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A Commentary on the Absarokite-Shoshonite-Banakite Series of Wyoming, U.S.A.

By *J. Nicholls* and *I. S. E. Carmichael* (Berkeley)*)

With 3 figures in the text and 5 tables

Abstract

The richly porphyritic volcanics of the absarokite-shoshonite-banakite series of Wyoming are characterized mineralogically by calcic plagioclase and sanidine coexisting in the groundmass. Both feldspars show a wide range of composition (determined by the electron-probe) and become more sodic as crystallization proceeds; the abundant phenocrysts of plagioclase, often with sanidine rims, are no more calcic than the associated groundmass phase. Augite and calcium-poor pyroxene, together with olivine, are found as phenocrysts and as groundmass constituents in many of the lavas. The augite phenocrysts commonly have almost no zoning, and virtually match the composition of their groundmass counterparts; groundmass olivine is however more iron-rich than the associated phenocrysts. Although these rocks are often extensively altered, or contain abundant xenocrysts, their overall composition is distinctive, as they are notably potassic and rich in the associated elements Sr, Ba, the light rare earths and P. However, the tholeiitic aspect of the shoshonites (siliceous residual glass), despite their distinctive chemistry, makes them inappropriate to give title to the potassic alkaline magma series proposed by JOPLIN.

INTRODUCTION

For generations, students of systematic igneous petrography have been told of absarokites, shoshonites and banakites, remembering, we suspect, rather more of their euphony than of their nature. These basaltic rocks, named after American Indian tribes by IDDINGS (1895) are a potassic suite "genetically related and connected by gradual transitions so that they constitute a natural group" (IDDINGS, 1899, p. 326). The basic members of the series, the absarokites and shoshonites, are readily distinguished one from the other because absaro-

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kites are the only member of this series without abundant plagioclase (labradorite) phenocrysts. Both rock-types contain phenocrysts of olivine and augite set in a groundmass of pyroxene, plagioclase and sanidine. It is this association of two feldspars (plagioclase and sanidine) that is the dominant, but not ubiquitous, characteristic of the series as a whole. The last rock-type of the series, banakite, is also porphyritic, but with the phenocrysts of labradorite, olivine and pyroxene enclosed by a highly feldspathic groundmass in which biotite is the predominant ferro-magnesian mineral.

Rocks of similar chemical and petrographic character to the absarokite series have been described from Bufumbira, Uganda (HOLMES and HARWOOD, 1937), Antarctica (PRIOR, 1907), South America (QUENSEL, 1911), and Australia (JOPLIN, 1965). HOLMES (op. cit. 1937) however suggested that the three rock-types described by IDDINGS were not related as a single series, and that some factor other than crystal fractionation was involved in their origin. JOPLIN (1965) urged the recognition of an alkali-rich magma series, analogous to the alkali olivine-basalt magma series, but characterized by high potash, and proposed that it be named the shoshonite magma series.

To the general petrologist, unaware of the prejudices and intricacies of igneous nomenclature, it may seem that rocks of similar composition and appearance found outside the Yellowstone region would not deserve, or have, the name shoshonite or banakite, but perhaps latite, or trachybasalt or even trachyandesite. To become submerged in the finer, and no doubt vital, points of classification of what all would concede (including IDDINGS) to be basaltic is not our purpose, so rather than debate the worth of these names, let us examine in detail whatever it was that IDDINGS originally described as absarokite, shoshonite and banakite. Having recorded this, the path may be clearer for those who wish to disentangle the complexities of nomenclature of the alkali-rich basic volcanics.

PETROGRAPHY

In Yellowstone Park and its surroundings, absarokites, shoshonites and banakites are found as dark, basaltic looking lavas and dikes, most of which unfortunately show varying degrees of secondary alteration, so that zeolites, carbonates and chlorite are almost always present to a greater or less extent. The samples described here are the least altered of a suite collected in 1966 by H. PROSTKA and J. NICHOLLS; as may be seen from the analyses given in Table 5, alteration, or the content of CO_2 and H_2O, is nevertheless considerable in some of the specimens. The modal analyses are given in Table 1; it was this series of rocks that IDDINGS said of their modes that "he did not know they had any" (JOHANNSEN, 1938, page 44).

Absarokites (225)

These are the most basic members of the series, and as has been noted before, they are the only members not to have phenocrysts of plagioclase (Table 1). The specimen available for study is a typical absarokite containing phenocrysts of olivine, or its alteration product, and augite in a holocrystalline fine-grained groundmass of alkali-feldspar, augite, subordinate calcium-poor pyroxene and a pervasive chloritic alteration product, possibly replacing glass. It should be noted that in the absarokites described by Iddings (1899), the groundmass invariably had either very subordinate amounts of plagioclase as cores to surrounding alkali-feldspar (orthoclase), or it was absent. Leucite was not identified in our specimen, although Iddings suspected its presence in many of the absarokites he examined. Biotite, apatite and iron-titanium oxides are accessory constituents of the groundmass.

Table 1. *Modal analyses (vol. percent)*

	Groundmass	Plagioclase	Orthopyroxene	Augite	Olivine	Oxides*)
Absarokite (225)	79.1	—	–	16.8	4.1	–
Shoshonites (114)	58.9	27.7	–	9.4	3.5	0.5
Shoshonites (118A)	57.4	34.5	1.5	6.2	3.0	0.1
Shoshonites (109A)	65.6	26.7	–	3.8	3.3	0.6
Banakite (119)	78.6	9.8	3.8	4.2	3.2	0.4

*) microphenocrysts

Shoshonites (190A, 114, 118A)

The specimens available for study are typical of their breed, having abundant plagioclase phenocrysts (Table 1) together with olivine, augite and rarely hypersthene. Two of the shoshonites (109, 114) have holocrystalline groundmasses comprised of stumpy equidimensional feldspars (plagioclase and sanidine), augite and either olivine or orthopyroxene. Apatite as minute needles, iron-titanium oxides, zeolites and carbonate are accessory.

The third shoshonite (118A) has a very basaltic appearance in thin section and is therefore a representative of Iddings' second trend of the absarokite series, namely the petrographic transition between shoshonite and basalt (Iddings, 1899, p. 346). Phenocrysts of plagioclase, augite, olivine and orthopyroxene (Table 1) are surrounded by a groundmass of elongate feldspar laths, dark interstitial glass, pyroxene (calcium-rich and calcium-poor), iron-titanium oxides and apatite. In all the shoshonites sporadic large crystals (microphenocrysts) of iron-titanium oxides are found.

One of the most striking and characteristic features of the shoshonites are the thin shells of alkali-feldspars which completely surround many of the plagioclase phenocrysts.

Banakites

No specimen typical of the banakites described by Iddings was available for study; although one of our specimens (119) is named a banakite, it does not clearly fit into any of the petrographic groups of Iddings. The phenocrysts of labradorite do not have enclosing shells of alkali-feldspar (cf. shoshonites), and occur together with clusters of augite, olivine and orthopyroxene (Table 1), some of which, to anticipate a later discussion, are undoubted xenocrysts. The groundmass is very fine-grained, holocrystalline and comprised of abundant sub-parallel feldspar laths (plagioclase and alkali-feldspar), intergranular pyroxene and opaque minerals. Biotite, so typical of banakites, is missing, but the feldspathic nature of the groundmass, coupled with the high silica percentage (Table 5) suggest inclusion with the banakite group. There is however no obvious petrographic criterion by which this rock can be identified as a member of the absarokite-shoshonite-banakite series; perhaps this will serve to illustrate one of the difficulties in naming the fine-grained variants or associates of this series without a chemical analysis.

MINERALOGY

It is well to remind the reader that in any study of volcanic rocks as richly porphyritic as these (Table 1), there is the inexorable question of the status of the phenocrysts. Do they represent the first phases to precipitate from liquids whose compositions are represented by the chemical analyses of the rocks; or do they represent either accidental or cognate xenocrysts? In the absence of obvious petrographic criteria, the mineralogical evidence is unlikely to be decisive. Moreover the liquid line of descent, necessarily defined by fine-grained (hence non-accumulative) rocks, is not known for the absarokite-shoshonite-banakite series, so that any departure from this cannot be ascribed to the accumulation of crystals, accidental or cognate.

The minerals were analyzed with the electron-probe, the details of which have been given elsewhere (Evans and Moore, 1968; Carmichael, 1967a, b, c); in what follows the bulk composition of the various mineral phases has been obtained by averaging the results from the analysis of between 10 and 50 crystals. Depending on the extent of zoning, this average may be close to or very far from the true average; for the purposes of this paper the results obtained this way are accounted satisfactory. Wherever possible the direction and extent of zoning in the various phases has been determined, and solely for ease of description, larger crystals have been called phenocrysts or microphenocrysts, whereas those crystals of small size found in the groundmass are called thus. No implication is intended about the cooling rate of the individual lavas, nor does the use of the term phenocryst exclude a foreign origin of the crystal phase concerned.

Feldspars

The most obvious petrographic criterion of shoshonites and banakites is the association of plagioclase and alkali-feldspar in the groundmass of the holocrystalline varieties. Although nothing is known of the structure or symmetry of this alkali-feldspar, the paragenesis would suggest that it is a high temperature modification, and hereafter it will be called sanidine. Sanidine has never been seen, or reported, as a phenocryst in any of the rocks of this volcanic series. The plagioclase phenocrysts have prominent oscillatory zoning, but show an overall tendency to become more sodic towards the crystal margins; there is no evidence of resorption or sieved texture, which could indicate a foreign origin of the feldspar phenocrysts.

The average analyses of the phenocryst and groundmass feldspars are given in Table 2¹), and the individual analyses are plotted in Fig. 1. From the individual analyses of the various feldspars, trend lines have been drawn (Fig. 2) to illustrate the range in composition of the feldspars, although in all cases the groundmass grains are too small for the direction of zoning to be determined.

The absarokite (225) has only one feldspar, a groundmass sanidine, which becomes increasingly rich in anorthite as it becomes progressively more sodic and is the most potassic feldspar found in these volcanics (Figs. 1 and 2). Although IDDINGS (1899) has identified leucite in many absarokites, its absence in this specimen (225) is not unexpected, as the normative ternary feldspar falls close to, but not in, the leucite field in the anhydrous synthetic system $CaAl_2Si_2O_8$-$KAlSi_3O_8$-$NaAlSi_3O_8$ (Fig. 1). IDDINGS (1899, p. 333) considered that leucite in the absarokites is antipathetic to biotite, a view supported by the flakes of accessory phlogopite in the groundmass of the absarokite examined by us.

The three shoshonites (114, 118A, 109A) have labradorite phenocrysts which, surprisingly to the writers, are no richer in anorthite than their associated groundmass plagioclases (Fig. 1); however, the groundmass plagioclases are zoned to more sodic compositions than the phenocrysts (Fig. 1). The analyses of the shoshonite groundmass sanidines are also plotted in Fig. 1 together with the analyses of the enclosing sanidine shells of the plagioclase phenocrysts; these shells tend to a more extreme potassic composition than their groundmass counterparts.

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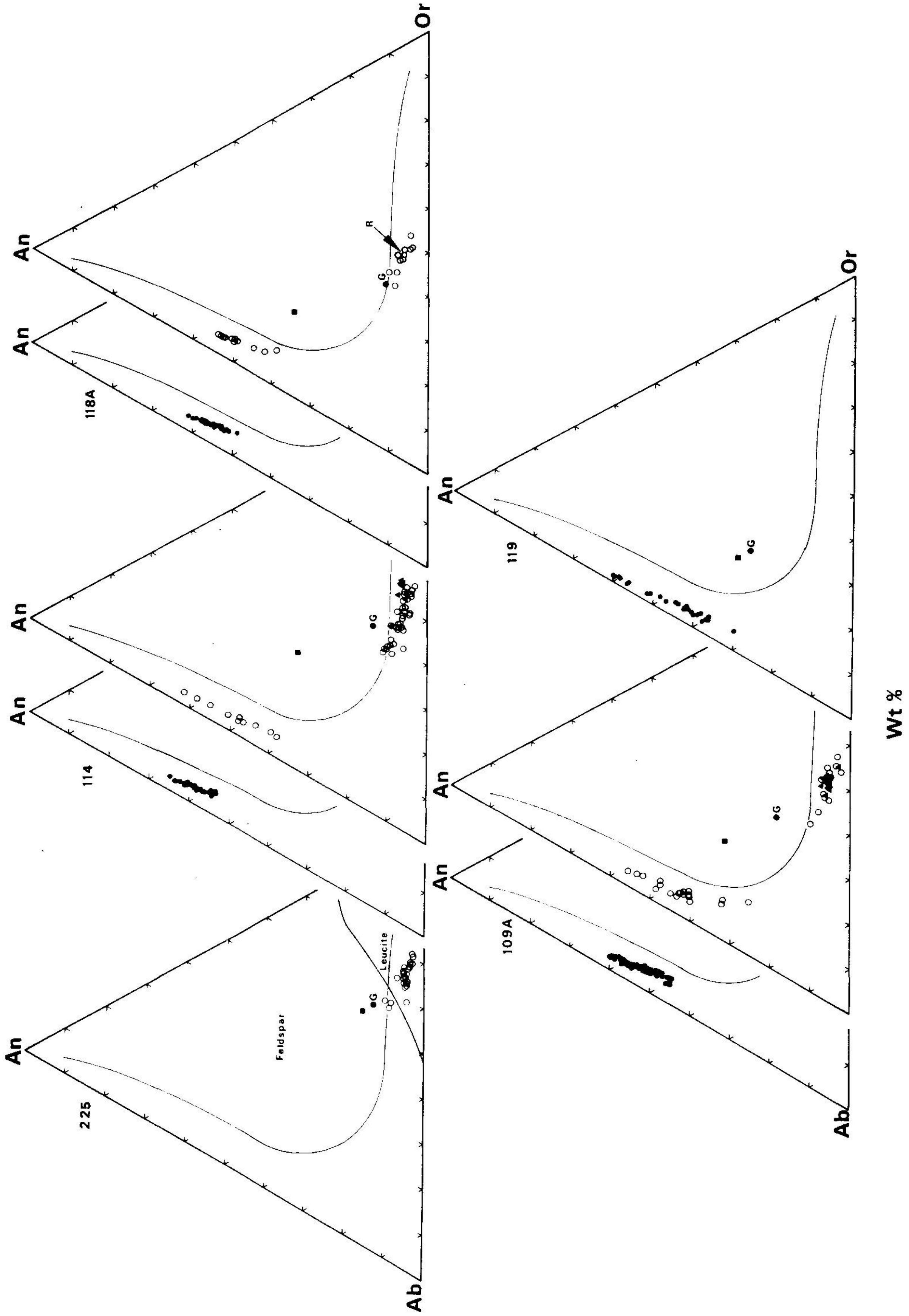
¹) In order to conserve space, the analytical data presented in Tables 2 and 3 has not been published, as the results are shown in Figs. 1 and 2. Tables 2 and 3 may be obtained by writing to the authors.


225
114
118A
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109A
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Feldspar
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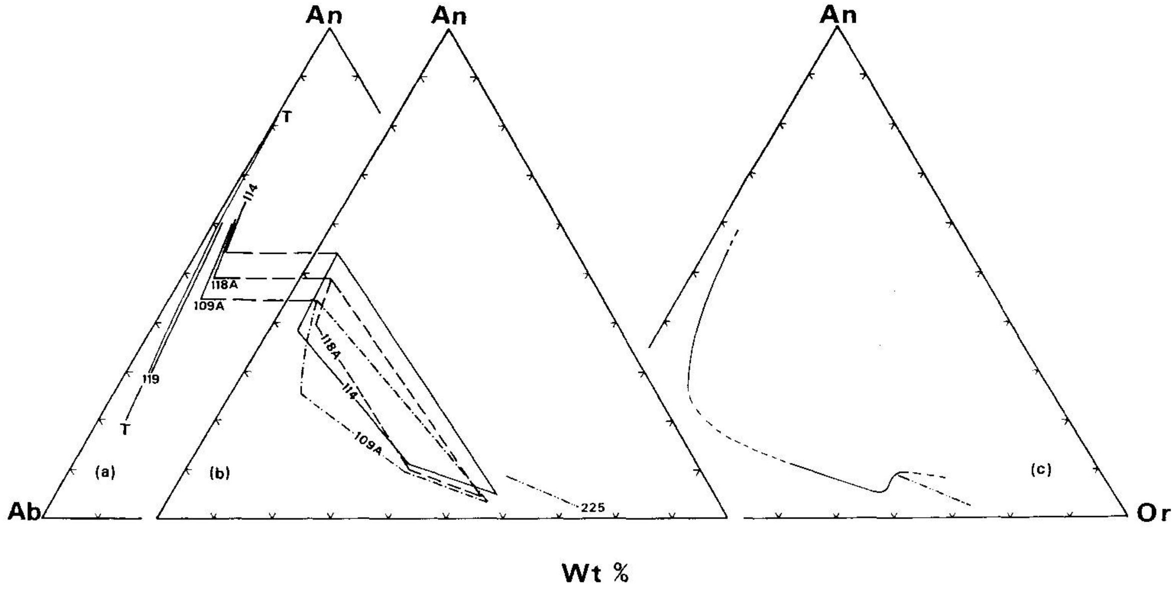

Fig. 2. Trends in the range of composition of the feldspars and interpretation of the feldspar solidus-solvus intersection in the absarokite and shoshonites. (a) Phenocryst composition ranges. T –T, Thingmuli trend (Carmichael, 1967). Others numbered as in Fig. 1. (b) Groundmass trends and tie lines. Only groundmass plagioclase less calcic than corresponding phenocrysts shown. (c) Interpretation of solidus-solvus intersection through the temperature interval of the crystallization of the absarokite *and* shoshonites. See text.

The plagioclase phenocrysts of the banakite (119) are strikingly less potassic than the labradorite phenocrysts of the shoshonites (Fig. 2) and show a larger range in composition; the groundmass feldspar of this rock is too fine-grained to be analyzed with the electron-probe.

Of the minor elements in the feldspars, only Ba and Fe have been determined. In the shoshonites, Ba is always concentrated in the sanidine in relation to plagioclase; within the sanidine however, celsian (up to 8 wt. percent) is most abundant in compositions with ten percent anorthite. Fe_2O_3 varies almost inversely as Ba, being dominant in the groundmass plagioclase, less so in the plagioclase phenocrysts, and is relatively impoverished in the sanidines (Table 2).

This volcanic series, as it is of unusual composition, offers new information on relationships in the ternary feldspar system ($CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$). Thus the composition of coexisting plagioclase and sanidine in

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Fig. 1. Feldspar analyses and normative feldspars. (225) absarokite; (114, 118A, 119) shoshonites; (119) banakite. Solid circles represent analyses on phenocrysts; solid triangles, analyses on shells of phenocrysts; open circles, analyses on groundmass grains; filled squares are normative feldspars of whole rocks (Table 5); filled circles marked G are the calculated normative feldspars of the groundmasses; open square marked R is the normative feldspar of the residual glass (118A Table 5). The leucite-feldspar field boundary in the synthetic system (225) (Franco and Schairer, 1951) and the limit of ternary solid solution in natural feldspars (Smith and MacKenzie, 1958) are shown.

the groundmass of a shoshonite will define a limit of ternary solid solution appropriate to the temperatures of their crystallization. Put another way, the composition of each of the coexisting feldspars lie on the intersection of the solidus with the solvus (Fig. 2c) in the ternary feldspar system.

The absence of sanidine phenocrysts in the shoshonites suggests that the more calcic zones of the groundmass plagioclase, corresponding to those found in the coexisting plagioclase phenocrysts, did not precipitate in association with the groundmass sanidine. Therefore the most calcic composition of the groundmass plagioclase which is *not found* in the phenocrysts is considered to have precipitated in equilibrium with the most potassic composition of the sanidine; this view is supported by the potassic nature of the sanidine shells enclosing the plagioclase phenocrysts (page 51, Fig. 1). Accordingly two tie-lines (Fig. 2b) have been drawn for each shoshonite, one connecting the most calcic groundmass plagioclase with the most potassic sanidine, and the other connecting the most sodic plagioclase with the most sodic sanidine. By analogy with the experimental results of Yoder, Steward and Smith (1957), the first, or calcic plagioclase tie-line is presumed to represent a higher temperature than the sodic tie-line (at constant pressure). The small differences in trend and position of the calcic-plagioclase potassic-sanidine tie-lines, if not due to analytical error, suggest some variation in the crystallization temperatures of the groundmasses of the shoshonites.

In Fig. 2c, an average trend for the variation in composition of the groundmass plagioclase and sanidine of the three shoshonites has been drawn (data of Fig. 1), which represents, if the interpretation given above is correct, the projected trace of the solidus-solvus intersection for plagioclase and sanidine through the temperature interval represented by the shoshonite groundmasses. This trace, in projection, for potassic sanidines must have an unusual dog-leg, as the groundmass sanidine of the absarokite (Fig. 1, 225), despite its calcic composition, does not coexist with a plagioclase, and thus must project into the region between the trace of the intersection and the alkali-feldspar side-line (Fig. 2c). Perhaps the amplitude of this dog-leg could be minimized if the temperature of crystallization of the absarokite groundmass (225) is assumed to be greatly in excess of the shoshonites; the dog-leg however is not entirely at variance with what may be extrapolated from experimental data (Yoder, et al., 1957) into natural liquids.

To conclude this section on the feldspars, there is no compelling petrographic evidence which could indicate that the plagioclase phenocrysts of the shoshonites are xenocrysts, either accidental or cognate. The observation that the most calcic zones in the phenocrysts are represented in the groundmass plagioclases is not an unusual feature, for it is becoming more and more evident as a result of microprobe investigation of feldspars in a wide variety of volcanic rocks (Smith and Carmichael, 1968). It may represent either metastable crystallization of the groundmass plagioclase, and/or a response to a pressure drop from intratelluric conditions to those of a surficial lava; it is not, in our opinion, evidence for a xenocrystic origin of the plagioclase phenocrysts. Furthermore the plagioclase phenocrysts are appropriately potassic for the environment in which they are found; this may be seen in Fig. 2a where the low-potassic plagioclase trend of the Thingmuli (Iceland) tholeiites, tholeiitic-andesites and icelandites (CARMICHAEL, 1967b) has been shown. So the only clue that these rocks, particularly the shoshonites, may be accumulative, is the abundance of their plagioclase phenocrysts (Table 1), and possibly the absence of sanidine phenocrysts. It follows that if foreign calcic plagioclase crystals are being resorbed by a shoshonitic liquid, then the incorporation of the plagioclase components into the liquid would tend to move the liquid away from the plagioclase-sanidine coprecipation surface. If the absence of sanidine *phenocrysts* can be convincingly accounted for in this way, then, of necessity, the shoshonites become accumulative rocks, and plagioclase has been added. In the absence of fine-grained non-porphyritic rocks of comparable composition, the analyses of which would define a liquid line of descent, the analyses of these shoshonites (Table 5) cannot be used to indicate any accumulation of plagioclase. The evidence for plagioclase accumulation is so indecisive, that we have plotted (Fig. 1) both the normative feldspars of the rocks (Table 5) and also the recalculated normative feldspar, having made allowance for the volume of phenocrysts (Table 1) of known composition (Tables 2 and 3); this latter composition will represent an *approach* to the composition of the original liquid before plagioclase accumulation.

Pyroxene and Olivine

With the exception of the banakite (119) which contains obvious xenocrysts of orthopyroxene, the ferromagnesian phenocrysts of the remaining rocks do not provide any indication that they are either foreign or out of equilibrium. Augite is the predominant ferromagnesian phase, either as a groundmass constituent or as a phenocryst (Table 1); olivine, often extensively altered, is also a ubiquitous phenocryst, but it has only been found in the groundmass of one of the rocks, a shoshonite (109A).

In only one shoshonite (118A) are orthopyroxene phenocrysts found, but neither they, nor their associated olivines give any textural indication of a reaction relationship of olivine to liquid. A calcium-poor pyroxene has been identified in the groundmass of two of the shoshonites (118A and 114), its place being presumably taken by olivine in the third shoshonite (109A); it has also been found in the groundmass of the absarokite (225). The banakite is too fine-grained for the groundmass pyroxene to be determined.

The analyses of the pyroxenes and coexisting olivines have been plotted in Fig. 3 which is largely self-explanatory. Perhaps the most salient or unexpected feature, is the very small range in composition (Fe replacing Mg) of the augite phenocrysts in the shoshonites, and particularly, the overall correspondence between the composition of the phenocrysts and the composition of the coexisting groundmass augite (Table 3[2]), Fig. 3). In contradistinction, in the only shoshonite (109A) with two generations of olivine, the groundmass phase is markedly enriched in iron (Table 3[2]), Fig. 3). In the absarokite (225), the augites are more extensively zoned, and are more magnesian than their associated groundmass phase (Fig. 3).

Although the zoning in the augite and olivine phenocrysts of the shoshonites and the absarokite may be limited in extent, it is normal in direction, with the outer zones being more iron-rich than the interiors of the crystals. In contrast, however, the banakite (119) has pyroxenes strongly zoned in an oscillatory manner. Some, but not all, have edges more magnesium- and chromium-rich than the centers. A few of the orthopyroxene crystals are undoubted xenocrysts as they contain coarse exsolution lamellae of augite. Some augite crystals have incomplete thin shells of enclosing orthopyroxene and *per contra*, crystals of orthopyroxene have partial jackets of augite. In addition, the augite microphenocrysts in the banakite have a slightly lower Fe to Ca + Mg ratio than the larger associated phenocrysts (Fig. 3).

Iron-titanium Oxides

In the shoshonites and the absarokite, a β-phase (Carmichael and Nicholls, 1967) occurs as relatively large microphenocrysts and as a groundmass phase. A coexisting discrete α-phase also occurs in the groundmass of some of these rocks. The oxide minerals of the shoshonites and the absarokite are all highly variable in composition, presumably in response to subsequent oxidation, and will not be considered further.

Only the banakite (119) contains one-phase oxide minerals, which occur both as microphenocrysts and as groundmass constituents. An α-phase, a Ti-poor and a Ti-rich β-phase are found as microphenocrysts and as inclusions in the pyroxene phenocrysts (Table 4). An α-phase, a β-phase and a discrete chromium-rich spinel are found in the groundmass (Table 4); this last mineral has not been found as inclusions in the pyroxenes nor as microphenocrysts.

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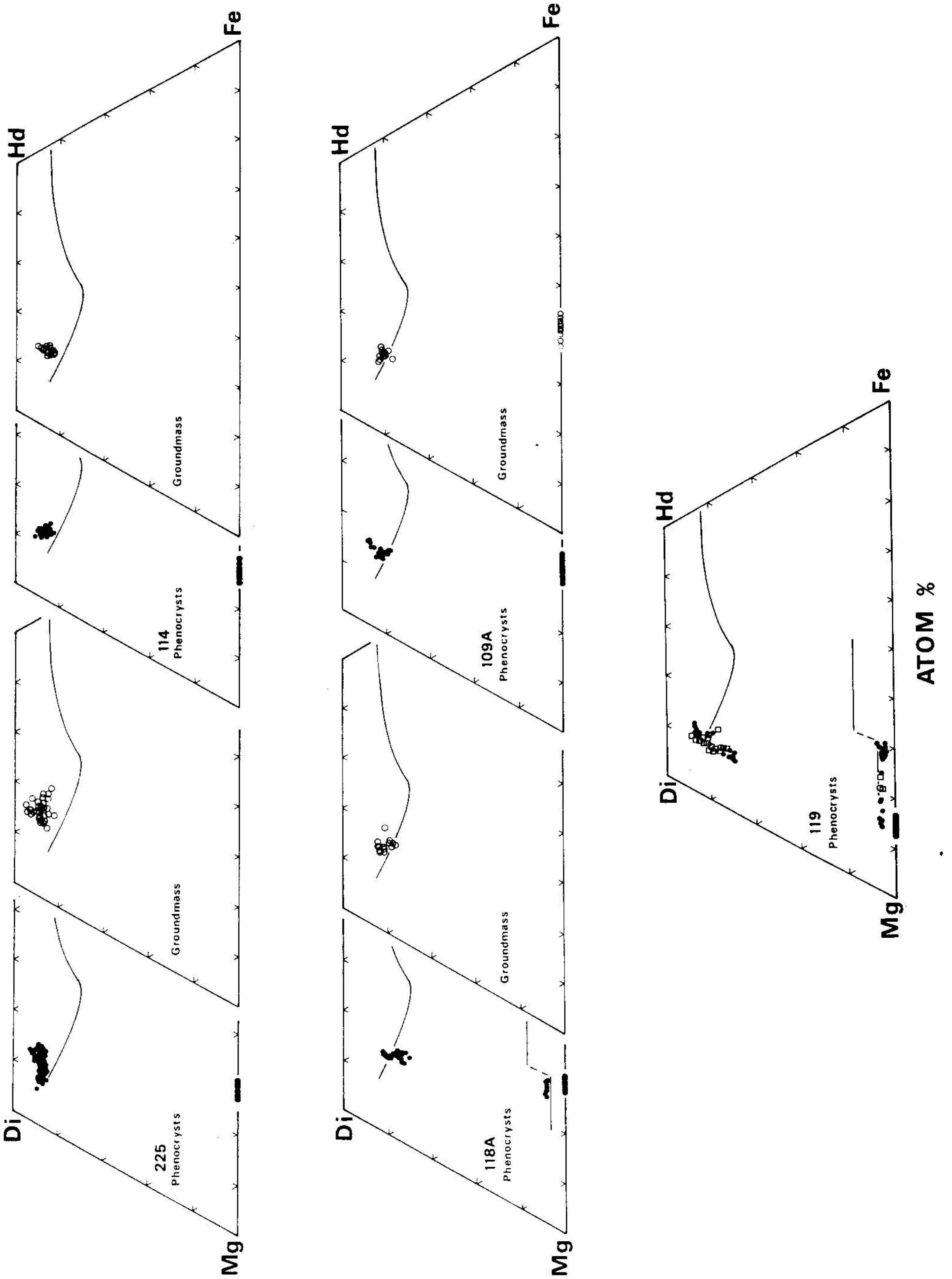
[2] See footnote on page 51.

Fig. 3. Ca-Mg-Fe ratios in pyroxenes and olivines. Olivines are plotted as large circles on the base of the quadrilateral. Open squares in 119 are microphenocrysts. The Skaergaard pyroxene trend is shown as a solid line (Brown, 1957).


Di
Hd
Fe
Mg
225
Phenocrysts
Groundmass
114
Phenocrysts
Groundmass
Di
Hd
Fe
Mg
118A
Phenocrysts
Groundmass
109A
Phenocrysts
Groundmass
Di
Hd
Fe
Mg
119
Phenocrysts
ATOM %

The occurrence of two β-phases as inclusions in the pyroxenes and as microphenocrysts, plus the presence of coarse exsolution lamellae in the orthopyroxene is considered evidence for the contamination of the banakite by basic material. The reversal in zoning of some of the pyroxene phenocrysts, the contrasted composition of the large and small pyroxene phenocrysts (Fig. 3) and the presence in the groundmass of chromium-rich spinel, normally an early crystallizing phase in basic liquids, is interpreted as a consequence of this contamination.

Accessory Minerals

Of the accessory minerals, most of which are secondary (carbonate, chlorite, zeolites), only the occasional flakes of biotite in the groundmass of the absarokite (225) have been analyzed. The analysis (Table 4) shows it to be a magnesian variety rich in fluorine, which is not unexpected in this paragenesis, as it is a necessary component to stabilize phlogopite (Kelley et al., 1959; Yoder and Eugster, 1954) at the presumed temperatures and pressures of a crystallizing lava. Apatite which was found as abundant tiny fluorescent crystals in all the rocks, is too small for analysis with the electron-probe.

Table 4. *Analyses of iron-titanium oxides in the banakite (119) and the biotite of the absarokite (225)*

	Microphenocrysts (119)			Groundmass (119)		
	β-phase	β-phase	α-phase	β-phase	β-phase	α-phase
SiO_2	0.03	0.03	0.03	0.04	0.04	0.04
TiO_2	29.7	10.6	44.0	8.8	18.4	42.5
Al_2O_3	0.53	1.51	0.16	1.57	0.84	0.22
V_2O_3	0.80	1.05	0.70	0.66	1.13	0.98
Cr_2O_3	1.28	1.97	0.30	19.3	1.88	0.45
FeO	60.6	77.7	48.5	61.6	70.0	49.8
MnO	0.27	0.24	0.29	0.38	0.47	0.33
MgO	2.20	1.12	2.49	1.70	0.98	2.50
CaO	0.10	0.17	0.24	0.15	0.15	0.15
ZnO	0.03	0.03	0.03	0.09	0.09	0.09
Total	95.54	94.42	96.74	94.29	93.98	97.06
Recalculated analyses. Ulvospinel basis						
FeO	53.9	38.6	39.2	35.7	45.1	38.7
Fe_2O_3	33.1	43.5	10.3	28.8	27.7	12.3
Total	96.3	98.8	97.7	97.2	96.8	98.3

	Biotite (225)
SiO_2	39.8
TiO_2	3.3
Al_2O_3	11.7
FeO	10.9
MnO	0.12
MgO	18.5
CaO	0.06
Na_2O	0.72
K_2O	9.0
F	4.8
Cl	0.16
Total	99.06

Mineralogical Summary

The predominant feature of these rocks is the occurence of sanidine and plagioclase in the groundmass of the shoshonites; sanidine is also found as rims on the plagioclase phenocrysts, which, perhaps surprisingly, are no more calcic than the groundmass plagioclase. Although these rocks are richly porphyritic, particularly the shoshonites (Table 1), only the banakite (119) presents any evidence that the phenocrysts could be foreign. Here the coarse exsolution lamellae in some of the orthopyroxenes, the reverse zoning in both types of pyroxene, and the plethora of iron-oxide phases, all suggest that the ferromagnesian phenocrysts could well be xenocrysts. In the shoshonites, the augite phenocrysts are weakly zoned, and have almost an identical composition to the augite of the groundmass; a second calcium-poor pyroxene, has also been found. It is the occurrence of the second pyroxene, coupled with the siliceous residual glass that gives the shoshonites a tholeiitic flavor.

CHEMISTRY OF THE ABSAROKITE-SHOSHONITE-BANAKITE SERIES

Analyses of an absarokite, three shoshonites and the banakite are given in Table 5 together with their CIPW norms; the electron-probe analysis of the residual glass of the basaltic-looking shoshonite (118A) is also given. For rocks of "basaltic aspect", these analyses tend to be high in silica, total alkalis and phosphorus, and low in titania. With the exception of the absarokite (225) all the rocks either have quartz in the norm, or only small amounts of olivine; the silica-rich nature of a shoshonitic residual liquid is clearly shown in the analysis and norm of the residual glass of 118A. It should be noted that any subsequent oxidation of the iron-titanium oxides will tend to increase normative quartz at the expense of normative olivine or pyroxene; as the oxide minerals are not abundant in these rocks (Table 1), it is unlikely that their alteration would be the sole cause of normative quartz.

The five analyses of Table 5 have been recalculated free of water and carbon dioxide and are set down in Table 6 together with the old recalculated analyses of IDDINGS (1899); there are consistent differences between the two groups, for example K_2O is always less than Na_2O in the shoshonites in contrast to the average of the old shoshonite analyses, and alumina also tends to be lower in the new analyses. The absarokite analysis (225) is not closely comparable to the average analysis of absarokites (Table 6) many of which are undoubtedly accumulative in ferromagnesian minerals (IDDINGS, 1899, p. 329); moreover, the new analysis has a most unusual K_2O/Na_2O ratio which is quite unlike existing data. The banakite (119) has a very different composition to the average banakite (Table 6), but because many of the ferromagnesian phenocrysts are accounted xenocrysts, the composition of the groundmass, rich in normative quartz, will be closer to banakite than to any other member of the series. Analyses of volcanics of similar chemical composition to the Wyoming volcanic series are also given in Table 6; thus the absarokite with its very high K_2O/Na_2O ratio, is (if it is a pristine feature) highly potassic and as may be seen for Table 6, it is not unlike the average minette. These lamprophyres, although of comparable composition, typically contain more than the odd

Table 5. *Analyses and norms of absarokite (225), shoshonites (114, 118A, 109A) and banakite (119) from Yellowstone National Park, Wyoming*

	225	114	118A	118A glass	109A	119
SiO_2	51.62	52.01	52.28	65.8	53.98	60.07
TiO_2	0.78	0.90	0.94	1.2	0.96	0.63
Al_2O_3	12.56	16.72	15.75	16.2	16.30	15.02
Fe_2O_3	3.39	3.92	3.28	1.9	4.13	1.36
FeO	4.61	3.52	4.88		3.90	3.95
MnO	0.16	0.12	0.16	0.04	0.11	0.11
MgO	7.69	5.55	4.76	0.23	4.51	5.21
CaO	7.37	8.09	8.30	1.3	7.09	5.72
SrO	0.06	0.15	0.13	—	0.13	0.09
BaO	0.24	0.24	0.16	—	0.19	0.15
Na_2O	2.26	3.26	3.44	4.5	3.61	3.67
K_2O	5.10	2.98	2.08	6.3	2.54	2.26
P_2O_5	0.60	0.52	0.36	—	0.49	0.17
H_2O^+	2.59	1.46	1.21	—	1.44	1.04
H_2O^-	0.97	0.63	0.47	—	0.68	0.24
CO_2	—	0.07	1.60	—	0.02	0.34
Total	100.00	100.14	99.80	97.5	100.08	100.03

		225	114	118A	118A glass	109A	119
Qz		—	—	3.98	12.6	3.95	10.51
Or		30.14	17.61	12.29	37.0	15.01	13.35
Ab		19.12	27.59	29.11	38.2	30.55	31.05
An		9.06	22.19	21.39	5.4	20.77	17.84
Di	Wo	10.09	6.24	3.32	0.4	4.91	3.25
	En	7.36	4.87	2.17	0.4	3.66	2.15
	Fs	1.80	0.69	0.92	—	0.77	0.88
Hy	Fs	1.17	7.95	9.68	0.2	7.57	10.83
	En	0.29	1.13	4.08	—	1.60	4.42
Ol	Fo	7.45	0.71	—	—	—	—
	Fa	2.00	0.11	—	—	—	—
mt		4.92	5.68	4.76	0.8	5.99	1.97
il		1.48	1.71	1.79	2.3	1.82	1.20
ap		1.42	1.23	0.85	0.1 (hm)	1.16	0.40
cc		—	0.16	3.64	—	0.05	0.77
Rest		3.56	2.09	1.68	—	2.12	1.28
Total		99.85	99.95	99.66	97.4	99.93	99.90

Analyses by I. S. E. Carmichael and J. Hampel.

Index of localities

225	Absarokite lava, Signal Pt. on Yellowstone Lake.
114	Shoshonite lava, Sth. ridge of Druid Peak at 8600 ft.
118A	Shoshonite lava, Sth. of Lamar river, nr. Fossil forest at 8600 ft.
118A glass	Residual glass from above.
109A	Shoshonite lava, pass between Mt. Hornaday and Druid Peak.
119	Banakite, north of Amethyst Mountain at 9200 feet.

flake of biotite found in the groundmass of the absarokite. Another explanation of the absarokite alkali ratio could be that the extensive interstitial chloritic material replaced a residual glass with a very different alkali content, now largely expelled; the chlorite cannot have a significant amount of alkali, as the normative feldspar of the rock, corrected for the alumina content of the associated pyroxene, matches fairly well the composition of the groundmass feldspar (Fig. 1).

Trachyandesites of comparable composition to the shoshonites have been described from the northern part of the Absaroka mountains (Nelson and Pierce, 1968). Although the descriptions given of these rocks do not indicate that they are petrographic members of the shoshonites (hornblende phenocrysts are often present), their average analysis (Table 6) and geological setting are closely comparable. Also set down in Table 6 are the average analyses of doreite and latite (Nockolds, 1954), rocks of allied but not identical petrographic type. If the doreites described by Brousse (1961) are typical of their class, then the presence of sanidine and hornblende (Ti-rich) phenocrysts sets them apart from the shoshonites; moreover the plagioclase phenocrysts tend to be more sodic than those of the shoshonites, and yet the normative feldspar of the average doreite has a composition close to that of the shoshonites (Fig. 4).

Table. 6. *Chemical analyses (recalculated H_2O and CO_2 free)*

	Absarokite	Shoshonites									? Banakite	
	225	A.	M.	114	118A	109A	S.	T.A.	Doreite	Latite	119	B.
SiO_2	53.53	51.29	53.90	53.08	54.16	55.11	54.68	55.0	56.52	54.45	61.04	55.37
TiO_2	0.81	0.98	1.43	0.92	0.97	0.98	0.84	0.95	1.30	1.19	0.64	0.73
Al_2O_3	13.02	13.18	14.61	17.06	16.32	16.64	18.25	17.5	16.97	17.36	15.26	18.87
Fe_2O_3	3.52	4.54	3.44	4.00	3.40	4.22	4.62	4.8	3.77	3.86	1.38	4.44
FeO	4.78	4.38	4.38	3.59	5.06	3.98	3.12	3.0	4.40	4.01	4.01	2.49
MnO	0.17	0.11	—	0.13	0.17	0.11	0.07	0.14	0.13	0.12	0.11	0.11
MgO	7.97	10.23	7.28	5.66	4.93	4.60	3.70	4.5	3.42	3.90	5.29	2.82
CaO	7.64	8.14	6.93	8.26	8.60	7.24	6.58	6.8	6.93	6.81	5.81	4.77
BaO	0.25	0.39	—	0.24	0.17	0.20	0.25	—	—	—	0.16	0.26
Na_2O	2.34	2.13	2.23	3.33	3.56	3.69	3.49	3.5	3.59	3.35	3.73	4.36
K_2O	5.29	3.94	5.78	3.04	2.15	2.59	3.84	3.2	2.62	4.46	2.30	5.16
P_2O_5	0.62	0.69	—	0.53	0.37	0.50	0.56	0.60	0.33	0.49	0.18	0.62

A:	average of Wyoming absarokites (IDDINGS, 1899, p. 329).
M:	average (recalculated) of 64 minettes (MÉTAIS and CHAYES, 1963, p. 157).
S:	average of shoshonites (IDDINGS, 1899, p. 340).
TA:	average of 10 trachyandesite lavas, Absaroka Mountains (NELSON and PIERCE, 1968).
Doreite and latite:	average analyses (recalculated) from NOCKOLDS (1954).
B:	average Wyoming banakite and quartz-banakite (IDDINGS, 1899, p. 347).

The average latite (Table 6) is less rich in calcium (lower ratio of $CaO/Na_2O + K_2O$) than the shoshonites, and accordingly has a normative feldspar richer in alkali components.

The results of X-ray fluorescence analysis of the minor and trace elements in the five rocks of Table 5 are given in Table 7. In common with the generality of potassic lavas (TURNER and VERHOOGEN, 1960; CARMICHAEL, 1967c), the representatives of the absarokite-shoshonite-banakite series (Table 7) contain notable amounts of P, Sr, Ba, La and the light rare earths, lesser amounts of Cr and Ni, and are rather poor in Zr especially in comparison to the average latite of the Sierra Nevada (NOCKOLDS and ALLEN, 1954), the only comparable rock-type with trace-element data.

Table 7. *X-ray fluorescence analyses of trace and minor elements of the rocks in Table 5*

	225	114	118 A	109 A	119
Ga	15	20	15	20	20
Cr	415	90	145	100	370
V	160	170	185	175	100
Ni	70	60	75	45	190
Cu	70	85	75	60	40
Zn	95	90	115	110	95
Zr	110	135	120	145	125
Y	20	15	20	20	10
La	60	80	70	80	40
Ce	50	110	80	100	50
Pr	<10	10	<10	10	<10
Nd	30	40	30	40	20
Sm	<10	<10	<10	<10	<10
Sr	485	1245	1075	1115	725
Ba	2130	2140	1460	1670	1360
Rb	180	80	55	50	35

Analyses by R. N. JACK.

THE ABSAROKITE-SHOSHONITE-BANAKITE SERIES

This series was considered by IDDINGS (1899) to be genetically related, but the nature of the relationship was not treated, except that banakites were suggested to be the highly feldspathic modification of shoshonite magma, and are complementary to absarokite, which represents the least feldspathic modification of the same magma. Shoshonite was also considered to be related to basalt, and petrographic transitions between the two rock-types were described by IDDINGS. HOLMES (HOLMES and HARWOOD, 1937) re-interpreted Iddings' data, and suggested that each of the three rock-types was itself a series, and some factor, other than differentiation (crystal fractionation), controlled the series. HOLMES later (op. cit., p. 147) suggested that the "olivine-rich absarokites of Montana may be syntectic products due to the action of alkali ultrabasic magma on sediments which were themselves transfused by alakli emanations from magma".

The new analytical and mineralogical data presented in this paper do not provide the solution to the genetic link between each of these rock-types. There must be considerable doubt over the original composition of most of these volcanics, some of which contain over three percent of water and carbon dioxide. However, if it is assumed that the absarokite (225) (Tables 5 and 6) has not been greatly changed in composition subsequently to its eruption, then no combination of phases present as phenocrysts in this volcanic series can be found, which by addition and/or subtraction to the absarokite (or the average absarokite (Table 6)) will give a close approximation to the composition of the shoshonites. Similarly, there seems to be no combination of phenocrysts either added to or subtracted from the shoshonites which will give either the absarokite (225) or the average absarokite (Table 6).

In porphyritic volcanics such as the absarokite-shoshonite-banakite series, where the liquid line of descent (if it exists) is unknown, the accumulative nature, or otherwise, of one rock-type cannot be established. Therefore there cannot be an unequivocal conclusion about the dominant control in the genesis of this series, especially as it would depend on accepting the analyses of Table 5 to be representative of the lavas in a pristine condition.

THE SHOSHONITE SERIES

This magma series, recently defined and proposed by JOPLIN (1965, 1966) is analogous to, and parallel with, the alkaline olivine-basalt magma series. The shoshonite magma series as conceived by JOPLIN (1965, 1966) has high potash as the dominant characteristic, and has two branches, one rich in feldspathoids, and highly undersaturated, and the other less undersaturated and which includes the absarokites, shoshonites and banakites, and the potassic trachytes and all their plutonic equivalents. The potassic lamprophyres are also considered representatives of the shoshonite magma series.

It should be clear that it is not our intention to question the existence of the postulated shoshonite magma series, or its implied genetic thread, although the series would seem to include a wide variety of rock-types, but rather to offer data on the rock-type (possibly accumulative) which gives its name to this alkaline magma series. Whatever the shoshonite series is, or is conceived to be, it has little or no affiliation with, or similarity to, the tholeiitic or the (calc-alkaline) orogenic series. Only in exceptional geological circumstances is Joplin (1966, p. 42) prepared to concede that orthopyroxene can crystallize in a representative of the shoshonitic magma series. It is difficult to encourage the name shoshonite, which, in the type locality of Wyoming, is a lava of tholeiitic aspect, containing calcium-rich and calcium-poor pyroxenes, and a siliceous glassy residuum, for the title of an alkaline magma series characterized largely of what it is not. We therefore advocate abandoning the title of shoshonite for this magma series. Chayes (1966) made an identical proposal concerning things tholeiitic, but the consequent challenge (Tilley and Muir, 1967) depended largely on preservation of the status quo, and the present widespread usage of the term. We hope therefore that this commentary will forestall shoshonite coming into common petrological usage.

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