

## **Petrographic significance of a carbonate-rich lamprophyre from Squaw Creek, northern Black Hills, South Dakota**

JAMES G. KIRCHNER

*Department of Geography-Geology, Illinois State University  
Normal, Illinois 61761*

### **Abstract**

A very small intrusion of a dark soda-minette rock occurs intermixed with a leuco-phase along Squaw Creek in the northern Black Hills. It consists of phenocrysts of pyroxene, phlogopite, and carbonate pseudomorphs of olivine(?), the latter surrounded by phlogopite, in a groundmass of aegirine, alkali feldspar, and secondary carbonate. Pyroxene phenocrysts are largely replaced by ferroan dolomite. Quartz xenocrysts show replacement rims of alkali feldspar and an inner rim of hematite. Chemically the rock is relatively low in silica and ferrous oxide, but relatively high in magnesia, lime, and potash, with carbon dioxide as the main volatile component. The rock probably originated as a differentiate of the alkaline magmas that produced the Tertiary phonolites in the northern Black Hills. Carbonate pseudomorphs of olivine(?), plus phenocrysts of pyroxene and phlogopite, suggest an origin in the lower crust or upper mantle. Crystallization of the phenocrysts most likely began at great depth and followed the sequence of olivine, phlogopite, and pyroxene, whereas the aegirine and feldspar groundmass crystallized after injection into the lower Paleozoic section.

### **Introduction**

Documentation of lamprophyres related to the Tertiary intrusive activity in the northern Black Hills area is minimal; they have been only rarely mentioned in geologic literature. Darton and O'Harra (1905) describe augite lamprophyres associated with nepheline syenite, monzonite porphyry, syenite porphyry, and pseudoleucite porphyry in the Tinton mining district. Welch (1974) has done further work on this area. Lamprophyres have not been reported from other areas in the northern Black Hills.

I have found a small outcrop of soda-minette (Fig. 1) on the northeast bank of Squaw Creek, about 50 meters north of the section line separating sections 16 and 21, T5N, R2E (Spearfish 7.5 minute quadrangle). This locality is approximately 13 km east of the Tinton area and is within the major area of Tertiary igneous activity in the Black Hills. The rock is associated with trachyte porphyry and phonolite porphyry intrusions along Squaw Creek, and also is probably genetically related to the intrusion of phonolites in the northern Black Hills.

The rock was observed in outcrop in several trips up Squaw Creek, samples were collected for pet-

rographic analysis, a chemical analysis was made and a norm was calculated. Microprobe analyses of the pyroxene, mica, and secondary carbonate minerals were made using a Kevex 7000 energy-dispersive unit attached to a JEOL scanning electron microscope. The composition of the groundmass feldspar was determined by X-ray.

### **Field occurrence**

The lamprophyre is exposed for a distance of about ten meters along the creek bank just above the water level. It is intruded into a Tertiary quartz-bearing trachyte porphyry sill, which is itself intruded into nearly flat-lying sandstone of the Cambrian Deadwood Formation. The lamprophyre has a very irregular contact with the sill, with apophyses of lamprophyre protruding into the trachyte. The shape of the lamprophyre body cannot be determined because of limited exposure. Exposed in the creek bottom is the top of a Tertiary phonolite porphyry sill, also intruded into the Deadwood Formation. About fifty meters upstream the phonolite porphyry cuts up across the sediments and the trachyte porphyry. Field relationships between the phonolite porphyry and the lamprophyre are not determinable.

### Petrography

In hand specimen the rock has a dark gray color with lighter gray streaks running irregularly through it. The darker portions, which represent the greater part of the rock, and hereafter referred to as the lamprophyre, are aphanitic and porphyritic with phenocrysts of pyroxene and phlogopite and ovoid pods of carbonate mineral, all mostly 1–2 mm long. The mica phenocrysts are noticeably absent in the lighter gray aphanitic portions of the rock, hereafter referred to as the leuco-phase. On the weathered surface the rock is slightly pitted and shows some iron-oxide staining.

The lamprophyre has a groundmass of alkali-feldspar microlites and acicular needles of aegirine. The feldspar has very low birefringence of 0.007; wavy extinction prevents determination of  $2V$ . It is mostly fresh, with only slight kaolinization in some samples. Acicular needles of aegirine, 0.03–0.09 mm long, are scattered in a random, felted arrangement. Apatite, in euhedral prisms 0.2–0.5 mm long, is the most abundant accessory mineral in the groundmass, with trace amounts of anhedral magnetite and shreds of phlogopite also present. Considerable amounts of fine granular carbonate are scattered throughout the groundmass and coarser carbonate replaces phenocrysts, probably representing deuteric alteration.

Groundmass feldspar was ground and X-rayed. The structural state and composition were determined by methods described by Wright and Stewart (1968) and by Wright (1968). Wright's "three-peak" method uses the  $2\theta$ ,  $\text{CuK}\alpha 1$ , values of  $\bar{2}01$ , 060 and  $\bar{2}04$  to determine the structural state. This feldspar had  $2\theta$  values of  $20.93^\circ$  for  $\bar{2}01$  and  $41.62^\circ$  for 060. The  $\bar{2}04$  reflection is broad and consists of multiple peaks between  $2\theta = 50.81^\circ$  and  $50.90^\circ$ . The 002 and  $\bar{1}13$  reflections both indicated that the  $\bar{2}04$  peak should be at  $50.70^\circ$   $2\theta$  (Wright, p. 90), which is off of its actual position. If the  $50.70^\circ$  calculated position of the  $\bar{2}04$  is used to determine the structural state (Wright, p. 91), the feldspar is orthoclase, but if the actual reflection is used, the feldspar is high sanidine. This indicates an anomalous cell structure. An anomalous structure is also indicated when unit-cell dimensions are used to determine the structural state (Wright and Stewart, 1968). Composition determination by cell volume and  $a$  (Wright and Stewart, p. 44) and by the  $\bar{2}01$  reflection (Wright, p. 93) all indicate a range of 95–100 weight percent Or, the variation depending on whether the feldspar is considered to be

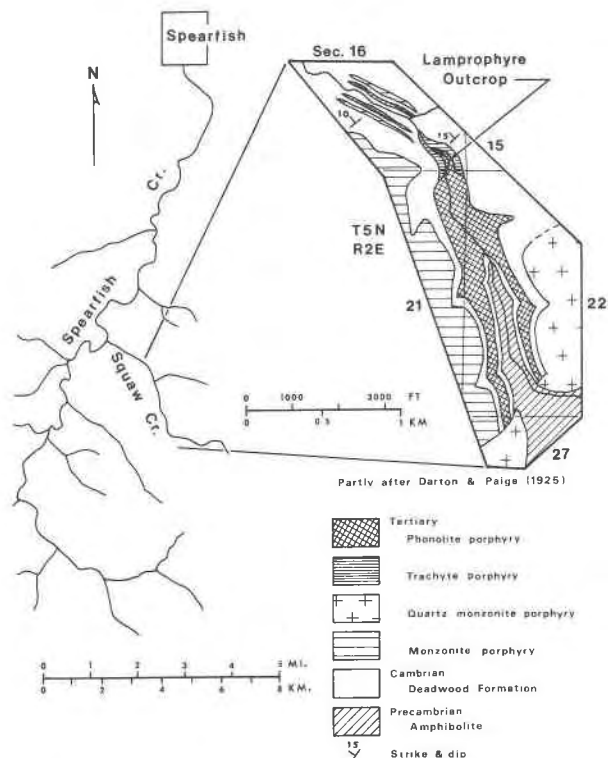


Fig. 1. Location map for Squaw Creek lamprophyre, Black Hills, South Dakota.

orthoclase or sanidine. In either case the Ab content is minimal.

Phenocrysts account for about 30 percent of the rock and consist of phlogopite, pyroxene, and pseudomorphs after olivine(?). Much of the pyroxene and all the olivine(?) have been replaced by carbonate minerals. Binocular microscopic examination of the rock while treating it with dilute HCl showed that the olivine(?) pseudomorphs reacted instantly and vigorously and the replaced pyroxene reacted only slightly and required scratching to initiate reaction.

The phenocrysts, including the carbonate replacement minerals, have been analyzed by a microprobe. Mineral compositions were determined by graphical methods in which average counts per minute for each element in known standards were plotted against weight percent and a trend line established. Silicate standards were used for silicate unknowns, and carbonate standards were used for carbonate unknowns. Weight percents were converted to relative mole percents, and the major results are plotted on FeO–MgO–CaO triangles in Figure 2. Other oxides were monitored, although only  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , BaO, MnO,

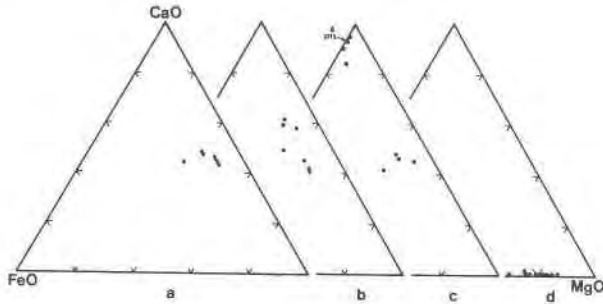


Fig. 2. Microprobe analyses of MgO, CaO, and FeO content of (a) pyroxene phenocrysts, (b) carbonate replacement of pyroxene phenocrysts, (c) carbonate pods, pseudomorphs after olivine(?), and (d) phlogopite phenocrysts. Points are plotted in molar amounts.

and  $K_2O$  were found in the samples. The combination of  $K_2O + Al_2O_3 + SiO_2$  always occurred in proportions equivalent to K-feldspar and are interpreted as parts of the groundmass. These sample points were not used in the data plots. The distribution of the other oxides is discussed below.

The pyroxene phenocrysts are light green in plane light, occurring as euhedral crystals 1–6 mm long. They have a  $\gamma\Delta c = 46^\circ$ , a birefringence of 0.026, and a  $2V$  of approximately  $52\text{--}58^\circ$ , as estimated by the Tobi (1956) method. The probe analyses (Fig. 2a) indicated only FeO, MgO, and CaO as metal oxides and a composition that places them on the borderline between diopside and salite according to the chemical classification of Poldervaart and Hess (1951, p. 474). The crystals are partially to completely replaced by optically clear ferroan dolomite with relative proportions of FeO, MgO, and CaO similar to those of the pyroxene (Fig. 2b). A small amount of BaO was found in one carbonate sample. Some microprobe analysis points within the altered areas indicated the presence of  $SiO_2$ , probably indicating residual silica or traces of secondary silicates. Some of the carbonate is clouded with a fine hematite dust that is red in reflected light.

Ovoid carbonate pods, 0.4–1.5 mm across, with magnetite-filled fractures, partially altered to hematite, appear to be pseudomorphs after olivine (Fig. 3). A euhedral crystal outline for the olivine is lacking, no doubt because of reaction and resorption, described below. Microprobe analyses reveal the presence of two carbonate minerals in the pods (Fig. 2c). The dominant mineral is a clear calcite that occasionally contains small amounts of MnO (the exact amounts were not determined). Clear ferroan dolo-

mite is the other mineral. Two of the points plotted included carbonate clouded with hematite and really represent the combination of separate phases of hematite and dolomite. Small patches of a light green secondary mineral with moderate birefringence, probably bowingite, are also present in some pods.

The carbonate pods are surrounded by multiple flakes, or in a few cases, large single flakes, of euhedral to subhedral phlogopite. These appear to have a reaction relationship with the mineral originally forming the pods, interpreted here as olivine. Single phlogopite phenocrysts not associated with the pods also occur in euhedral to subhedral crystals up to 2 mm long. In thin section the phlogopite is pleochroic from brown to very pale yellow-brown with slightly darker rims. Analyses (Fig. 2d) indicate an average molar ratio of MgO:FeO equal to 4.15:1. There is no apparent difference in the single phenocrysts compared to those grouped around the carbonate pods.

The lamprophyre also contains rounded quartz xenocrysts, 0.2–0.8 mm, some of which are polycrystalline. Some may have come from the Deadwood Formation, but the polycrystalline grains most likely came from the crystalline basement. The xenocrysts show partial to complete resorption (Fig. 4) and typically have an inner rim of dusty hematite and an outer reaction rim of radial alkali feldspar (Fig. 5). Some grains consist entirely of patchy feldspar, indicating complete resorption and replacement of the quartz. Such grains often contain a ring of dusty hematite similar to that found around the partly-resorbed quartz grains. Within these masses of feldspar the felted aegirine typically found throughout the groundmass is absent. Both the unresorbed quartz grains and those replaced by feldspar may

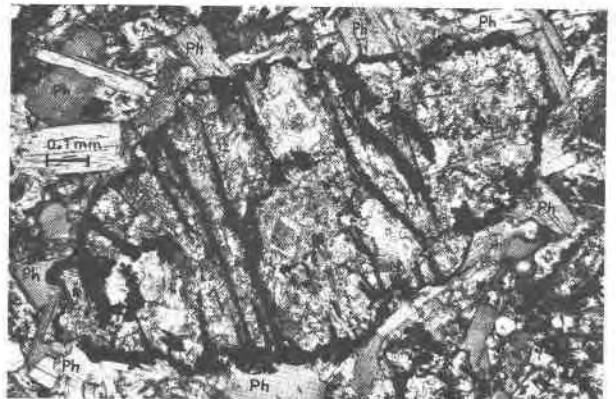


Fig. 3. Calcite pseudomorph of olivine(?) showing magnetite-filled cracks and surrounding crystals of phlogopite (Ph). Plane-polarized light.

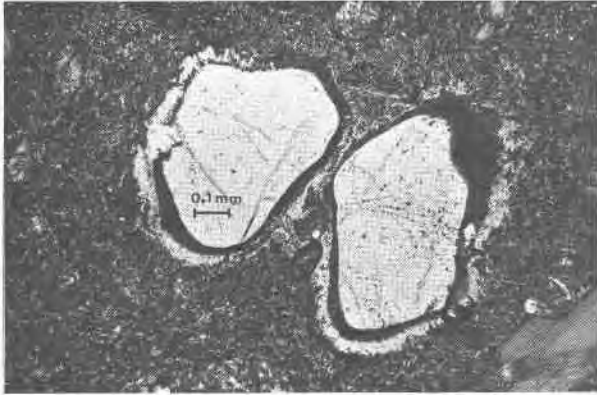


Fig. 4. Quartz xenocrysts with reaction rim of hematite (dark rim) and outer rim of alkali feldspar (light rim). Plane-polarized light.

show varying amounts of later replacement by carbonate minerals.

An average of four 1000-point counts shows the lamprophyre phase to have the following mineral percentages:

Groundmass (69.5%)	
Alkali feldspar	43.5%
Aegirine, carbonate, epidote	25.0%
Apatite	0.5%
Secondary magnetite	0.5%
Phenocrysts (30.5%)	
Phlogopite	10.4%
Pyroxene (up to 60% replaced by carbonate)	16.3%
Olivine pseudomorphs (carbonate and magnetite)	3.8%
	100.0%

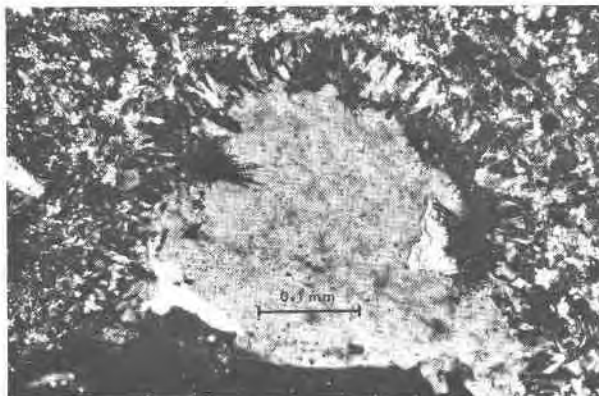


Fig. 5. Quartz xenocryst with outer rim of alkali feldspar growing perpendicular to the quartz. Some hematite (dark acicular aggregate) and secondary carbonate (bright, high relief) occur in the quartz, just inside the feldspar rim. Cross-polarized light.

The separation of groundmass aegirine from the feldspar is only approximately accurate because the diameter of the aegirine microlites was much less than the thickness of the sections, thus introducing a volume error each time an aegirine was counted.

The leuco-phase runs in irregular streaks and veins through the lamprophyre (Fig. 6). The contact between the light and dark phases appears to be gradational over a distance of several millimeters when viewed in the hand specimen, though in places it is sharp but very irregular when seen in thin section. Some phenocrysts cut across the contact.

The leuco-phase has a microcrystalline hypidiomorphic-granular groundmass of alkali feldspar, secondary epidote, and granular carbonate. Euhedral pyroxene phenocrysts, 1–2 mm long, are common in some parts, making up about 20 percent of the rock. These are completely replaced by feldspar and carbonate. The groundmass aegirine, olivine pseudomorphs, accessory apatite, and the phlogopite phenocrysts characteristic of the lamprophyre phase are noticeably absent. There is also an abundance of very fine granular pyrite and hematite within both the leuco-phase and the lamprophyre phase, particularly concentrated near the contact between the two phases. The leuco-phase is noticeably less mafic than the lamprophyre.



Fig. 6. Section showing intermixed lamprophyre (dark patches) and the leuco-phase (medium gray). Light spots are carbonate replacements.

The leuco-phase also contains quartz inclusions showing resorption as described above and inclusions of phlogopite xenocrysts, particularly near the contact with the lamprophyre phase. The phlogopite xenocrysts show effects of reaction with the magma and of deuteric replacement. These have been partly to completely replaced first by patchy alkali feldspar, with low negative relief, wavy extinction, and low birefringence. The feldspar appears optically like that which replaced the quartz xenocrysts. The phlogopites were later partly replaced by granular carbonate.

### Chemical data

A chemical analysis of the lamprophyre phase is shown in Table 1. It is low in silica and ferrous oxide, but high in magnesia, lime, and potash. The high carbon dioxide content reflects the degree of carbonate replacement of pyroxene, olivine, and some of the groundmass. A CIPW norm calculated from the chemical analysis indicates the following normative mineralogy (in weight percent):

Orthoclase	47.26%	Dolomite	18.26
Albite	9.43	Magnetite	3.25
Acmite	7.85	Ilmenite	1.98
Enstatite En 86	6.79	Apatite	1.68
Diopside	2.66	Quartz	0.24
			99.40%

The norm was calculated with a slight departure from the directions provided by Washington (1917, p. 1162-1165), because the original directions do not allow for cases in which there are more molecules of carbon dioxide than lime and in which the dominant carbonate mineral is dolomite instead of calcite. Therefore I calculated the norm by first pairing molecules of lime and magnesia with carbon dioxide to make dolomite, then using the excess lime and magnesia to make pyroxene. The normative mineralogy, as calculated in the above manner, yields a pyroxene more magnesian and less calcic than that determined by microprobe. Phlogopite is not calculated in the norm. If phlogopite could be calculated in the norm it would consume considerable magnesia. The calculated alkali-feldspar composition is Or 82.5:Ab 17.5 (mole percent).

### Discussion

According to commonly accepted terminology (Williams *et al.*, 1954, p. 85-87; Moorhouse, 1959, p. 329-330), minette lamprophyres contain biotite as

Table 1. Chemical data

	1	2	3	4
SiO <sub>2</sub>	46.69	42.95	51.17	51.13
Al <sub>2</sub> O <sub>3</sub>	10.51	12.44	13.87	14.35
Fe <sub>2</sub> O <sub>3</sub>	4.97	10.16	3.27	3.63
FeO	2.54	5.18	4.16	4.74
MgO	6.58	5.82	6.91	6.84
MnO	0.21	0.29		
CaO	7.17	13.11	6.58	7.05
Na <sub>2</sub> O	2.17	2.10	2.12	3.00
K <sub>2</sub> O	7.95	2.29	5.49	3.81
TiO <sub>2</sub>	1.02	1.34	1.36	1.44
P <sub>2</sub> O <sub>5</sub>	0.65	1.37		
CO <sub>2</sub>	8.76		1.30	0.74
H <sub>2</sub> O (total)	0.41		2.42	2.62

1. Squaw Creek lamprophyre (Anal. by Technical Service Laboratories, Toronto)
2. Augite-voogesite from the Tinton mining district (Darton and O'Harra, 1905).
3. Average of 64 minettes (Metais and Chayes, 1963).
4. Average of 30 voogesites (Metais and Chayes, 1963).

the dominant mafic mineral in a groundmass of alkali feldspar, and voegesites contain hornblende or pyroxene as the dominant mafic mineral. Plagioclase is usually also present in voegesites. Soda varieties of the above two lamprophyres also contain sodic amphibole or pyroxene. Mineralogically, the rock falls between a soda-minette and a soda-voegesite because it contains aegirine and clinopyroxene as mafic constituents characteristic of soda-voegesite, but also has feldspar and mica more typical of a minette. A comparison of the chemical composition of the Squaw Creek lamprophyre with the average compositions of several varieties of lamprophyres given by Metais and Chayes (1963) indicates that the rock most closely resembles a minette (Table 1), particularly in relation to the amount of the alkalis and lime. Both mineralogically and chemically this rock falls into the orenditic group of potassic rocks discussed by Sahama (1974, p. 96-100) and into the shoshonitic group described by Rock (1977, Table III, p. 134).

The Squaw Creek lamprophyre is only the second reported occurrence of lamprophyres associated with the Tertiary intrusions in the Black Hills. The other lamprophyres, reported by Darton and O'Harra (1905), consist of a group of augite-voegesites, augite-camptonites and augite-fourchites intruded as dikes associated with a soda-rich igneous complex sur-

rounding the Tinton mining district. A chemical comparison of one of the augite–vogesites to the Squaw Creek lamprophyre is shown in Table 1. The chemical and petrographic data indicate that the Squaw Creek lamprophyre is significantly less mafic and more potassic than those of the Tinton area.

The mineral assemblage of this rock suggests that the lamprophyre may have originated in the mantle. That pyroxene and olivine are stable mantle phases is commonly accepted. Recent experimental work has also shown that phlogopite (Yoder, 1970; Yoder and Kushiro, 1969) and carbonate minerals (Eggler, 1974; Eggler *et al.*, 1976) are stable under mantle conditions. Studies by Eggler (1974, 1975a, b) and Mysen (1975) indicate that mafic magmas originating in the lower crust or in the mantle form under sufficiently high temperatures and pressures to dissolve the quantity of CO<sub>2</sub> found in this rock analysis.

The common dichotomy of both high mafic and alkali contents in lamprophyres is often attributed either to contamination of a silicic magma by mafic materials (Moorhouse, 1959, p. 330–331) or to contamination of a mafic magma as it passed through granitic rocks. Turner and Verhoogen (1960, p. 249–250, 255–256) suggest that lamprophyres are formed from alkali-olivine basalt magma, either by differentiation or by reaction with granite or mica schist. In his comparison of different types of lamprophyres, Rock (1977, Table III, p. 135) indicates that the petrogenesis of the alkaline group is from “volatile-enriched basaltic magma,” and that the shoshonitic group is most commonly explained by “hybridization between basic magma and granitic residue or sediments.” Although the presence of quartz xenocrysts undergoing resorption suggests that some contamination of the magma did occur, the low SiO<sub>2</sub> content indicates that such contamination was minimal and insufficient to account for the high K<sub>2</sub>O content, assuming that granite or mica schist were the contaminants. Contamination of an original ultramafic or mafic magma by biotite schist is also not in evidence, because the micas show primary crystallization characteristics with no evidence of resorption. In addition, outcrops of basaltic or more mafic rocks are exceptionally rare in the Tertiary igneous complex in the Black Hills. (After nine field seasons I have seen only one basalt dike.) Darton and O’Hara (1905) suggested that the lamprophyre from the Tinton area was a differentiate of magma that produced the nepheline syenite and other igneous rocks in that area. I propose that this lamprophyre is similarly re-

lated to associated non-basaltic igneous activity in the area. The presence of aegirine in the Squaw Creek lamprophyre and the similar occurrence of aegirine in numerous trachytes and phonolites in the northern Black Hills, together with the alkaline character of these intrusions, suggests a genetic relationship between this lamprophyre and the phonolitic intrusions, perhaps through differentiation of the parent magma or by varying degrees of anatexis at the source.

My interpretation is that crystallization began at depth with the formation of olivine crystals, which were probably magnesium-rich, as indicated by the general rock chemistry and the phlogopite reaction rims surrounding the olivine. Similar reaction rims are described by Carmichael *et al.* (1974, p. 253–254) in rocks from the Leucite Hills, Wyoming. Phlogopite was the second mineral to crystallize, both by reacting with the olivine and by direct crystallization. The pyroxene phenocrysts probably began crystallizing after the phlogopite started, and the two then continued to come out simultaneously. In support of this, the pyroxene phenocrysts occasionally enclose small flakes of phlogopite, but never *vice versa*, and a few pyroxenes were observed to enclose entire olivine–pseudomorph pods with their surrounding phlogopite crystals (Fig. 7). The pyroxene and phlogopite occasionally interfere with each other’s growth. Groundmass aegirine and potash feldspar crystallized after intrusion. This sequence coincides with that determined experimentally by Luth (1967) and is similar to that observed by Němec (1973) for minettes in the Central Bohemian pluton. Similar crystallization sequences of olivine–phlogopite–pyroxene (near diopside)–sanidine in orenditic rocks from Australia, Spain, and Wyoming are discussed and summarized by Sahama (1974).

Volatile constituents were mainly CO<sub>2</sub>, which appears in the form of the carbonate minerals. It seems most likely that these carbonates represent phases formed by deuteric replacement as CO<sub>2</sub> came out of solution when the magma cooled. (Minor carbonate alteration is also observable in the adjacent trachyte.) However, the presence of two carbonate minerals suggests that they may represent two periods of formation, and one of the carbonate phases, particularly in the olivine pseudomorphs, possibly represents higher-temperature formation. Eggler (1975a) and Eggler *et al.* (1976) have shown that carbonate minerals are anticipated phases at high temperatures in olivine–pyroxene rocks in which CO<sub>2</sub> is an important



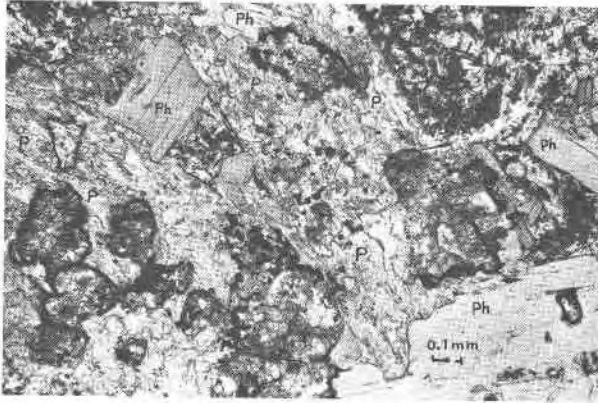


Fig. 7. Phenocrysts of pyroxene (P) with included calcite pseudomorphs of olivine(?), including some with phlogopite (Ph) reaction rims. Phlogopite and pyroxene phenocrysts have interfered with each other's growth. Plane-polarized light.

component. Water content in this magma was probably very low, with the small amount of water in the analysis present in the phlogopite. The presence of pyroxene instead of amphibole and a lack of hydrous deuteric phases support this.

The relationship of the lamprophyre to the associated leuco-phase is perplexing. The two rock types are similar in that they both contain an alkali-feldspar-rich groundmass, phenocrysts of carbonate-replaced pyroxene, and inclusions of quartz with reaction rims. They differ in that the leuco-phase lacks the phlogopite, aegirine, and carbonate pseudomorphs of olivine characteristic of the lamprophyre. The intimate physical mixing of the two rock types along with phenocrysts extending into both sides of the contact suggest that both magmas were fluid at the same time, *i.e.*, they may represent a case of magma mixing. The source of the leuco-phase magma is unknown, though it is probably another differentiate of the magma that produced the lamprophyre.

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### References

Carmichael, I. S. E., F. J. Turner and J. Verhoogen (1974) *Igneous Petrology*. McGraw-Hill, New York.  
 Darton, N. H. and C. C. O'Hara (1905) Sundance Folio. *U. S. Geol. Surv. Geologic Atlas, No. 127*.

- and S. Paige (1925) Central Black Hills Folio. *U. S. Geol. Surv. Geologic Atlas, No. 219*.  
 Egger, D. H. (1974) Effect of CO<sub>2</sub> on the melting of peridotite. *Carnegie Inst. Wash. Year Book, 73*, 215–244.  
 — (1975a) Peridotite-carbonate relations in the system CaO–MgO–SiO<sub>2</sub>–CO<sub>2</sub>. *Carnegie Inst. Wash. Year Book, 74*, 468–474.  
 — (1975b) CO<sub>2</sub> as a volatile component of the mantle: the system Mg<sub>2</sub>SiO<sub>4</sub>–SiO<sub>2</sub>–H<sub>2</sub>O–CO<sub>2</sub>. *Phys. Chem. Earth, 9*, 869–881.  
 —, I. Kushiro and J. R. Holloway (1976) Stability of carbonate minerals in a hydrous mantle. *Carnegie Inst. Wash. Year Book, 75*, 631–636.  
 Luth, W. C. (1967) Studies in the system KAlSi<sub>3</sub>O<sub>8</sub>–Mg<sub>2</sub>SiO<sub>4</sub>–SiO<sub>2</sub>–H<sub>2</sub>O: I, inferred phase relations and petrologic applications. *J. Petrol., 8*, 372–416.  
 Metais, D. and F. Chayes (1963) Varieties of lamprophyre. *Carnegie Inst. Wash. Year Book, 62*, 156–157.  
 Moorhouse, W. W. (1959) *The Study of Rocks in Thin Section*. Harper and Row, New York.  
 Mysen, B. O. (1975) Solubility of volatiles in silicate melts at high temperature: the role of carbon dioxide and water in feldspar, pyroxene and feldspathoid melts. *Carnegie Inst. Wash. Year Book, 74*, 454–468.  
 Němec, D. (1973) Differentiation series of minettes in the Central Bohemian Pluton. *J. Geol., 81*, 632–642.  
 Poldervaart, A. and H. H. Hess (1951) Pyroxenes in the crystallization of basaltic magma. *J. Geol., 59*, 472–489.  
 Rock, N. M. S. (1977) The nature and origin of lamprophyres: some definitions, distinctions and derivations. *Earth Sci. Rev., 13*, 123–169.  
 Sahama, Th. G. (1974) Potassium-rich alkaline rocks. In H. Sørensen, Ed., *The Alkaline Rocks*, p. 96–09. Wiley, New York.  
 Tobi, A. C. (1956) A chart for measurement of optic axial angles. *Am. Mineral., 41*, 516–519.  
 Turner, F. J. and J. Verhoogen (1960) *Igneous and Metamorphic Petrology*. Wiley, New York.  
 Washington, H. S. (1917) *Chemical Analyses of Igneous Rocks*. U. S. Geol. Surv. Prof. Pap. 99.  
 Welch, C. M. (1974) Preliminary report on the geology of the intrusive ring dike complex at Mineral Hill, Crook County, Wyoming (abstr.). *Geol. Soc. Am. Abstracts with Programs, 6*, 481–482.  
 Williams, H., F. J. Turner and C. M. Gilbert (1954) *Petrography, An Introduction to the Study of Rocks in Thin Section*. Freeman, San Francisco.  
 Wright, T. L. (1968) X-ray and optical study of alkali-feldspar. II. An X-ray method for determining the composition and structural state from measurements of 2-theta values for three reflections. *Am. Mineral., 53*, 88–104.  
 — and D. B. Stewart (1968) X-ray and optical study of alkali-feldspar. I. Determination of composition and structural state from refined unit-cell parameters and 2θ. *Am. Mineral., 53*, 38–87.  
 Yoder, H. S., Jr. (1970) Phlogopite–H<sub>2</sub>O–CO<sub>2</sub>: an example of the multi-component gas problem. *Carnegie Inst. Wash. Year Book, 68*, 236–240.  
 — and I. Kushiro (1969) Melting of a hydrous phase: phlogopite. *Am. J. Sci., Schairer Vol. 267A.*, 558–582.