

SAPPHIRE-BEARING ULTRAMAFIC LAMPROPHYRE FROM YOGO, MONTANA: A OUACHITITE

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ABSTRACT

The Yogo lamprophyre dyke, central Montana, is the only known igneous rock from which sapphire is mined. The rock consists of subhedral grains of phlogopite and clinopyroxene set in a finer groundmass of mica, clinopyroxene, titaniferous magnetite and apatite within a mesostasis of chlorite, calcite, serpentine and rare K-feldspar. Pyroxene also occurs as polycrystalline aggregates. Phlogopite occurs as euhedral crystals that have been distorted during emplacement and subsequently deformed and altered. The original mica appears to have been homogeneous $[Mg/(Mg + Fe) = 0.83, TiO_2 = 3.0 \text{ wt. \%}]$, and may have formed at approximately 900°C . The pyroxene, a Ti-Al diopsidic augite showing a compositional trend toward increasing Ti and Al with decreasing Si and Fe, is considered to be of low-pressure origin. Narrow irregular rims of acmite on the major pyroxene phase appear to be the result of late-stage crystallization or possibly deuteric alteration. Spinell is compositionally uniform and is in the magnesioferrite - ulvöspinell - magnetite series. Sapphire occurs as an accessory phase and is thought to be xenocrystic. Based on chemical and mineralogical evidence the Yogo lamprophyre is classified as a ouachitite.

Keywords: lamprophyre, phlogopite, pyroxene, ouachitite, sapphire, spinell, ultramafic rock, Yogo, Montana.

SOMMAIRE

Le dyke lamprophyrique de Yogo, dans la partie centrale du Montana, est la seule roche ignée d'où on exploite le saphir. Cette roche contient des grains sub-idiomorphes de phlogopite et de clinopyroxène dans une pâte plus fine de mica, clinopyroxène, magnétite titanifère et apatite, dans une matrice de chlorite, calcite, serpentine et, rarement, feldspath potassique. Le pyroxène se présente aussi sous forme d'agrégats polycristallins. Les cristaux idiomorphes de phlogopite ont été déformés pendant la mise en place, et plus tard, au cours d'une altération. Le mica original semble avoir été homogène $[Mg/(Mg + Fe) = 0.83, 3\% TiO_2]$ et aurait été formé à environ 900°C . Le pyroxène est une augite Ti-Al diopsidique qui montre un enrichissement en Ti et Al avec diminution de Si et Fe; il aurait cristallisé à basse pression. Un liseré d'acmite sur le pyroxène principal serait le résultat d'une cristallisation tardive ou peut-être même deutérique. Le spinelle est homogène, et fait partie de la série magnésioferrite - ulvöspinelle - magné-

tite. Le saphir est accessoire et probablement xénochrystique. À la lumière des données chimiques et minéralogiques, le lamprophyre de Yogo est une ouachitite.

(Traduit par la Rédaction)

Mots-clés: lamprophyre, phlogopite, pyroxène, ouachitite, saphir, spinelle, roche ultramafique, Yogo, Montana.

INTRODUCTION

The sapphire-bearing lamprophyric dyke of Yogo Gulch occurs in central Montana (Fig. 1), about 95 km southeast of Great Falls and roughly 20 km east of the Little Belt Mountains where syenites, monzonites, shonkinites and lamprophyres are common (Pirsson 1897, Weed & Pirsson 1900, Witkind 1970). The dyke belongs to the Central Montana petrographic province of predominantly alkaline rocks (Larsen 1940). The Yogo lamprophyre is unusual in that it contains gem-quality sapphire. Most gem sapphire

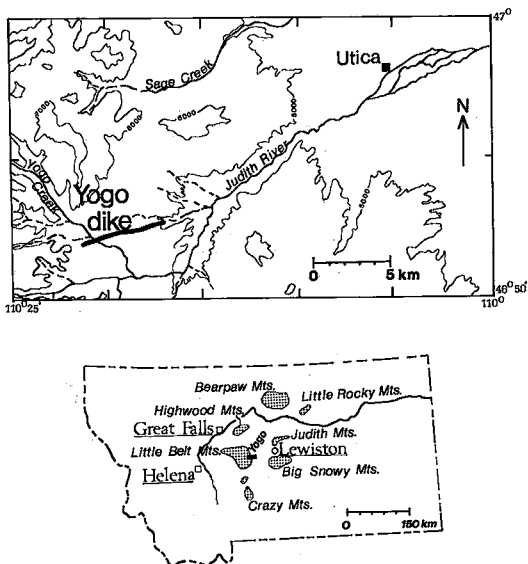


FIG. 1. Location map of the Yogo ultramafic lamprophyre (ouachitite) dyke, Montana.

in the world is recovered from alluvial deposits in which the sources of sapphire have not been clearly identified.

The Yogo dyke is vertical, varies in width between 2 to 7 m, and extends for over 6.5 km in an approximately east-west direction (Claybaugh 1952). The dyke intruded massive Mississippian limestone (Madison Fm.) and shales (Amsden Fm.) of Mississippian and Pennsylvanian age. A second dyke parallels the main dyke about 200 m to the north and reportedly (Weed & Pirsson 1900) is mineralogically similar, though devoid of sapphire.

On the basis of field evidence, the dyke is post-Carboniferous. Radiometric ages are 44 to 57 Ma, based on whole rock and on biotite and hornblende in lamprophyre sills and dykes that are roughly 30 km north and northwest, and that are associated with the Little Belt Mountains (Marvin *et al.* 1973). Although the above rocks are not petrologically similar to that at Yogo, it is suggested, in the absence of evidence to the contrary, that the Yogo lamprophyre is probably also Early Tertiary in age. The most comprehensive work on the geology, historical development, and economic aspect of the Yogo lamprophyre is by Claybaugh (1952).

The dyke was referred to by Pirsson (1897) as an

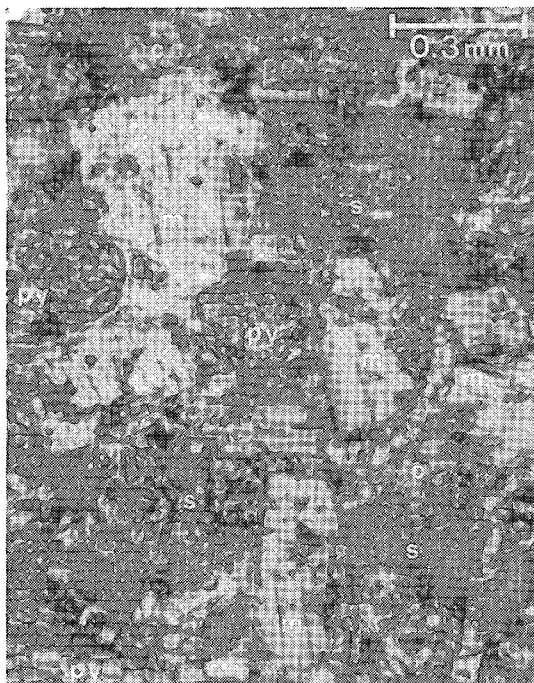


FIG. 2. Photomicrograph of Yogo ouachitite showing laths of phlogopite (m) and euhedral to subhedral clinopyroxene (py) in a matrix of calcite (c) and serpentine (s). Euhedral spinel (black) occurs randomly throughout the section.

altered basic rock allied to monchiquite; Weed & Pirsson (1900) called it an altered analcime basalt (monchiquite) and commented that, being rich in mica, it showed a relationship to minette. Although analcime was not observed, Pirsson (1897) considered it, or possibly leucite, was now indicated by an interstitial aggregate of cloudy brownish kaolinite.

Claybaugh (1952) showed that pyroxene and biotite constitute 50 and 20 modal % of the rock, respectively. The remaining 30% consists of matrix, possibly 25% analcime and 5% others, the latter of which includes apatite, magnetite, zircon, hematite, feldspar, spinel, aegirine-augite and fibrous zeolites. Calcite and dolomite, although present, were ignored as being xenolithic. Claybaugh (1952) noted that the Yogo dyke falls in the family classified by Johannsen (1938) as monchiquite and analcime basalt, but observed that the nearest mineralogical equivalent was ouachitite (Kemp 1891).

PETROGRAPHY

The dyke weathers very rapidly which, although considerably aiding the recovery of sapphires, makes petrographic studies difficult. Both this study and previous descriptions (*e.g.*, Claybaugh 1952) are based on the examination of cobbles and small boulders (<20 cm) of hard, relatively fresh rock that occur randomly throughout an otherwise soft, weathered, greenish grey material. These nodules are probably formed by spheroidal weathering and are not globular segregations (Clement & Skinner 1985).

The predominant macroscopic phase in hand specimen is a dark brown mica, 2-3 mm across. Madison limestone, occurring as xenoliths varying in size up to several cm, is abundant in parts of the dyke. In thin section, subhedral crystals of phlogopite (38%) and diopside (12%) occur in a ground-mass of titaniferous magnetite (4%) and apatite

TABLE 1. BULK COMPOSITION OF YOGO DYKE ROCK AND OTHER OUACHITITES, MONCHIQUITES AND AN ALNOITE

	1*	2	3	4	5	6
SiO ₂	38.54	36.40	36.1	42.46	41.06	27.30
TiO ₂	1.06	0.42	2.6	2.47	2.63	3.68
Al ₂ O ₃	11.73	12.94	12.8	12.04	13.20	8.95
Fe ₂ O ₃	3.33	8.27	8.4	3.19	4.39	8.87
FeO	3.58	4.59	7.7	5.34	7.16	7.01
MgO	11.30	11.44	10.4	12.40	8.88	12.34
CaO	15.60	14.46	13.0	12.14	11.15	17.18
Na ₂ O	1.00	0.97	1.6	1.21	3.25	0.38
K ₂ O	2.32	3.01	2.8	2.68	1.99	2.99
P ₂ O ₅	1.18	1.04	2.4	0.84	0.84	

1. Yogo dyke, Montana (Oslund, in Claybaugh 1952)
2. Ouachitite, Arkansas (Kemp 1891)
3. Average of 5 ouachitites (Rock 1977)
4. Monchiquite, Montana (Pirsson 1897)
5. Average of 90 monchiquites (Rock 1977)
6. Alnoite, Alno, Sweden (Blix, in Von Eckermann 1948)

* inc. Cr₂O₃ 0.10 wt.%; MnO 0.14 wt.%.

(<1%), plus a mesostasis (approx. 45%) of chlorite, serpentine, calcite, and very rare minute areas of potassium feldspar. Pyroxene also occurs as polycrystalline aggregates.

The phlogopite occurs as euhedral to subhedral distorted and fragmented crystals up to 0.5 mm in size. Smaller subhedral laths and equidimensional plates are present in the groundmass and are, in part, fragments of the larger crystals. Clinopyroxene, which forms the largest crystals in the rock, is up to 1.5 mm in length and commonly is euhedral. Smaller (0.3 mm) subhedral grains occur in the groundmass. The mica and pyroxene constitute the major portion (~50%) of the rock; the remainder (~45%) consists of a matrix in which calcite, serpentine and minor chlorite occur. Within this matrix, or groundmass, small (<0.05 mm) euhedral spinel, apatite, very rare K-feldspar, and minor small grains of acmite are to be found. Some of the acmite is present as thin discontinuous rims on pyroxene. Rarely does spinel occur enclosed within phlogopite or pyroxene (Fig. 2). No analcime was observed.

ROCK CHEMISTRY

Oslund (in Claybaugh 1952) provides a bulk chemical analysis of the Yogo dyke rock (Table 1). The closest comparable data are for a ouachitite dyke from Arkansas (Kemp 1891), as well as an average of five ouachitites cited in Rock (1977), which presumably includes Kemp's data. The major differences are in the iron oxide contents, which are generally lower in Yogo than in the other ouachitite specimens. For comparison, data for a monchiquite (Pirsson, in Weed & Pirsson 1896, p. 135) from Castle Mountain, Montana, and the average of 90 mon-

chiquite analyses from worldwide localities (Rock 1977) are listed in Table 1, as are also data for an alnöite (Von Eckermann 1948).

COMPARATIVE MINERAL CHEMISTRY

Clinopyroxene

The cores of the larger grains are predominantly diopsidic (Table 2), whereas the rims and small grains are richer in FeO, Al and Ti (Figs. 3,4). All pyroxenes contain small and variable amounts of Na (Fig. 4). Representative compositions are presented in Table 2. Na₂O, and to a lesser extent Cr₂O₃, display a slight decrease from core to rim. The most highly evolved pyroxene that was analyzed in the Yogo dyke contains 2.7 and 9 wt.% of TiO₂ and Al₂O₃, respectively, and has a high FeO content (7 wt.%).

The general moderate increase in Ti, and greater increase in ^{IV}Al (Fig. 5a) represent a trend of increasing CaTiAl₂O₆ and CaAlSiAlO₆ (CaTs) as crystallization proceeded. However, the deviation of the data from the 1Ti:2Al line suggests that the Ca-Tschermaks component is more prominent than CaTiAl₂O₆. This trend has been noted previously in experimental studies of the system Di-CaTs-Tp (Akasaka & Onuma 1980, Onuma & Kimura 1978).

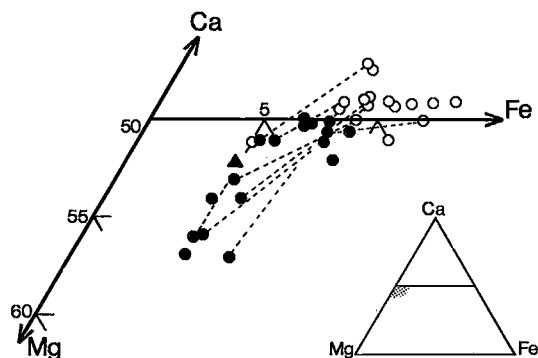


FIG. 3. Compositions in terms of Ca-Mg-Fe of clinopyroxene from the Yogo ouachitite. Solid black symbols represent cores of pyroxene, whereas open circles are rims of pyroxene where joined by dashed lines to cores. Open circles without dashed lines represent small pyroxene grains in the groundmass. The solid triangle represents compositions from an aggregate of pyroxene crystals.

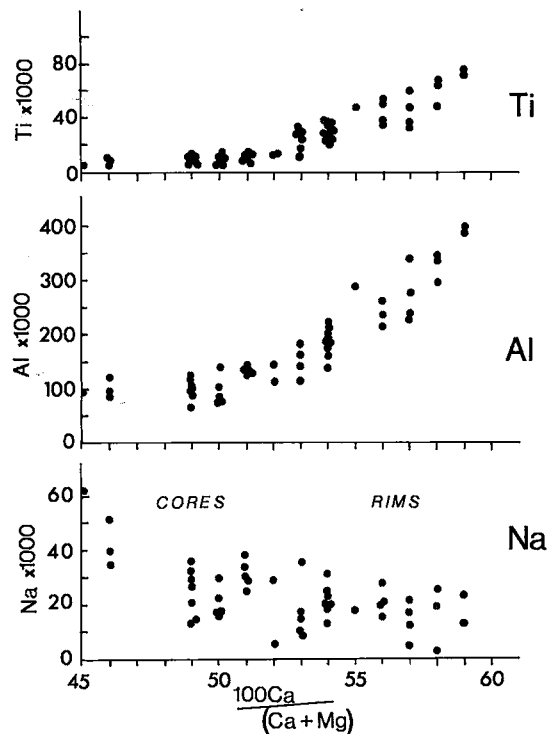


FIG. 4. Compositional data for pyroxene from the Yogo dyke shown as Ti, Al and Na (atomic %) versus Ca/(Ca+Mg).

TABLE 2. COMPOSITION OF PYROXENE, YOGO DYKE, MONTANA

	Large grains						Small grains		Acmite
	Core - Rim		Core - Rim		Core	Core	Core	Core	
	Core	Rim	Core	Rim					
SiO ₂	53.4	53.4	47.4	53.7	47.6	46.2	48.2	52.6	
TiO ₂	0.27	0.30	1.75	0.24	1.39	1.63	1.38	2.66	
Al ₂ O ₃	1.84	2.04	6.46	2.86	5.39	6.55	4.86	0.37	
Cr ₂ O ₃	0.65	0.89	0.58	0.54	0.04	0.86	0.00	0.07	
FeO	2.78	3.55	5.39	3.29	5.81	5.29	6.21	25.2	
MgO	17.6	17.2	13.9	17.7	13.9	14.0	14.3	0.37	
CaO	23.6	22.8	24.6	21.5	25.1	24.2	24.6	3.04	
MnO	0.09	0.16	0.00	0.09	0.04	0.14	0.14	0.78	
NiO	0.05	0.00	0.00	0.01	0.00	0.08	0.00	0.00	
NiO	0.19	0.53	0.30	0.75	0.19	0.27	0.31	12.0	
K ₂ O	-	0.00	0.02	0.00	0.01	0.00	0.00	0.05	
Total	100.5	100.9	100.4	100.7	99.5	99.2	100.0	97.1	
							Fe ₂ O ₃	23.2	
							FeO	4.3	
								39.4	

In natural pyroxenes from alkaline rocks similar Al and Ti enrichment trends have been reported, for example, Magonthier & Velde (1976), Lowder (1973), Best & Brimhall (1974), Tracy & Robinson (1977).

Wass (1979) noted that in alkali basalts in eastern Australia and in the Massif Central, France, the low-pressure pyroxene generally exhibits small values of ^{VI}Al/^{IV}Al. This is a feature of the Yogo dyke-rock (Fig. 5b). Furthermore, Wass noted that the low-pressure pyroxene is richer in (Al + Ti) and poorer in Si than cognate high-pressure phases. In the Yogo dyke, the pyroxene follows a similar trend, and none of the compositions is comparable with any of the high-pressure pyroxene noted by Wass. In view of the continuum of compositions at Yogo, the clinopyroxene probably defines a differentiation trend, all compositions being products of relatively low-pressure crystallization.

As noted above, the overall trend at Yogo is from a Mg-rich (diopside) composition toward hedenber-

gite, accompanied by a slight decrease in Na (acmite), and a marked increase in Al and Ti (Figs. 3,4,5). The trend toward a slight decrease in Na as Al increases (Fig. 4) is somewhat different from that of clinopyroxene in alkaline rocks from Tenerife (Scott 1976), and Shonkin Sag (Nash & Wilkinson 1970), in which Na continuously increases as crystallization proceeds, as shown by the increasing acmite contents. At Yogo, acmite is present (Table 2, Anal. 8) as a rare discontinuous margin to some of the clinopyroxene grains. In view of the large compositional gap between acmite and the main diopside-hedenbergite series, plus the textural relationship, acmite in the Yogo rocks is thought to be of late-stage origin. The overall trend observed in pyroxene, albeit very restricted at Yogo, is common to many alkaline rocks, for example, South Qoroq (Stephenson 1972), Nandewar (Abbott 1969) and early stages of crystallization at Fen (Mitchell 1980).

Mica

Mica in the Yogo dyke is phlogopitic (Table 3); although generally homogeneous, alteration to chlorite has occurred at the margins of the grains. The phlogopite has a restricted range of Mg/(Mg + Fe), between 0.80 and 0.85, as well as limited ranges of Ti (2.2 to 4.0 wt. % TiO₂), Al (15.0 to 16.8 wt. % Al₂O₃) and total iron (6.8 to 8.2 wt. % FeO) (Figs. 6a,b). Cr₂O₃ contents are less than 0.1 wt. %.

The phlogopite in the Yogo dyke falls in the general range of Al₂O₃, TiO₂, FeO, and Mg/(Mg + Fe) of micas from lamprophyres, including calc-alkaline lamprophyres (e.g., minettes, vogesites; Streckeisen 1979, Rock 1984) and melilitic lamprophyres (e.g., alnöites, polzenites). Comparative data for mica from alkaline lamprophyres (e.g.,

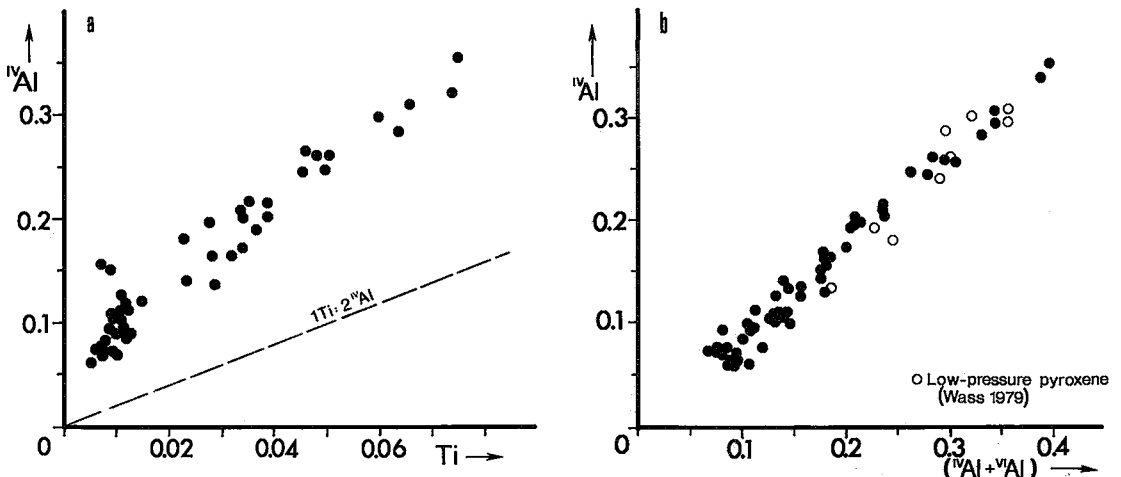


FIG. 5. Compositional data of pyroxene in the Yogo ouachtitite; a. ^{IV}Al versus Ti; b. ^{IV}Al versus (^{IV}Al + ^{VI}Al). Low-pressure clinopyroxene (Wass 1979) is shown for comparison.

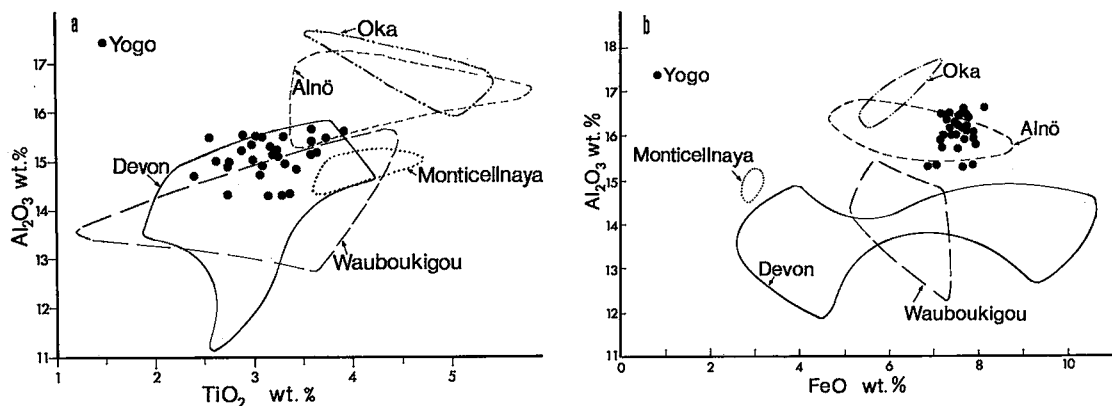


FIG. 6. Compositions of mica from the Yogo ouachitite shown in terms of (a): Al_2O_3 wt.% versus TiO_2 wt.%, and (b): Al_2O_3 wt.% versus FeO wt.%. Fields for mica from alnöitic rocks in Oka, Canada; Alnö, Sweden; Monticellnaya, Siberia, and Wauboukigou, southern Illinois are from Mitchell (unpubl. data); data for mica from minettes in Devon, England (Jones & Smith 1985) are shown for comparison.

monchiquites, camptonites) are scarce, as are data for most lamprophyres (e.g., Rock 1986).

The Yogo phlogopite does not have a unique chemical signature: various element (or oxide) contents resemble those of phlogopite from several types of lamprophyres, including alnöite. For example, in Figure 6a in terms of Al_2O_3 and TiO_2 , the mica from Yogo is similar to the Al-rich mica that occurs in minettes from Devon (Jones & Smith 1985), and also lies in part of the field outlined for mica from the Wauboukigou alnöitic province of western Kentucky and southern Illinois (R.D. Lewis & R.H. Mitchell, unpubl. data). In contrast, if plotted in

terms of Al_2O_3 and total iron as FeO (Fig. 6b), the Yogo mica compositions fall within a limited portion of the field for micas in an alnöite from Alnö, but outside the Wauboukigou alnöitic field.

Hansen (1980) utilized the results of an experimental study of the solubility of Ti in iron-free phlogopite solid solutions (Robert 1976) to determine that phlogopite in lamprophyric rocks from Greenland formed at 1000°C . Based on Al-Ti-(Mg + Fe) relationships (Fig. 7), the Yogo phlogopite may have crystallized at about 900°C .

In Figure 7 the Yogo phlogopite compositions lie close to the join $\text{K}_2\text{Mg}_6\text{Si}_6\text{Al}_2 - \text{K}_2\text{Mg}_5\text{TiSi}_4\text{Al}_4$,

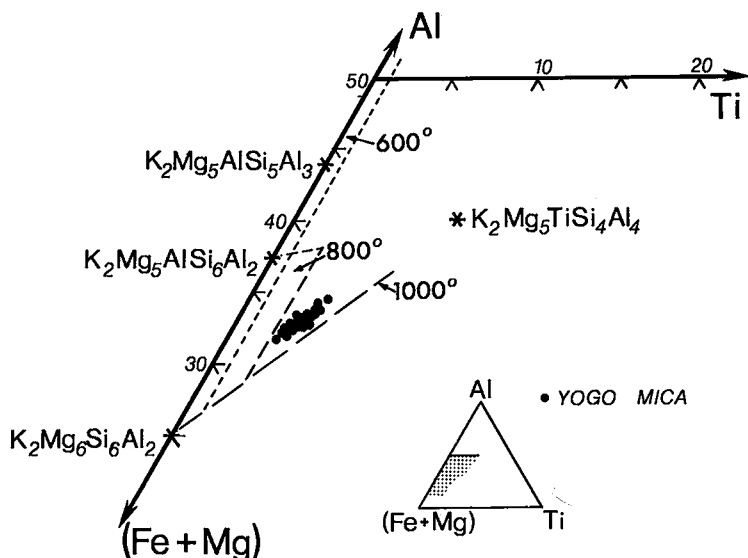


FIG. 7. Compositions of mica from the Yogo dyke plotted in terms of Al-Ti-(Mg+Fe) after Hansen (1980) and modified from Robert (1976).

TABLE 3. REPRESENTATIVE COMPOSITION OF PHLOGOPITE AND CHLORITE, YOGO DYKE, MONTANA

	Phlogopite				Chlorite
SiO ₂	36.1	34.8	36.2	34.8	33.8
TiO ₂	3.11	3.43	2.84	3.41	2.14
Al ₂ O ₃	16.5	16.1	16.5	16.4	17.3
Cr ₂ O ₃	0.07	0.00	0.00	0.02	0.00
FeO	7.60	7.89	7.27	7.78	7.05
MgO	21.6	19.4	21.9	20.4	24.9
CaO	0.45	0.12	0.66	0.23	0.51
MnO	0.08	0.07	0.07	0.07	0.27
NiO	0.06	0.04	0.04	0.00	0.00
Na ₂ O	0.34	0.41	0.19	0.32	0.02
K ₂ O	5.46	8.00	4.75	6.49	0.34
Total	91.4	90.3	90.4	89.9	(86.4)

which suggest that a scheme of substitution of the form $[^{VI}Mg(Fe), 2^{IV}Si] \rightleftharpoons [^{VI}Ti, 2^{IV}Al]$ may be important (Robert 1976).

Spinel

Spinel grains in the Yogo dyke are generally small and many show considerable resorption. They occur both in the groundmass and enclosed in mica and in pyroxene, all of which are usually chemically similar. All the spinel grains analyzed are titaniferous magnetite; they contain between 5.3 and 7.8 wt. % TiO₂, 1.5 and 6.6 wt. % MgO, 2 and 6 wt. % Al₂O₃, and less than 1.3 wt. % Cr₂O₃. Mn contents range between 0.6 and 1.4 wt. % MnO (Table 4). Apart from a minor increase in Fe toward the edge of some grains, the spinel is generally homogeneous. Very

rare occurrences of almost pure magnetite occur in the groundmass.

The limited compositional range of the spinel is illustrated in Figure 8, which is a modified spinel prism that takes into account the very low contents of Al and Cr by accommodating them in the magnesian and iron end-members. The general trend is from Mg to Fe enrichment, albeit at fairly constant values of Ti.

Data on spinel from other lamprophyres are virtually non-existent; hence it is not possible to make a comparison. Meyer & Villar (1984) provided analytical data for spinel from an alnöitic-type body in Argentina. Although also titaniferous magnetite in composition, these grains contain less Al and Cr than those from Yogo. Spinel compositions in the alnöite from Malaita, Solomon Islands (Nixon *et al.* 1980) are somewhat comparable in their Mg, Al and Cr contents, but are higher in Ti. Mitchell (1980) noted that a decrease in Ti is accompanied by an increase in Fe/(Fe + Mg) within the ulvöspinel-magnetite range in lamprophyric and alnöitic spinel from Fen, Norway and Ile Bizard, Quebec. The increasing Fe/(Fe + Mg) is apparent in Yogo spinel, but not the decrease in Ti.

DISCUSSION

On the basis of modal mineralogy, the Yogo dyke may be considered to be either a ouachitite or a minette. The absence of monticellite and melilite indicates that the dyke has no affinity with alnöitic rocks (*sensu lato*). In terms of bulk composition, the rock closely resembles ouachitite (Table 1). Although potassium feldspar is present as a rare constituent (Table 5), the rock is not sufficiently potassic to be considered a minette.

Kemp (1891) proposed the term *ouachitite* for basic lamprophyre dykes from Arkansas. The dykes occur over a wide area and may be spatially associated with the Magnet Cove carbonatite, as well as local syenitic intrusive bodies. Most dykes contain abundant pyroxene, mica and "... magnetite with smaller amounts of a colorless, isotropic substance or glass" (Kemp 1891). Apatite is common in all occurrences of ouachitite examined by Kemp, who also commented on the presence of two generations of pyroxene.

Following Kemp's (1891) original definition for ouachitite, it is apparent that the Yogo dyke-rock is comparable to it both chemically and mineralogically. The major difference seems to be textural. The originally described Arkansas ouachitites contain very large phenocrysts of pyroxene (15 to 22 mm) and mica (25 mm), whereas similar minerals at Yogo are generally smaller (*e.g.*, pyroxene 1.5 mm, mica 0.5 mm). The groundmass at Yogo consists mostly

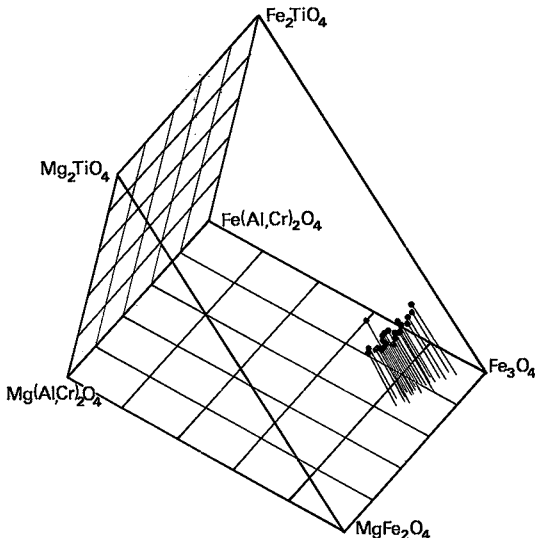


FIG. 8. Titaniferous magnetite from the Yogo ultramafic lamprophyre (ouachitite) plotted in a modified spinel compositional prism.

of chlorite and serpentine alteration products. Although nepheline was occasionally observed by Kemp (1891) in the Arkansas samples, none was observed in the Yogo material.

Some of the Arkansas ouachitites contain altered olivine. Kemp recognized that with an increase in olivine such rocks were transitional to true monchiquite. Rock (1977) suggested that ouachitites are chemically more closely allied with alnöites than monchiquites, but admitted that data are sparse. Recently, Rock (1986) suggested retaining the term ouachitite and that this rock, together with alnöite, be included as part of the group of ultramafic lamprophyres.

The Yogo dyke, and presumably the mineralogically similar adjacent dyke, are the only known examples of ouachitites in the Little Belt Mountains. However, minettes, monchiquites, kersantites, and vogesites have been recognized in the area (Weed & Pirsson 1900). Witkind (1970) presented evidence that some dykes that had been referred to as kersantites are composite dykes, in which the margin consists of kersantite and the interior of granophyre (quartz + K-spar) in one case, and a granite porphyry in another. Witkind suggested that the kersantite margin represents the lighter fraction of a differentiated alkaline magma having the composition of shonkinite. However, the Yogo ouachitite is much more basic than the kersantite and is chemically akin to nephelinite, except that K exceeds Na, which is the reverse of nephelinites in general.

Based on the mineral chemistry of the pyroxene, especially the $^{VI}Al/^{IV}Al$ and Al-Ti-Si relationships (Wass 1979), the rock probably formed at low pressures. The phlogopite chemistry suggests crystallization at approximately 900°C (Robert 1976, Hansen 1980).

The mineral that makes the Yogo ouachitite unique is corundum (var. sapphire: Table 5). Within the Yogo dyke the sapphire is randomly distributed. However, Claybaugh (p. 18) noted that when observed *in situ*, the sapphire is invariably coated with a thin layer of a fine aggregate of dark green spinel. This feature and the etched, pitted, and rounded nature of the surfaces of the sapphires was thought to indicate reaction between sapphire and the magma that produced the host rock. Presumably, therefore, the sapphire at Yogo is xenocrystic and is an accidental inclusion in the ouachitite from some unknown source within the basement succession. However, corundum apparently can coexist with titanian phlogopite because Robert (1976) noted the occurrence of corundum + rutile with titanian phlogopite in the products of experimental studies of the Ti solubility in phlogopite solid solutions. Unfortunately, these experimental results are not directly applicable because of the presence of Fe in the Yogo phlogopite.

TABLE 4. COMPOSITION OF SPINEL IN THE YOGO DYKE, MONTANA

	1	2	3	4	5	6	7	8
TiO ₂	6.76	6.32	5.91	6.03	6.97	5.68	6.13	6.41
Al ₂ O ₃	2.71	4.16	4.22	4.40	3.00	5.53	5.40	4.33
Cr ₂ O ₃	1.10	1.18	0.71	1.32	0.16	0.26	0.13	0.86
FeO	79.1	77.2	78.2	78.0	81.1	76.2	78.6	77.8
MgO	3.36	3.06	2.79	3.72	2.22	5.43	4.03	4.22
CaO	0.10	0.40	0.29	-	-	-	-	-
MnO	1.04	1.18	1.28	1.13	1.23	0.84	1.07	1.01
Total	94.2	93.5	93.4	94.6	94.7	93.9	95.4	94.6
Fe ₂ O ₃ *	52.8	51.6	52.5	52.7	53.0	53.7	53.4	52.9
FeO	31.6	30.8	31.0	30.5	33.4	27.9	30.6	30.2
	99.5	98.7	98.7	99.8	100.0	99.3	100.8	99.9

* Fe₂O₃ calculated on the basis of 3 total cations, 4 oxygen atoms.

TABLE 5. COMPOSITION OF SAPPHIRE AND K-FELDSPAR FROM THE YOGO DYKE, MONTANA

	Sapphire	K-feldspar
SiO ₂	0.12	65.2
TiO ₂	0.05	0.04
Al ₂ O ₃	98.6	16.9
Cr ₂ O ₃	0.04	-
FeO	0.50	0.71
MgO	0.03	0.05
CaO	0.00	0.07
MnO	0.01	0.01
NiO	0.00	0.00
Na ₂ O	0.00	0.28
K ₂ O	0.00	15.0
Total	99.4	98.3

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