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On Lamprophyres

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ABSTRACT—It is argued that camptonites and analcime- and nepheline-monchiquites are differentiates of the alkali basalt magma, whilst minettes, vogesites, kersantites and spessartites, which commonly invade granites and other plutonic rocks, are differentiates of the potash-rich basaltic magma, shoshonite. The leucite monchiquite may also be related to the shoshonites.

Rare types of lamprophyre, such as alnöite and the leucite lamproites of Western Australia, are not discussed, but it is suggested that they may belong to an ultramafic magma-type.

I. Introduction

Many attempts have been made to classify the lamprophyres and they have posed an especially difficult problem to those who have written text-books for students. Harker (1895 and subsequent editions) gave them a separate chapter among the hypabyssal rocks; Hatch (1891) placed them in a special family of melanocrates in his hypabyssal group and in a later edition of this book by Hatch, Wells and Wells (1960) they are dealt with in a separate chapter; Williams, Turner and Gilbert (1958) described them with the Ultramafic Clan; and in the first edition of their text-book Turner and Verhoogen (1951) dealt with them in the same chapter as the pegmatites and nepheline syenites because all of these rocks contain high alkalies, carbon dioxide, water and phosphorus; but in the second edition of their book these authors (1960) place them with the potash-rich volcanic rocks, where, I believe, most of them rightly belong.

In writing a text-book on Australian igneous rocks, I was also confronted with the problem of the lamprophyres and came to the conclusion that the camptonites and most of the monchiquites should be included with the differentiates of the alkali basalt magma and that all the other common lamprophyres, as well as the leucite monchiquites, were related to a potash-rich basaltic magma and should be discussed with the differentiates of the shoshonite magma (Joplin, 1964, 1965).

Before attempting to justify this classification, it is pertinent to outline the characteristics of the lamprophyres, and to suggest the main reasons for the difficulties in classifying this seemingly anomalous rock group.

II. Characteristics of Lamprophyres

1. *Texture.* Some lamprophyres are aphyric, but most of them are porphyritic and all are panidiomorphic granular, that is to say, all minerals show idiomorphic outlines whether they occur in one or in two generations.

2. *Mineral Composition.* Some petrographers define lamprophyres as rocks containing only mafic phenocrysts, but actually many contain small phenocrysts of feldspar as well, and with an increase in the content of feldspar phenocrysts, they pass into porphyrites with which many lamprophyres are closely associated in the field. The mafic phenocrysts may be olivine, augite, hornblende or mica and in many lamprophyres several of these minerals occur together. The groundmass consists of a second generation of the mafic mineral or minerals and either potash feldspar or plagioclase (oligoclase to andesine), and undersaturated types contain feldspathoids with or without melilite. Opaque minerals are abundant, apatite is always present and may be very abundant in some types. Carbonates and other alteration products are ubiquitous in the minettes, vogesites, kersantites and spessartites, though not present in all camptonites and monchiquites. Mafic phenocrysts such as olivine and augite are commonly pseudomorphed by serpentine, carbonates or clay minerals, and though hornblende and mica are less commonly altered, they may be pseudomorphed by chlorite and a secondary amphibole with separation of sphene and iron ore granules. Hornblende and mica phenocrysts typically show resorption and marginal alteration.

Three common types of lamprophyre contain hornblende: two, vogesites and spessartites, common green hornblende; and camptonites, a brown oxyhornblende said to be barkevikite, but possibly kaersutite. Lime-rich pyroxene occurs in many lamprophyres, but in the camptonites and in many of the monchiquites it is also titaniferous. Monchiquites containing titanaugite commonly contain oxyhornblende, analcime and/or nepheline, but leucite monchiquites usually contain mica and rarely hornblende. The leucite monchiquites thus appear to show some relation to the minettes and the analcime and nepheline monchiquites to the camptonites.

3. *Chemical Composition.* Many authors state that the lamprophyres show a wide range of chemical composition, and this might be expected when the range of mineral composition is taken into account. Cross (1915) and Knopf (1936) have pointed out however that many of the common lamprophyres, such as minettes, vogesites, kersantites and spessartites, are almost chemically identical, and this is borne out by a recent set of averages based on a very large number of carefully selected analyses (Métais and Chayes, 1963).

Reference to Table 1 will show that, except for alkalies, minettes, vogesites, kersantites and spessartites have a very similar chemistry, and that they all show high potash, which is in excess of soda except in the spessartites. Camptonites and monchiquites on the other hand contain less silica, more magnesia, lime, iron and titania with soda in excess of potash.

Unfortunately these averages do not give BaO and SrO, probably because these oxides have been rarely estimated. An inspection of lamprophyre analyses in Washington (1917) and in Joplin (1963) suggests that BaO is high in the minettes, vogesites, kersantites and spessartites and ranges from about 0·06% to about 0·50%, whereas in the camptonites it is lower and ranges from about 0·04% to about 0·08%.

4. *Field Occurrence.* Von Gümbel first gave the name lamprophyre to certain dark, lustrous dyke rocks in Saxony, and most lamprophyres occur in dykes, though they have been described from sills, small laccoliths and as marginal phases of larger bodies.

There is no doubt that a close field association exists between camptonites, many monchiquites and fourchites and members of the alkali basalt series, such as alkali basalts, hawaiites, mugearites, nepheline basanites, nephelinites etc. and though dykes of camptonite and nepheline- or analcime-monochiquite are recorded among the rocks of other suites, and are in places associated with other types of lamprophyre, the association is probably accidental and the two suites usually have a different geological age.

Minettes, vogesites, kersantites and spessartites are commonly associated with granites, diorites, syenites and monzonites, which they cut as dykes. Dykes of aplite, pegmatite and porphyrite are also associated with these plutonic rocks and it was earlier suggested that the felsic dyke-rocks and the lamprophyres were complementary variants of the associated plutonic type. Because of their close field association and mineralogical resemblances to certain plutonic types, vogesites have been called syenite-lamprophyres and spessartites diorite-lamprophyres.

As indicated by the work of Pirsson (1905) and Cross (1906, 1915), lamprophyres appear to be especially abundant in the monzonitic

TABLE 1

Average Analyses of Lamprophyres

	Minette	Vogesite	Kersantite	Spessartite	Camptonite	Monchiquite
	Av. 64	Av. 30	Av. 95	Av. 45	Av. 78	Av. 61
SiO_2	51·17	51·13	51·80	52·37	44·67	40·68
Al_2O_3 ..	13·87	14·35	14·84	15·44	14·35	13·20
Fe_2O_3.. ..	3·27	3·63	3·03	3·27	4·50	4·87
FeO	4·16	4·74	5·32	5·35	7·19	6·47
MgO	6·91	6·84	6·29	6·27	7·02	9·17
CaO	6·58	7·05	6·24	7·36	9·45	11·02
Na_2O ..	2·12	3·00	2·98	3·30	2·99	3·06
K_2O	5·49	3·81	3·68	2·54	1·91	2·16
H_2O	2·42	2·62	2·56	2·36	3·12	3·52
CO_2	1·30	0·74	1·14	0·41	1·58	1·38
TiO_2	1·36	1·44	1·32	1·31	2·46	2·34

complexes where they are associated with shonkinites and potash-rich syenites. Many types of lamprophyre are also associated with the monzonitic complex of Mount Dromedary, New South Wales (Brown, 1930). In the Spanish Peaks region of Colorado, Knopf (1936) recorded numerous lamprophyres associated with microsyenodiorites, augite microsyenites, syenogabbros, trachydolerites and shonkinites—a suite which, I believe, belongs to the monzonite or shoshonite series.

Some of these dykes cut the monzonitic rocks and others radiate out from them, the latter occurrence suggesting a close tectonic relation.

In the Walhalla-Woods Point district of Victoria (Junner, 1920; Hills, 1952), a dyke-swarm consisting largely of lamprophyres, includes hornblende pyroxenites, diorites and diorite porphyrites, which contain orthoclase, and this series is also suggestive of a monzonitic type of magma.

In the Snowy Mountains region of New South Wales I (Joplin, 1958) described a number of co-linear intrusions consisting of pyroxenites, hornblende pyroxenites, monzonites, orthoclase-bearing diorites and lamprophyres and explained the presence of potash feldspar by hybridization with adjacent granite. I now believe that these rocks have differentiated from a monzonitic magma, and though some hybridization has certainly taken place, most of the potash feldspar has originated from the mafic magma.

5. *Tectonic Environment.* As noted above, camptonites and analcime- and nepheline-monchiquites occur with the alkali basalt suite, which is associated with a typically stable environment.

Granites and diorites, which are invaded by lamprophyres, occur characteristically in *subsequent* bathyliths (Browne, 1931), that is, in bathyliths associated with the late stages of diastrophism (Joplin, 1962). The lamprophyritic dyke-swarm at Walhalla-Woods Point is truncated by still later granites occurring as ring-dykes (Hills, 1959).

Recent dating by the potassium-argon method has shown that the monzonitic complex of Mount Dromedary is probably Cretaceous (Evernden and Richards, 1962), and this points to an almost stable environment for these intrusions, with which lamprophyres appear to be genetically related.

According to Knopf (1936) the intrusions from which the lamprophyre dykes radiate in the Spanish Peaks region took place during a late phase of the Laramide Revolution and in Montana and Wyoming the shoshonite complexes, with their accompanying lamprophyres were also late in the diastrophic cycle.

Thus, lamprophyres appear to be intruded during or after the late stages of the stabilization of the geosyncline.

III. Main Difficulties of Classification

Because all lamprophyres are very similar texturally, and most of them occur as dykes, there is good reason for placing them together in one group and the almost ubiquitous presence of carbonates and other alteration products also serves to link them.

On the other hand, the diversity of mineral composition and their apparent association with a number of different plutonic rocks suggest different parentages. Because dykes of lamprophyre and of aplite invade subsequent bathyliths so commonly, a genetic relation between granite, aplite and lamprophyre seems obvious, and when Bowen's theory of magmatic differentiation was applied to a granitic complex, the late appearance of these mafic dykes was puzzling, and was explained by complementary differentiation which give rise to diaschistic dykes—mafic and felsic. Tyrrell (1926) stated, "minettes, vogesites, kersantites and spessartites occur as basic differentiates of granitic or granodioritic magmas, and are complementary to aplites and pegmatites". Bowen (1928) suggested that lamprophyres and allied alkaline rocks may be produced by remelting earlier crystallized hornblende and biotite, and Eskola (1954) suggested that the crystallization of mafic minerals might be delayed in a mafic magma with a high concentration of carbon dioxide and that a late magmatic liquid rich in alkalies and mafic materials could thus be produced.

Although the original camptonite was said to contain barkevikite a good deal of confusion has stemmed from the loose usage of the term "hornblende lamprophyre", which has been applied to camptonites with their brown hornblende and to spessartites and vogesites with their green. Undoubtedly, more work needs to be done on the amphiboles of the lamprophyres, and it is possible that in some cases the so-called barkevikite of camptonites may prove to be kaersutite. Nevertheless, it seems obvious that different mineral assemblages accompany brown hornblende and green hornblende, and that the lamprophyres containing brown hornblende, such as the camptonites and analcime- and nepheline-bearing monchiquites and fourchites have the same mineralogy, field association and tectonic environment as the alkali basalts.

Other lamprophyres, however, have a different mineralogy, chemical composition and field association and are intruded a little earlier in the stabilization of the orogenic belt. I believe that all these lamprophyres are related to one another and are members of the shoshonite series, so it is now necessary to outline the characteristics of this series and to compare them with those of the lamprophyres.

IV. Characteristics of the Shoshonite Series

The characteristics of the shoshonites are discussed elsewhere (Joplin, 1965) and only a brief outline is presented here.

These rocks fall into two groups—those that are slightly saturated, or undersaturated only with respect to olivine, and those that are completely undersaturated and contain feldspathoids. The first group ranges in composition from ultramafic to felsic: intrusive rocks include pyroxenites, olivine monzonites, monzonites, banatites, akerites and some syenite porphyries, whilst the corresponding lavas are absarokites, shoshonites, latites (in the Ransome (1898) sense) and potash-rich trachytes. The undersaturated intrusive rocks are nepheline monzonites, shonkinites, covites, ijolites, jacupirangites, leucitophyres and certain tinguites, and the lavas include such rocks as leucite absarokites, leucite shoshonites and leucite basalts. The leucite monchiquites are chemically and mineralogically related to this group.

1. *Mineral Composition.* With the exception of the ultramafic types all these rocks are characterized by the presence of potash feldspar which is commonly orthoclase in the plutonic rocks and sanidine in the lavas and minor intrusives. In addition to potash feldspar, plagioclase is commonly present, and though much work needs to be done on these feldspars, and though there is a range in composition throughout the series, the plagioclase seems to be rather a lime-rich variety and is commonly labradorite. The shoshonite lavas contain phenocrysts of both feldspar and mafic minerals, but the absarokites contain only mafic minerals as phenocrysts.

The mafic minerals of the shoshonite series are typically clinopyroxene and biotite, but green hornblende occurs in the more felsic differentiates. Pyroxene is a diopsidic type, and is commonly pale green in thin section (Boesen, 1964). Many of the undersaturated members of the series also contain these minerals as well as one or more feldspathoids which may be nepheline, leucite, hauyne or nosean. Extremely undersaturated rocks are feldspar-free. Melanite garnet is very common in these rocks and some undersaturated felsic types contain aegirine or aegirine-augite. Melilite occurs in some rare types.

In the Spanish Peaks region of Colorado, Knopf (1936) has recorded potash feldspar, plagioclase, clinopyroxene and biotite in most of the rocks of the suite and it is my belief that this is a shoshonitic province.

2. *Chemical Composition.* Because these rocks form a differentiation series, there is a range in chemical composition. Nevertheless certain chemical peculiarities are common to the whole suite.

Alkalies are high, with potash about equal to or in excess of soda; alumina, lime and phosphorus are high and magnesia a little lower than in rocks of comparable silica content in the alkali basalt series. Barium and strontium have been estimated in comparatively few of these rocks, but when these results are available they appear to be high and barium shows a range from 0·06% to 0·46%.

A rock from the Crazy Mountains of Montana, a typical shoshonite province, was originally described by Rosenbusch as a theralite, but the "plagioclase" subsequently proved to be barium-bearing orthoclase, and it would be of interest to know whether the presence of a notable amount of barium is characteristic of the potash feldspar of this rock-suite.

Knopf has stated that the Spanish Peaks rocks contain high potassium, barium, strontium and phosphorus—a further confirmation of their shoshonitic affinities.

3. *Tectonic Environment.* Ransome (1898) showed that the latites of the Sierra Nevada are interbedded with pyroclastic rocks which cover an eroded surface consisting of granites and steeply dipping schists, and that only faulting and tilting have affected this area since the outpouring of the latites. The shoshonites of Yellowstone Park are also associated with ash beds that have inflled valleys cut out of the Laramide fold mountains

TABLE 2

Some Members of the Shoshonite Series

	1	2	3	4	5
SiO_2	49·71	51·32	51·68	51·75	52·86
Al_2O_3	13·30	18·82	14·07	17·48	17·51
Fe_2O_3	4·41	4·50	4·71	6·42	5·18
FeO	3·37	2·97	4·57	1·46	3·31
MgO	7·96	3·58	7·72	4·05	4·18
CaO	8·03	6·42	6·65	8·20	6·51
Na_2O	1·49	3·97	2·45	3·33	3·22
K_2O	4·81	3·31	4·16	3·72	3·41
H_2O+	4·07	2·89	2·09	2·26	1·76
H_2O-	—	0·87	—		
CO_2	—	0·10	—	—	—
TiO_2	1·57	0·56	1·08	0·86	—
P_2O_5	0·66	0·42	0·72	0·67	0·53
MnO	0·17	0·23	—	tr	—
BaO	0·46	0·22	—	—	—
Etc.	—	0·07	0·13	0·17	0·42
	100·01	100·25	100·03	100·37	99·90

1. Absarokite, Yellowstone Park, U.S.A. Anal. L. G. Eakins
2. Latite (Minnamurra Latite), South Coast, N.S.W. Anal. H. P. White
3. Absarokite, Yellowstone Park, U.S.A. Anal. J. E. Whitfield
4. Shoshonite, Yellowstone Park, U.S.A. Anal. J. E. Whitfield
5. Shoshonite, Yellowstone Park, U.S.A. Anal. J. E. Whitfield

(Thoms, 1955), and Knopf (1936) has stated that the intrusions at Spanish Peak have occurred during a late stage of the Laramide Revolution. The great differentiated laccoliths of Montana and Wyoming, such as Highwood Mountains, have also been intruded after the cessation of folding, so all of these American examples suggest that the shoshonitic magma is associated with a late phase of the stabilization of a tectonic belt.

In Australia shoshonitic rocks occur as lavas and shallow intrusions in the Upper Permian on the south coast of New South Wales, and further south, in the differentiated intrusion of Mount Dromedary, now believed to be Cretaceous. More felsic types also occur in a series of small Cretaceous intrusions at Port Cygnet in Tasmania.

The Permian rocks on the south coast of New South Wales were laid down in either an exogeosyncline (Voisey, 1959) or on a shelf, and their very low angle of dip indicates that no orogeny has taken place since the shoshonites were emplaced. By Cretaceous time the Tasman Geosyncline in the vicinity of Tasmania and southern New South Wales was essentially stable, so in Australia also the shoshonitic magma is associated with stable or near stable conditions.

V. A Comparison of Certain Lamprophyres with Shoshonites

A comparison of the minettes, vogesites, kersantites and spessartites with members of the shoshonite series shows a number of mineralogical similarities, and some specimens of kersantite from the type area at Brest in France are almost identical with monzonite porphyries.

Although many lamprophyres contain small phenocrysts of feldspar, the phenocrysts are mainly mafic minerals and in this respect they resemble the absarokites of the shoshonite series.

Although a comparison of actual chemical analyses with average analyses is not satisfactory, and a perusal of a compilation of analyses (Washington, 1917; Joplin, 1963) will reveal that some analyses of lamprophyres are almost identical to some analyses of shoshonitic rocks, a comparison of Tables 1 and 2 will show common characteristics, particularly high alkalies and high potash compared with soda. As might be expected, the analyses of the lamprophyres compare more closely with the absarokites, the lower feldspar and higher mafic content being reflected in the lower alumina and higher magnesia.

Like members of the shoshonite series, the lamprophyres are also injected during a late stage in the stabilization of the geosyncline.

VI. An Attempt to Explain some Characteristics of Lamprophyres

If the camptonites and most monchiquites belong to the alkali basalt magma and the rest of the lamprophyres to the shoshonitic magma, then some of the characteristic features of lamprophyres find a ready explanation.

1. *Occurrence in Dykes.* If lamprophyres are derived from the alkali basalt and shoshonite magmas they are associated with late and very late phases in the stabilization of the geosyncline when it is subjected to tensional stress; dykes and dyke-swarms are the most common forms of intrusion under these tectonic conditions.

2. *Panidiomorphic Texture.* Idiomorphic crystals will develop in a fluid magma that cools relatively quickly and it is not uncommon to find this texture in many mafic lavas and small intrusions.

When it was thought that many lamprophyres were differentiates of plutonic bodies and were perhaps complementary variants of aplites and pegmatites, the panidiomorphic texture of the lamprophyre was remarkable. However, if the lamprophyres have crystallized from mafic magmas, whether they be soda-rich (alkali basalt) or potash-rich (shoshonite), and if these magmas have crystallized in relatively small intrusive bodies under fairly stable conditions, the panidiomorphic texture ceases to be remarkable and might be expected to occur.

3. *Typical Alteration.* So-called deuteric alteration is fairly common in mafic rocks and many examples are to be found among the members of the alkali basalt series. Nevertheless, the camptonites and monchiquites belonging to this suite are perhaps less altered than the lamprophyres which I believe belong to the shoshonite series, so the question arises, why should shoshonitic rocks be more altered?

If during the stabilization of the geosyncline, the shoshonitic magma precedes the alkali basalt, it probably makes its way up through only partly consolidated sediments still containing much water and organic matter, whereas the later alkali basalt invades a more consolidated and drier environment. Although almost stable, the site of the old geosyncline is probably transgressed by shallow seas at the time when the shoshonite magma is coming in and the magma becomes charged with carbon dioxide and sulphur and has a high water content. Phenocrysts brought up by the magma are no longer stable under these near surface conditions and are thus partly resorbed or pseudomorphed completely. The high water pressure also may explain the presence of common green hornblende and the rare occurrence of orthopyroxene in these rocks.

4. *Presence of Xenoliths and Xenocrysts.* The abundance of xenocrystal material in some lamprophyres has led to a suggestion that the lamprophyres are contaminated rocks, though few petrologists have accepted this theory.

If magma is extremely fluid with a high water and high carbon dioxide pressure, it is capable of rifting fragments of the country rocks and mechanically disintegrating them, so it is not surprising that shoshonitic rocks would contain abundant foreign material (Wilshire and Hobbs, 1962).

VII. Rare Types of Lamprophyre

Alnöites and other less common types such as the leucite lamproites (Prider, 1960) are not dealt with in this paper. They may represent a group derived from an ultramafic magma. The alnöites are typically associated with carbonitites and with kimberlites (Campbell-Smith, 1956) and Prider has suggested mica peridotite as the parent of the leucite lamproites.

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