The observations of Benson himself,[9] that euhedral fresh augite occurs in vesicles of a Tertiary basalt from the Tamworth district in direct contact with the opal and natrolite filling, demonstrate, however, that augite does not necessarily decompose in contact with hydrothermal solutions and that the association of albite with fresh augite is not decisive of its magmatic origin. This was also the conclusion of Cox,[10] one of the leading British investigators of the "spilitic" rocks.

[8] Benson, W. N.: Spilite lavas and radiolarian rocks in New South Wales: Geol. Mag., Decade 5, vol. 10, pp. 17-21, 1913; The geology and petrology of the great serpentine belt of New South Wales: Proc. Linnean Soc. N. S. W., vol. 38, pp. 490-517, 569-596, 662-724, 1913; vol. 40, pp. 121-173, 540-622, 1915.

[9] Benson, W. N.: op. cit., pp. 618-619, 1915.

[10] Cox, A. H.: The geology of the district between Abereiddy and Abercastle, Pembrokeshire: Quart. Jour. Geol. Soc. London, vol. 71, p. 328, 1915.

In the literature pertaining to the "spilitic" rocks a prominent place is taken by the greenstones and keratophyres of the Kiruna district, Sweden. The highly albitic feldspars of the greenstones were at first regarded as original.[11] Upon more exhaustive study, Sundius[12] concluded, because of the regional extent of the albitic rocks, their freedom from contact metamorphic minerals or structures, and the independence of the albitization of any controlling joints, as well as the absence of notable hydration or carbonation (to be expected under the autolysis theory of Dewey and Flett), that the albitization of these rocks is due to regional metasomatism. The cause of the albitization he referred to the instability of the anorthite and the stability of the albite molecules under metamorphic conditions, coupled with the mobility of the potential epidote set free in this process (a sort of regional saussuritization). Over wide areas, this led to practical decalcification of the feldspar but elsewhere caused local concentration of epidote, so that the bulk composition of the formation as a whole may not differ greatly from the original. In parts of the region there are considerable masses of epidote-poor, albitic rocks, which, however, seemed to indicate a large scale expulsion of lime during the metamorphism. Some actual introduction of soda, in solutions derived either from neighboring formations or from other parts of the same formation, was also admitted.[13] The keratophyres associated with the basic greenstones carry flecks of calcic oligoclase ($An_{28}$) in nearly pure albite crystals. These were interpreted as the residuals left by a slight albitization of these rocks for they contain little epidote but considerable sericite. An emigration of CaO occurred,[14] similar to that in the more basic rocks, but its effect was less striking because of the original composition of the rocks. According to this concept, the so-called keratophyres may be really, in part at least, merely albitized porphyrites. The sericite in the albite can readily be explained by the breaking down of anorthite to zoisite which leaves $Al_2O_3$ and $SiO_2$ in excess. If the zoisite emigrates, the excess materials have only to take up

[11] Lundbohm, H.: (based on observations of Sundius and Zensen) Sketch of the geology of the Kiruna district: Geol. Fören. Förhandl. Bd. *32*, p. *757*, 1910.

[12] Sundius, N.: Beiträge zur Geologie des südlichen Teils des Kirunagebiets: Vetenskapliga och praktiska Undersötningar i Lappland, pp. 17-76, Uppsala, 1915.

[13] Idem, p. *227*.

[14] Op. cit., pp. *233-237*.

alkalies to yield sericite or paragonite.[15] The work of Termier on the rocks of Pelvoux was cited as an example of similar processes.[16] It may be pointed out that the decalcification of the Pelvoux rocks, with concomitant development of residual (though partly recrystallized) albite was thought by Termier to result from the action of percolating meteoric waters; this process could hardly be quantitatively adequate to produce albitization of large rock masses. If the analogy seen by Sundius was merely in the action of moderately heated circulating solutions, it seems that the decomposition of calcic feldspar is explicable, but the large-scale elimination of lime from the formations remains obscure, as does the metasomatic alteration of the plagioclase to albite, while the crystal forms are retained.

Sundius' conception of the origin of the Kiruna rocks was criticized by Geijer,[17] who, though accepting the idea that in the Kiruna greenstones the albite replaces an earlier more calcic feldspar, believed that the albite of the associated keratophyres is primary and that the albitization of the less siliceous rocks is a result of Na transfer by hydrothermal solutions derived from the common magmatic source of the two rock groups (autolytic action of Bailey and Grabham).

Sundius' reply to the critique of Geijer was to emphasize again[18] that the alteration of the Kiruna greenstones was more a decalcification of the feldspar than an introduction of Na from an external source. He further criticized the hypothesis of Dewey and Flett on the grounds that the date of albitization is not proved by them to be immediately post-volcanic; that it is unlikely that as much Na can be retained in the hydrothermal solutions as was originally present in the precipitated feldspars; that the absence of albite from the associated cherts, and the absence of relation between albitization and joints are incompatible with the autolysis interpretation. In the Kiruna area the absence of hydrated minerals in the southern part was also regarded as inimical to the hydrothermal theory while

[15] Op. cit., p. 236; see also Cathrein, Zeitschr. für Krystall., vol. 7, p. 243, cited by Sundius, 1883.

[16] Termier, P.: Sur l'elimination de la chaux par métasomatose dans les roches éruptives basiques de la région du Pelvoux: Bull. Soc. Géol. France, T. 26, pp. 165-192, 1898.

[17] Geijer, P.: Notes on albitization and the magnetite-syenite-porphyries: Geol. Fören. Förhandl. Bd. 38, pp. 243-264, 1916.

[18] Sundius, N.: Zur Frage der Albitisierung im Kirunagebiet: Geol. Fören. Förhandl. Bd. 38, pp. 446-462, 1916.

explicable on the basis of regional metamorphism at depth too great for their stability. The associated keratophyres were shown to carry relicts of andesine, demonstrating that, contrary to Geijer's theory, the same albitization occurred here as in the more basic rocks. This, according to Sundius, proved that the time of albitization was long after the magmatic period, for the keratophyres are believed to be considerably younger than the greenstones.

Wells[19] discussed the spilitic rocks in 1922 and concluded that the independence of the suite as suggested by Dewey and Flett was well established by the absence of association of the spilitic rocks with normal basalts. He even proposed that the name keratophyre be restricted to rocks only of spilitic associations, separating them from bostonites, for example, on this basis.[20] Wells also remarked that the physical conditions of extrusion of the spilites do not alone determine their mineralogic character, as many pillow-lavas have labradorite feldspar and hence the differences between spilites and the normal basalts are original magmatic characters, chiefly higher $Na_2O$ and lower MgO contents. In defense of this thesis he computed an "average spilite" that was quite different from either the "average basalt" or "average nephelite basalt." See Table 1. To explain the common but not invariable albitization of these rocks, he appeals to autolysis, conditioned by the quick chilling during their submarine eruption and formation of an "impervious membrane" imprisoning the residual magmatic liquids.

Eskola,[21] while not accepting the concept of an independent spilitic magma, concluded, from studies of diabasic rocks of Russian Carelia, that the albitization shown by these rocks is due to hydrothermal residual solutions rich in soda and silica, derived from the magma and permeating and replacing the rock body in a late magmatic stage. Naturally such solutions could

[19] Wells, A. K.: The nomenclature of the spilitic rocks, Part I, The keratophyric rocks: Geol. Mag., vol. 59, pp. 346-354, 1922; Part II, The problem of the spilites, idem., vol. 60, pp. 62-74, 1923.

[20] The attempt to apply this criterion of "line of descent" in nomenclature would seem questionable, in view of the confusion in parallel cases, such as that of discriminating the essexites from ordinary diabases. Indeed, the keratophyres of Nassau have been attributed to a line of descent distinct from that of the spilites by Brauns (Neues Jahrbuch, Beil. Bd. vol. 27, pp. 320 ff., vol. 28, pp. 411-419, 1909), although in the same paper he was making a plea for the "line of descent" principle in rock nomenclature.

[21] Eskola, Pentti: On the petrology of Eastern Fennoscandia: I, The mineral development of basic rocks in the Karelian formations: Fennia vol. 45, No. 19, 1925.

escape from their source rocks and alter other rock bodies by a sort of contact metamorphism. The ophitic texture shown by several of the rocks he studied, he regarded, from consideration of Bowen's studies of haplobasaltic mixtures, as incompatible with an original feldspar composition so sodic as the existing one and hence as evidence of albitization. Albite and calcite veins, widespread in the region, are regarded as conformable corollaries of this theory. He pointed out, citing observations by several writers, that albitization is not rare in rocks in which pyroxene has been preserved, hence that this association is not evidence of the primary crystallization of albite. The spilitic rocks in his area are associated with normal basaltic rocks of the same geologic age, and regional trends in the distribution of soda can be traced.

A comprehensive discussion of the spilite problem, based upon rocks of Swedish Lappland, has been given by Beskow.[22] The association of keratophyres and spilites is recognized here as well as in the Caledonian Mountains of Norway and Great Britain, but both the Lappland rocks are referred by Beskow to a normal basaltic parentage. The spilites are considered to owe their mineralogy to hydrothermal replacements under the influence of heated sea water, the major chemical changes being the leaching out of K, the increase in Na (partly of marine source), and the replacement of part of the $SiO_2$ by $CO_2$ in the rocks, while the mineralogic changes include the albitization of the feldspars and the chloritization of the mafic minerals. The work of Beskow shows that most of the British spilites, upon which the concept of a distinct magmatic suite was founded, are, if allowance be made for replacement of $SiO_2$ by $CO_2$, of normal basaltic composition. Nevertheless, he agrees that the keratophyres associated with the British rocks, as in the Skomer volcanic series, are, because of their low $SiO_2$ and high Fe:Mg ratios, probably of alkaline parentage, while insisting that the Lappland keratophyres and quartz keratophyres are the results of a trondhjemitic type of differentiation from a normal basaltic magma. The associated albite granites he regards as products of similar differentiation processes at a later time, since the keratophyres are all pre-

[22] Beskow, Gunnar: Södra Storfjället im südlichen Lappland: Sver. Geol. Undersökn. Årsbok 21 (1927), Ser. C., No. 350, 1929.

orogenic, the albite granites late-orogenic in age and preceded by less differentiated plutonic rocks. The similarities between the structural and igneous features of Beskow's area and those of eastern Oregon are striking.

The interesting Kiruna rocks were again discussed by Sundius in 1930.[23] An analysis of a composite sample of an albitic intrusive body in this district has a normative feldspar corresponding to that of a normal diabase or basalt. This confirms, in part, Sundius' earlier conclusion that the epidote has migrated during the metamorphism of the rocks, leading locally to extraordinarily albitic feldspar residua and elsewhere to epidote enrichment, without great changes in bulk composition of the formation as a whole. Nevertheless the variation between the composite and a particular sample were such that he concluded that the mass was originally heterogeneous. His studies of the chemistry of the spilitic rocks led him to the conclusion that they are a distinct magmatic suite, characteristically poor in $K_2O$ and $Al_2O_3$, high in $Na_2O$, $FeO$, and $TiO_2$ and with a high $FeO:MgO$ ratio. These features inhibit the crystallization of olivine, throw the maximum $CaO$ into the mafic minerals and, by the lowering effect of the high $FeO$ content on the melting point of the pyroxene, displace the equilibrium so that albite crystallizes as a primary mineral contemporaneously with pyroxene. "In this way the textural relations of the rocks are explained without the hypothesis of autometamorphic changes and of an earlier An-rich plagioclase." Sundius makes no effort to reconcile this view with his earlier careful descriptions of relict labradorite in the Kiruna greenstones and andesine in the associated keratophyres.

Backlund has described the Devonian picrites, spilites, quartz keratophyres, and albite diabases of Novaya Zemlya.[24] Of these rocks the albite diabase is most clearly an albitization product, many of his so-called spilites having andesine or even labradorite feldspars. In considering the spilite problem, Backlund concluded that the theory of albitization by the action of marine water finds no support in his area, as none of the rocks is certainly submarine and the intrusive rocks are more albitized than the extrusive. Circulating meteoric solutions, such as were appealed to by Termier at Pelvoux, he excluded

[23] Sundius, N.: On the spilitic rocks: Geol. Mag., vol. 67, pp. 1-17, 1930.
[24] Backlund, Helge G.: Die Magmagesteine der Geosynklinale von Nowaja Semlja: Report of the scientific results of the Norwegian expedition to Novaya Zemlya, 1921, especially pp. 23-61, Oslo, 1930.

because of the intimate association of non-albitic effusives with albitic intrusives. Eskola's theory of autolysis by $Na_2SiO_3$ solutions he thought incompatible with the relations in Novaya Zemlya, as it leaves unexplained the differences between the effusive and intrusive rocks and the peculiarities of the effusive rocks as such. Sundius' later theory, that the original high FeO:MgO ratio permits retention of the mafics in the magma so that the sodic feldspars can crystallize with them, he believed to be excluded by the absence of albitization in the most vesicular carbonatized and partly epidotized (hence watery), rocks and its presence in the most coarsely crystallized and olivine-bearing varieties. Accordingly he concluded that Dewey and Flett's autolysis theory was best accordant with the facts in his area; and that this autolysis is to be expected in basaltic rocks erupted in dominantly subsiding areas, for these magmas may be expected, in his opinion, to be enriched in volatile constituents, which would lead to a lowering of temperatures of final consolidation and greater crystallization differentiation than those of plateau basalts.

The spilitic rocks of Dewey and Flett have thus, since 1911, received much attention from European geologists although in America they have been given scant consideration. Daly discussed them briefly[25] and pointed out that inasmuch as it is impossible to distinguish many basalts syngenetic with the typical alkaline rocks of Atlantic suites from basalts of Pacific suites, it is doubly difficult to distinguish spilites, admittedly rocks of basaltic habit, from the basalts of the other suites. Daly further points out the intimate association of the typical German spilites with ordinary basalts and diabases and suggests that their albitization is due to concentration of soda from underlying masses of normal basaltic magma. The especially intense albitization of the submarine spilites is, according to Daly, probably due to the fact that they have been erupted *through* wet sediments of greater or less thickness. Resurgent water from these sediments is supposed to have transferred the soda, and the spilites are regarded by him as pneumatolytic derivatives of normal basaltic magma.

Lewis[26] also regarded the "albitized basic rocks with pillow structure" as "doubtless modified basalts."

[25] Daly, R. A.: Igneous rocks and their origin: New York, pp. 338-340, 1914.

[26] Lewis, J. Volney: Origin of pillow-lavas: Bull. Geol. Soc. Amer., vol. 25, pp. 591-654, 1914.

These divergent interpretations of the spilitic rocks raise, among others, the following questions:

1. Are the spilitic rocks of normal alkali-calcic parentage, as contended by Daly, Sundius (1915), Eskola, and Beskow, or are they derived from an independent magma suite, as thought by Dewey and Flett, Geijer, Wells, Backlund, and Sundius (1930)?

2. Is the soda-rich character determined in the magma, as contended by Dewey and Flett, Daly, Geijer, Wells, Backlund, Sundius (1930), and Eskola, or is it a product of post-magmatic influences as thought by Termier, Sundius (1915), and Beskow?

3. Is their mineral composition (as distinct from their chemical composition) primary throughout as stated by Sundius (1930), and for the more siliceous members by Dewey and Flett, Geijer, Wells, Beskow, and Backlund, or is it largely of metasomatic origin as contended by Termier, Daly, Sundius (1915), Eskola, and for the less siliceous members by all except Sundius (1930)?

In the following section the attempt is made to summarize the information bearing on these questions available in the literature, although it may be well to emphasize in the first place the pertinent remark of Beskow,[27] that since albite and chlorite, the green schist facies of Eskola, are characteristically stable at low temperatures, it should not be surprising that the association may form in more than one way. First it seems desirable to ascertain in how far the associations of the "spilitic" rocks are constant and must be regarded as controlling their genesis.

## THE PETROGRAPHIC ASSOCIATIONS OF THE "SPILITIC" ROCKS.

The argument most strongly emphasized by the advocates of a "spilitic suite," distinct from the "alkalic" and the "alkali-calcic" suites, is the supposed constant association of the rocks of the spilitic series and their absence from ordinary alkali-calcic associations.[28] In order to prove the existence of an independent spilitic magma, demonstration of both of these associational generalizations would be required, for there is

[27] Beskow, G.: op. cit., p. 289.
[28] Dewey, H., and Flett, J. S.: op. cit., p. 209.
Wells, A. K.: The nomenclature of the keratophyres: Geol. Mag., vol. 59, p. 351, 1922; The problem of the spilites: Geol. Mag., vol. 60, pp. 72-74, 1923.

compelling evidence that both alkalic and subalkalic rocks can be derived from one magma as has been pointed out by several writers, among them Bowen.[29] Hence, if spilitic rocks (granted their primary magmatic origin) occur with normal subalkaline rocks they may well, indeed probably do, have a common parentage. Furthermore, if the minerals of one of the group are demonstrably of metasomatic origin, similar replacements would be expected in the associated rocks so that, to demonstrate magmatic origin, the spilite association should exclude normal alkali-calcic rocks. The associations are accordingly of interest as clues to the question of whether the albitic rocks owe their peculiarities to magmatic differentiation or to subsequent events, and it is a striking and significant fact that there is a very marked association of albitic subsilicic rocks (commonly pillow-lavas and albite diabases) with keratophyres and quartz keratophyres in many parts of the world.

In Europe this association is known from Wales,[30] Devonshire,[31] Scotland,[32] Sweden,[33] Germany,[34] and Greece.[35] In

[29] Bowen, N. L.: The later stages of the evolution of the igneous rocks: Jour. Geol., vol. 23, supplement, pp. 59-60, 1915.

[30] Thomas, H. H.: The Skomer volcanic series, Pembrokeshire: Quart. Jour. Geol. Soc. London, vol. 67, pp. 175-212, 1911.

Cox, A. H.: Note on the igneous rocks of Ordovician age: Rept. Brit. Assoc. Birmingham, pp. 496-498, 1913.

———: The geology of the district between Abereiddy and Abercastle, Pembrokeshire: Quart. Jour. Geol. Soc. London, vol. 71, pp. 273-340, 1915.

———: The geology of the Cader Idris Range, Merioneth: Quart. Jour. Geol. Soc. London, vol. 81, p. 564, 1925.

Greenly, E.: Geology of Anglesey, vol. I: Mem. Geol. Survey Great Britain, pp. 71-76, 1919.

——— and Matley, C. A.: The pre-Cambrian complex and associated rocks of southwestern Lleyn, Carnarvonshire: Quart. Jour. Geol. Soc. London, vol. 84, pp. 454-456, 1928.

Wells, A. K.: The geology of the Rhobell Fawr district, Merioneth: Quart. Jour. Geol. Soc. London, vol. 81, pp. 463-533, 1925.

Stamp, L. D., and Wooldridge, S. W.: The igneous and associated rocks of Llanwrtyd: Quart. Jour. Geol. Soc. London, vol. 79, pp. 18-20, 1923.

[31] Flett, J. S., and Dewey, H.: The geology of Dartmoor: Mem. Geol. Survey Great Britain, p. 19, 1912.

———: The geology of the country around Newton Abbot: Mem. Geol. Survey of Great Britain, pp. 53, 57, 1913.

[32] Flett, J. S.: The geology of Knapdale, Jura and Kintyre: Mem. Geol. Survey of Great Britain, p. 92, 1911.

Balsillie, D.: The Ballantrae igneous complex, S. Ayrshire: Geol. Mag. vol. 69, pp. 107-130, 1932.

[33] Sundius, N.: Zur Frage der Albitisierung im Kirunagebiet: Geol. Fören. Förhandlingar, vol. 38, pp. 446-462, 1916.

Geijer, P.: Pre-Cambrian geology of the iron-bearing region Kiruna-Gällivare-Pajala: Sver. Geol. Undersökn. Årsbok vol. 24, No. 2, ser. C., No. 366, p. 216, 1930.

Beskow, G.: Södra Storfjället im südlichen Lappland: Sver. Geol. Undersökn. Årsbok vol. 21, No. 5, p. 61 ff., 1927 (1929).

extra-European localities the association is known from New South Wales[36] and many places in the Canadian Shield[37] as well as from eastern Oregon.

Osann[38] considered the quartz keratophyres and keratophyres merely as altered (paleotypal) pantellerites, comendites, and alkaline trachytes, accounting for the usual absence of alkalic mafic minerals by later alteration, an opinion also held by Beskow.[39] Wells,[40] however, has shown that they are chemically and mineralogically distinct, being marked by higher $Al_2O_3$ and lower $Fe_2O_3$ and FeO than correspondingly siliceous comendites and alkaline trachytes, thereby accounting for their freedom from alkalic mafics. This corresponds to the commonest usage of the terms and is borne out by the representative analyses given by Rosenbusch.[41]

If the position taken by Wells,[42] in assigning the name keratophyre to albitic effusive and dike rocks only when asso-

[34] Pelikan, A.: Die Schalsteine des Fichtelgebirges, aus dem Harz, von Nassau und aus dem Vogesen: Sitzungsber. k. k. Akad. Wiss., Wien, vol. 108, pt. 1, p. 785, 1899.

Brauns, R.: Beiträge zur Kenntnis der chemischen Zusammensetzung der devonischen Eruptivgesteine im Gebiete der Lahn und Dill: Neues Jahrb. für Min., etc., Beil. Bd. 27, p. 320, 1909.

Erdmannsdörfer, O. H.: Ueber die systematische Stellung der harzer Keratophyre: Centr. für Min., pp. 33-41, 1909.

Weber, M.: Ueber Diabase und Keratophyre aus dem Fichtelgebirge: Centralbl. für Min., pp. 37-43, 1910.

Lehmann, E.: Beiträge zur Kenntnis der varistischen Gesteins und Mineralprovinz im Lahn-Dillgebiet: Neues Jahrb. für Min., etc. Beil. Bd. 64 Abt. A., pp. 549-592, 1931.

[35] Ktenas, K. A.: Ueber die eruptiven Bildungen des Parnesgebirges in Attika: Centralbl. für Min., pp. 557-558, 1909.

[36] Benson, W. N.: The geology and petrology of the great serpentine belt of New South Wales: Proc. Linn. Soc. New South Wales, vol. 38, p. 666, 1913, vol. 40, pp. 137, 599, and elsewhere, 1915.

[37] Wilson, M. E.: Kewagama Lake map area, Quebec: Geol. Surv. Canada, Mem. 39, pp. 47-58, 1914.

Cooke, H. C.: Geology of the Matachewan district, northern Ontario: Geol. Surv. Canada, Mem. 115, pp. 11-15, 1919.

Alcock, F. J.: The Reed-Wekusko map area, northern Ontario: Geol. Surv. Canada, Mem. 119, pp. 16-19, 1920.

[38] Rosenbusch, H.: Elemente der Gesteinslehre, 4th edition, by A. Osann, pp. 367-368, 381-382, 1923.

[39] Beskow, G.: op. cit., p. 304.

[40] Wells, A. K.: op. cit., pp. 352-353, 1922.

[41] Rosenbusch, H.: op. cit., p. 366. Rosenbusch states that the absence of alkalic mafic minerals in them and their common association with alkalicalcic rocks suffices to show that some, at least, of the keratophyres and quartz-keratophyres are not derived from alkalic magmas. See Mikroscopische Physiographie der massigen Gesteine, 4th Ed., vol. 2, part 2, pp. 1492-1493, 1908.

[42] Wells, A. K.: op. cit., pp. 350-351, 1922.

ciated with other spilitic rocks is adopted, it is naturally easy to demonstrate the restriction of keratophyres to the spilitic association. Similarly, by selecting analyses for the purpose of illustrating the independence of a rock type, as has been done by Sundius[43] in his compilation of spilitic rocks, it is possible to establish a large hiatus between the spilites and more normal basalts. This seems to the writer a matter of definition, not the recognition of natural relationships, and a study of analyses of submarine and related rocks appears to show complete gradation from perfectly normal basalts to highly albitic spilites, with no real gaps between them. That the distinction of the spilites and albite diabases from normal basaltic rocks is not objectively established seems clear from inspection of the pronounced differences between the average spilite as computed by Wells and that by Sundius, both based on analyses chosen to exclude transition rocks. See Table 1, page 235.

Accordingly, it appears justifiable to include with the rocks of the above mentioned localities, such as have highly albitic feldspars, low $K_2O$ and no notably sodic pyriboles, and to ascertain in how far their associations are exclusive of normal basalts and diabases with labradorite or andesine feldspars.

As has been emphasized by Daly[44] for the German spilites, and shown by the work of many other petrologists cited below, normal basalt and diabase occur with keratophyres or spilites or both in Wales,[45] Derbyshire,[46] Scotland,[47] Norway,[48] Sweden,[49] Finland,[50] Germany,[51] Czechoslovakia,[52] Switzer-

[43] Sundius, N.: On the spilitic rocks: Geol. Mag., vol. 67, pp. 7-11, 1930.

[44] Daly, R. A.: op. cit., pp. 338-339.

[45] Thomas, H. H.: The Skomer volcanic series, Pembrokeshire: Geol. Soc. London, Quart. Jour., vol. 67, pp. 201-204, 1911.

Wells, A. K.: The geology of the Rhobell Fawr district, Merioneth: Geol. Soc. London, Quart. Jour., vol. 81, pp. 511, 513, 523, and elsewhere, 1925.

Williams, D.: Geology of the country between Nant Peris and Nant Ffrancon: Geol. Soc. London, Quart. Jour., vol. 86, pp. 208, 223, 1930.

[46] Sargent, H. C.: On a spilitic facies of Lower Carboniferous lava-flows in Derbyshire: Geol. Soc. London, Quart. Jour., vol. 73, pp. 17-23, 1917.

[47] Balsillie, D.: The Ballantrae igneous complex, S. Ayrshire: Geol. Mag., vol. 69, p. 110, 1932.

[48] Goldschmidt, V. M.: Geologische-petrographische Studien im Hochgebirge des südlichen Norwegens, IV., Uebersicht der Eruptivgesteine im kaledonischen Gebirge zwischen Stavanger und Trondhjem: Vidensk. Skrifter, 1, analyses on p. 15, 1916.

Carstens, C. W.: Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet, Norsk Geol. Tidsk., vol. 7, pp. 207-208, 1924.

[49] Sundius, N.: Geologie des Kirunagebiets: Vetenskapliga praktiska Undersökninger i Lappland anordnede av Luossavaara-Kirunavaara Aktiebolog. vol. 4, p. 62, Uppsala, 1915.

Beskow, G.: op. cit., p. 291.

land,[53] as well as in New South Wales[54] and Canada.[55] In the western United States the keratophyres are by no means restricted to associations containing other albitic rocks. The Triassic keratophyres of Nevada[56] are intimately associated with normal andesites and potash-rich trachytes, those of the Mother Lode (Jurassic) with apparently normal basalts,[57] and the Tertiary keratophyres of Nevada with andesites[58] or basalts.[59] The eastern Oregon keratophyres and spilites are associated with a few normal andesites and basalts.

It is true that several of these albite-rich rocks would not fall within the rigorous limits permitted to spilites by either Wells or Sundius, though many do, and have been cited as "typical," but in view of the divergences noted above between the "average spilites" of these two writers, the list indicates the absence of antipathy between a "spilitic" association and "normal" basalts.

The question of chemical distinction between spilites and other rocks has been approached by Hackman,[60] who plotted many analyses on Hommel's projection. He found that the British and Australian spilites appear intermediate between gabbro and essexite, the Aunus (Carelia) rocks chiefly in the monzonite field, the Kiruna rocks are widespread in all fields.

[50] Hackman, V.: Studien über den Gesteinsaufbau der Kittilä-Lappmark: Bull. Comm. Géol. de Finland, No. 79, p. 17, 1927.
Eskola, P.: op. cit., pp. 17, 78-79.

[51] Erdmannsdörfer, O. H.: op. cit., pp. 33-41, 1909.
Lehmann, E.: Beiträge zur Kenntnis der varistischen Gesteins- und Mineralprovinz im Lahn-Dillgebiet: Neues Jahrb. für Min. Geol. und Paläontologie, Beil. Bd. 64, Abt. A., pp. 549-592, 1931.
Pelikan, A.: op. cit., pp. 749-754, 763-765.
Brauns, R.: op. cit., pp. 411-420.
Weber, M.: op. cit., p. 43.

[52] Kettner, R.: Versuch einer stratigraphischen Einteilung des böhmischen Algonkiums: Geol. Rundschau, vol. 8, p. 173, 1917.

[53] Grubenmann, U.: Beiträge zur Geologie des Unterengadins: Beitr. zur geol. Karte der Schweiz. No. 23, pp. 232-244, 1909.

[54] Benson, W. N.: op. cit. Proc. Linn. Soc. N. S. W., vol. 38, pp. 509-510, 667, and elsewhere, 1913.

[55] Alcock, F. J.: op. cit., pp. 16-17.

[56] Knopf, Adolph: Geology and ore deposits of the Yerington district, Nevada: U. S. Geol. Surv. Prof. Paper 114, pp. 13-16, 1918; Geology and ore deposits of the Rochester district, Nevada: U. S. Geol. Surv. Bull. 762, pp. 20, 22, 1924.

[57] Knopf, Adolph: The Mother Lode system of California: U. S. Geol. Surv. Prof. Paper 157, pp. 14-18, 1929.

[58] Knopf, Adolph: Ore deposits of Cedar Mountain, Mineral County, Nev.: U. S. Geol. Survey Bull. 725, p. 368, 1921.

[59] Nolan, T. B.: Underground geology of the western part of the Tonopah Mining district, Nevada: Univ. of Nevada Bull., vol. 24, No. 4, p. 15, 1930.

[60] Hackman, V.: Studien über den Gesteinsaufbau der Kittilä-Lappmark: Bull. Comm. Géol. de Finlande, No. 79, pp. 35-36, 1927.

Inasmuch as the projections prove the spilites to have a considerable range, including rocks of the gabbro, anorthosite, essexite, and monzonite fields, he concluded that in the sense that gabbro is an independent magma type the spilites are not, but that they may reasonably be regarded as a geologic group because they are all more or less related basic eruptives, chiefly effusive, which have all undergone similar metamorphism, either autolytic or regional metasomatic.

Beskow[61] also made a thorough study of the analyses of spilites. He reached the conclusions that Hackman's projection method (in which the $CO_2$ was rejected but no correction to the lime made) was in conformity with Wells' assumption that the present mineral composition of the spilites is entirely autogenous and that, on this assumption, Hackman's conclusion that the spilites are not a unified rock group distinct from others was sound. Beskow's own computations, however, were made on the contrasted assumption that the $CO_2$ present in the rocks has replaced $SiO_2$ which has migrated from them. On this assumption he found a remarkable agreement among the spilites themselves and between them and quite normal basalts when all were plotted in the triangle involving the Niggli ratios for Femca Alk-$SiO_2$. His conclusion was that they constitute merely a peculiarly altered group of normal basalts in which the alteration was exogenous.

The available analyses representing spilitic associations, compiled by the writer, are plotted in the normative feldspar triangle of Fig. 2. The analyses have been computed without regard to $CO_2$ which of course assumes the CaO to have been originally present in anorthite. From the plotted feldspar compositions there seems to be a complete gradation from the spilitic to the normal subalkaline rocks. The only persistent feature shown by these analyses is poverty in $K_2O$. This is discussed in Part II.

The associational and analytical data thus seem to render untenable the hypothesis of an independent magma type as the source of all spilitic rocks. They do not, however, exclude a magmatic origin for the peculiarities of the rocks, since magmatic differentiation may have produced offshoots, abnormal in greater or less degree, from a normal series,—thus accounting for the striking, though clearly not exclusive, association of keratophyres and spilites.

[61] Beskow, G.: op. cit., pp. 279-311, criticism of Hackman in footnote, p. 292.

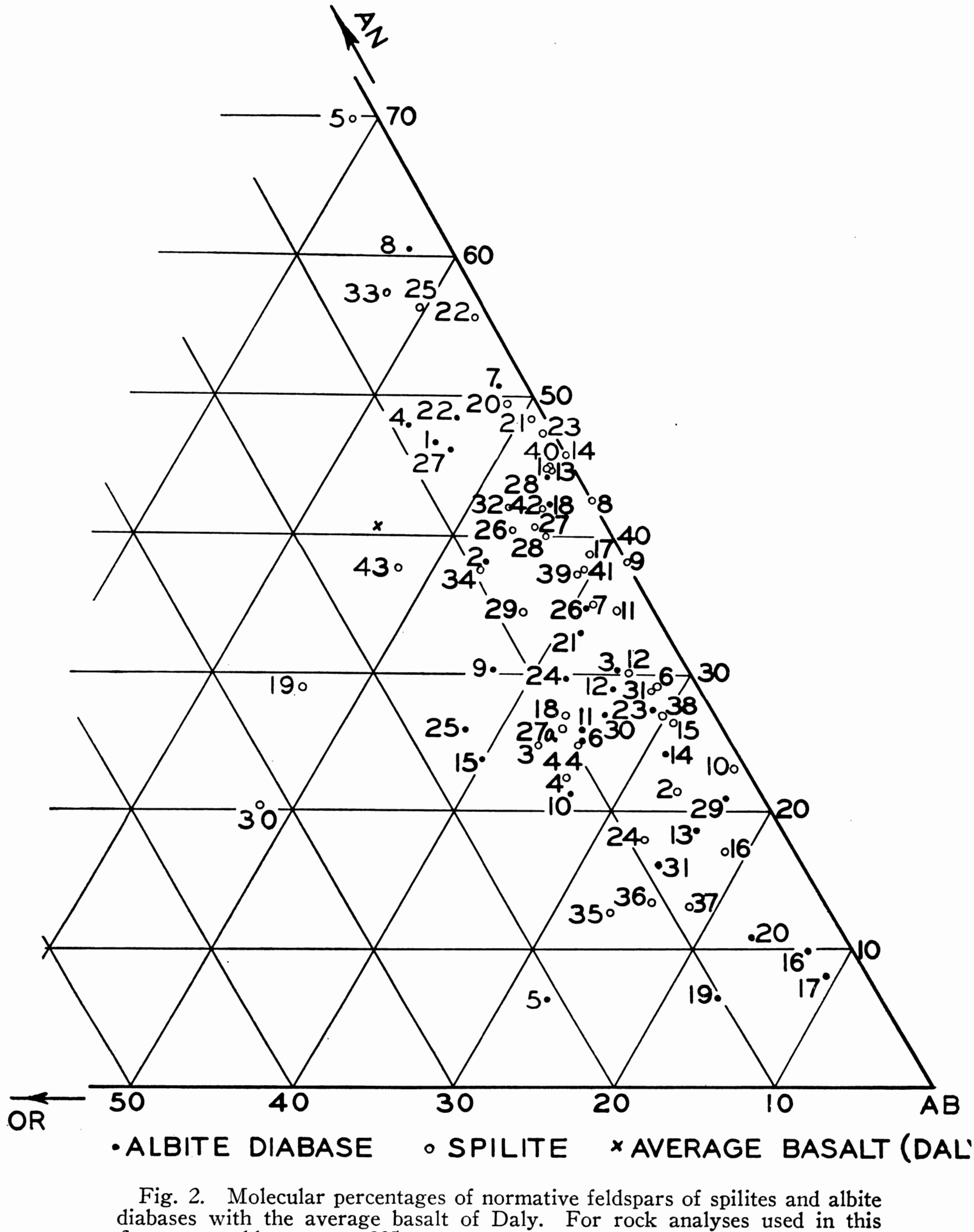


Fig. 2. Molecular percentages of normative feldspars of spilites and albite diabases with the average basalt of Daly. For rock analyses used in this figure see table on page 235.

If this conclusion is sound, that the parent magma of the keratophyres and spilites is not notably abnormal, it becomes of interest to investigate the geologic environment of the rocks to ascertain, if possible, what factors determine their peculiar mineralogy. Prominent among the environmental features which have been regarded as of genetic significance in the "spilite problem," is the common association with marine sediments in a manner suggesting eruption of the rocks under submarine conditions. The influence of the marine environment, if it is general with these rocks, may be thought of as direct: due to circulating sea water (Beskow), to quick chilling and consequent retention of volatiles (Wells); or as indirect: passage of the eruptive through watery sediments (Daly), absorption of wet sediments (Daly, Goldschmidt?) or to an obscure control of magmatic evolution under the tectonic condition of the continuous sinking of the sea floor (Dewey and Flett).

## GEOLOGIC ENVIRONMENT OF THE ALBITIC VOLCANIC ROCKS.

Spilites or keratophyres are associated with marine sediments in such manner as to suggest their submarine eruption in Australia,[62] East Indies,[63] Germany,[64] Czechoslovakia,[65] Norway,[66] Sweden,[67] Wales,[68] Cornwall,[69] and Devon.[70] In

[62] Benson, W. N.: Spilite lavas and radiolarian rocks in New South Wales: Geol. Mag., pp. 17-21, 1913; The geology and petrology of the great serpentine belt of New South Wales: Proc. Linnean Soc. N. S. W., vol. 38, pp. 574-575, vol. 40, pp. 123, 130, 1915.

[63] Verbeek, R. D. M.: Description géologique de l'île d'Ambon; Jaarb. van het Mijnwezen in Nederl. Oost Ind. Batavia, vol. 34, p. 126, 1905.

[64] Brauns, R.: Beiträge zur Kenntnis der chemischen Zusammensetzung der devonischen Eruptivgesteine im Gebiete der Lahn und Dill: Neues Jahrb. Beil. Bd. 28, pp. 391-393, 1909.

Pelikan, A.: Die Schalsteine des Fichtelgebirges, aus dem Harz, von Nassau und aus dem Vogesen: Sitzungsber. k. k. Akad. Wiss., Wien, Bd. 108, H. 1, p. 789, 1899.

[65] Kettner, R.: Versuch einer stratigraphischen Einteilung des böhmischen Algonkiums: Geol. Rundschau, Bd. 8, p. 174, 1917.

[66] Carstens, C. W.: Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet, Norsk Geol. Tidsk. vol. 7, pp. 192-193, 1924.

Goldschmidt, V. M.: Geologische-petrographische Studien im Hochgebirge des südlichen Norwegens, IV., Uebersicht der Eruptivgesteine im kaledonischen Gebirge zwischen Stavanger und Trondhjem; Vidensk. Skr. 1, p. 10, 1916.

[67] Beskow, G.: op. cit., pp. 39-127.

[68] Cox, A. H., and Jones, O. T.: On various occurrences of pillow-lavas in North and South Wales: Geol. Mag. Decade V, vol. 10, pp. 516-517, 1913.

————: op. cit. supra. 1915, pp. 307-310, 1913, pp. 496-498.

Thomas, H. H.: op. cit., pp. 209-210, 1911.

Greenly, E.: op. cit., pp. 71-76, 1919.

Matley, C. A.: op. cit., pp. 464-466.

America, the Triassic keratophyres of Nevada[71] are interbedded with marine sediments as are the Jurassic keratophyres of the Mother Lode country[72] of California and the Permian rocks of eastern Oregon. Several occurrences of basaltic rocks of probable submarine origin whose analyses suggest that they are albitic, although conclusive microscopic evidence has not been presented respecting them, are found in America. These include the ellipsoidal greenstones from the Crystal Falls district, Michigan,[73] and the ellipsoidal basalts of Point Bonita, California.[74]

Although it is seen that many of these spilites and keratophyres are of submarine origin, the Tertiary keratophyres of Nevada[75] are definitely sub-aerial and so are the Ordovician Skomer rocks,[76] of Wales, at least some of the ultra-sodic hälleflintas of Sweden,[77] and possibly the spilites of Novaya Zemlya,[78] although Backlund's conclusion as to their environment does not appear to rest on compelling evidence. The conclusion seems permissible that although the "spilitic" rocks are chiefly products of submarine eruption this locus is not essential for their development—nor conversely, do all submarine volcanics fall into this group.

[69] Flett, J. S., and Hill, J. B.: Geology of the Lizard and Meneage: Mem. Geol. Survey Great Britain, p. 177, 1912.

[70] ——— and Dewey, H.: The geology of Dartmoor: Mem. Geol. Surv. Great Britain, p. 19, 1912.

[71] Knopf, A.: Geology and ore deposits of the Yerington district, Nevada: U. S. Geol. Surv. Prof. Paper 114, pp. 13-16, 1918.

[72] Knopf, A.: The Mother Lode system of California: U. S. Geol. Survey Prof. Paper 157, pp. 14-18, 1929.

[73] Clements, J. M.: The Crystal Falls iron-bearing district of Michigan: U. S. Geol. Survey Mon. 36, p. 106, 1899. As has been pointed out by Sundius, the extinction angles given by Clements (17°-18°) as characterizing the "labradorite" are compatible with the feldspar being albite, as is suggested by the rock analysis.

[74] Ransome, F. L.: The eruptive rocks of Point Bonita: Univ. of California Dept. of Geology Bull., vol. 1, pp. 77-114, 1893.

[75] Knopf, A.: Ore deposits of Cedar Mountain, Mineral Co., Nevada: U. S. Geol. Survey Bull. 725, p. 368, 1921.

Nolan, T. B.: Underground geology of the western part of the Tonopah mining district, Nevada: Univ. of Nevada Bull., vol. 24, No. 4, p. 15, 1930.

[76] Thomas, H. H.: op. cit., p. 175.

[77] Sundius, Nils: Grythyttefältets geologi: Sver. Geol. Undersökn. Ser. C, No. 312, p. 340, 1922.

[78] Backlund, A. G.: op. cit., pp. 37-40.

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(Continued in next issue.)