

Chayesite, $K(\text{Mg}, \text{Fe}^{2+})_4\text{Fe}^{3+}[\text{Si}_{12}\text{O}_{30}]$: A new rock-forming silicate mineral of the osumilite group from the Moon Canyon (Utah) lamproite

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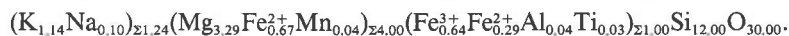
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ABSTRACT

Microprobe analyses (mean of 10 grains) of chayesite gave $\text{SiO}_2 = 69.19$, $\text{TiO}_2 = 0.25$, $\text{Al}_2\text{O}_3 = 0.20$, $\text{Fe}_2\text{O}_3 = 4.88$, $\text{FeO} = 6.60$, $\text{MnO} = 0.29$, $\text{MgO} = 12.71$, $\text{Na}_2\text{O} = 0.31$, $\text{K}_2\text{O} = 5.17$, total = 99.60 wt%, leading to the formula (based on $\text{O} = 30$, with Fe valences partitioned to give $\text{Si} + \text{Al} + \text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mg} + \text{Mn} + \text{Ti} = 17$)



The idealized end-member is $\text{K}(\text{Mg}, \text{Fe}^{2+})_4\text{Fe}^{3+}[\text{Si}_{12}\text{O}_{30}]$, which (with $\text{Mg}:\text{Fe}^{2+}:\text{Fe}^{3+} = 3.32:0.99:0.69$) requires SiO_2 69.15, Fe_2O_3 5.28, FeO 6.82, MgO 12.83, K_2O 5.92, total 100.00 wt%.

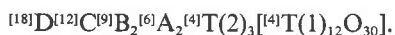
X-ray powder data prove chayesite to be a member of the osumilite group. It is related to roedderite, $(\text{Na}, \text{K})_2(\text{Mg}, \text{Fe})_5[\text{Si}_{12}\text{O}_{30}]$, by the substitution $\text{Fe}^{3+} + \square = \text{Fe}^{2+} + (\text{Na}, \text{K})$. The strongest powder lines are 7.14 (st) 002, 5.08 (vst) 110, 3.75 (vst) 202, 3.24 (vst) 121, 2.782 (st) 204. Chayesite is hexagonal, probably $P6/mcc$ (by analogy with the osumilite group) with $a = 10.153(4)$ Å, $c = 14.388(6)$ Å, $V = 1284.4$ Å³, $Z = 2$.

Chayesite occurs microscopically as a late-crystallizing phase in a lamproite at Moon Canyon, Utah, U.S.A. The crystals are deep blue, transparent, and tabular; their streak is white, and their luster is vitreous. They show no cleavage. $D_{\text{calc}} = 2.68$ g/cm³. Uniaxial positive with $\omega = 1.575(1)$ (O , sky blue) and $\epsilon = 1.578(1)$ (E , colorless). There is probably a second occurrence in a lamproite from Cancarix, Spain.

The name is for Dr. Felix Chayes, Geophysical Laboratory, Washington, D.C., U.S.A. Type material is deposited in the Institut für Mineralogie, Ruhr-Universität Bochum, F.R.G., and in the National Museum of Natural History (Smithsonian Institution), Washington, D.C., U.S.A., number NMNH 165807.

INTRODUCTION AND OCCURRENCE

The osumilite-group minerals form a constantly growing family of double-ring silicates with a milarite-type structure. Six-membered double rings are linked by R^{2+} octahedra and by distorted tetrahedra. A review of milarite-type minerals was published by Forbes et al. (1972), who gave their general formula as



This crystal-chemical formula allows for the incorporation of cations with very different sizes and leads to an enormous chemical variability and complexity. Besides

the common elements Na, K, Mg, Fe^{2+} , Fe^{3+} , and Al mostly present in members of the osumilite group, the milarite-type minerals as a whole may also contain other element such as Li, Be, B, Ba, Sn, and Zr, as well as water.

The present publication deals with the description of chayesite, a new member of the osumilite-group that has been found as a rock-forming mineral in a lamproite from Utah and probably also in a lamproite from Cancarix, Spain. It has the idealized formula $\text{K}(\text{Mg}, \text{Fe}^{2+})_4\text{Fe}^{3+}[\text{Si}_{12}\text{O}_{30}]$ and is related to roedderite, $(\text{Na}, \text{K})_2(\text{Mg}, \text{Fe}^{2+})_5[\text{Si}_{12}\text{O}_{30}]$, by the substitution $\text{Fe}^{3+} + \square = \text{Fe}^{2+} + (\text{Na}, \text{K})$. Thus it contains only one alkali atom per formula unit like osumilite itself, which has a composition near $\text{K}(\text{Mg}, \text{Fe}^{2+})_2\text{Al}_3[\text{Al}_2\text{Si}_{10}\text{O}_{30}]$.

Within the osumilite group, a chemical distinction is made by Bunch and Fuchs (1969) between the Al-rich osumilite-yagiite subgroup and the Al-poor merrihueite-roedderite subgroup, the latter being defined by an atomic ratio $\text{Si}/\text{Al} > 7$. Chayesite thus belongs to the merrihueite-roedderite subgroup.

Chayesite has been found in lamproite specimen MC7, originally described from Moon Canyon, east of Francis, Summit County, Utah, by Best et al. (1968). It is present in all thin sections cut from this specimen but has not been found in other samples collected from the same outcrop.

Unlike roedderite, which in terrestrial occurrences is restricted to melt-coated cavities in gneiss xenoliths in volcanic rocks (Hentschel et al., 1980), chayesite is part of the igneous mineral assemblage and apparently crystallized as a late phase from the lamproite liquid. A mineralogical description of the Moon Canyon lamproite already mentioning the new phase was given by Wagner and Velde (1986, p. 27–28).

The name has been given in honor of Dr. Felix Chayes, a petrologist formerly on the staff of the Geophysical Laboratory of the Carnegie Institution of Washington and past-president of the Mineralogical Society of America. Dr. Chayes showed deep interest in the mineralogy of alkaline rocks before creating a new discipline, statistical petrology. The name and mineral have been approved by the International Mineralogical Association.

Type material has been deposited in the collections of the Institut für Mineralogie, Ruhr-Universität, Bochum, F.R.G., as well as in the Museum of Natural History (Smithsonian Institution), Washington, D.C., U.S.A., number NMNH 165807.

CHEMICAL COMPOSITION

Table 1 gives selected electron-microprobe analyses covering the range of chemical composition of chayesite from the Moon Canyon sample, together with some analyses of terrestrial roedderite from the literature. Analyses were performed with an automated CAMEBAX electron microprobe at the Laboratoire de Pétrologie Minéralogique, Paris. Experimental conditions were the following: acceleration voltage, 15 kV; current intensity, 10 nA; counting time, 30 s; standards were oxides or natural minerals. No elements with atomic number >9 , other than those listed, were detected. An ion-microprobe analysis showed a very small amount of Li, but not enough to be considered a significant constituent of the mineral. The $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios were calculated by assuming full occupancy for all tetrahedral and octahedral sites, bringing this cation sum without the alkalis to $\Sigma = 17.0$ and charge-balancing the total cations including the alkalis against 30 oxygens.

It should be emphasized here that a recalculation of the structural formulae of chayesite with the assumption that all Fe is present as FeO leads to impossibly high Si values per formula unit (up to 12.18) and to sums of tetrahedral plus octahedral cations far above 17.00, which cannot be accommodated in the structure of a double-

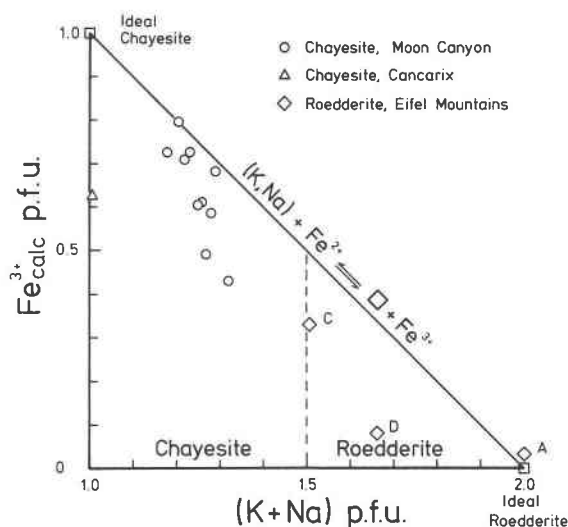


Fig. 1. Plot of calculated Fe^{3+} contents of chayesite (this study) and selected roedderite from the literature versus alkali contents analyzed. For method of calculation, see text. Solid line indicates the substitution from ideal chayesite to ideal roedderite end-members. Dashed line separates the chayesite and roedderite solid solution fields as defined by the alkali values.

ring silicate. If the method of calculating the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios as outlined above is used, however, the Si values per formula unit of Table 1 show only a small scatter around 12.00. For values below 12.00, some Al can be used to complete the tetrahedral T(1) sites to the ideal occupancy (analyses 1–3 of Table 1). Only analysis 4 shows a somewhat larger deviation from the theoretical Si maximum of 12.00. The generally excellent fit of the tetrahedral and octahedral occupancies is considered indirect support for the calculations as well as for the presence of a considerable amount of Fe^{3+} . The presence of Fe^{3+} is also in agreement with the deep blue color of chayesite, because Goldman and Rossman (1978) have already interpreted the very similar blue color of most osumilites as being due to Fe^{2+} - Fe^{3+} charge transfer.

It can also be seen from the empirical chayesite formulae of Table 1 that the excess of the alkali sums ($\text{K} + \text{Na}$) over 1.00—that is, over that of the idealized chayesite formula $\text{K}(\text{Mg}, \text{Fe}^{2+})_4 \text{Fe}^{3+} [\text{Si}_{12} \text{O}_{30}]$ —is charge-balanced by a numerically similar deficiency of Fe^{3+} against 1.0. The data are plotted for a total of 10 chayesite analyses in Figure 1 and provide good evidence for the cation substitution $\text{Fe}^{3+} + \square = \text{Fe}^{2+} + (\text{Na}, \text{K})$, which relates the idealized chayesite end-member given above to roedderite, $(\text{Na}, \text{K})_2 (\text{Mg}, \text{Fe}^{2+})_5 [\text{Si}_{12} \text{O}_{30}]$. Analysis A of Table 1 and Figure 1 represents a terrestrial example of roedderite (Hentschel et al., 1980) recalculated according to the method used in the present paper.

The substitutional mechanism $\text{Fe}^{3+} + \square = \text{Fe}^{2+} + \text{Na}^+$, which leaves a vacancy in one of the alkali sites, has already been suspected by Hentschel et al. (1980) as well as by Abraham et al. (1983) in analytical studies of blue

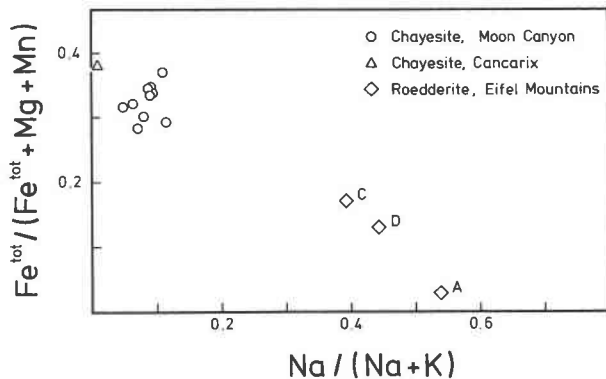


Fig. 2. $Fe_{tot}/(Fe_{tot} + Mg + Mn)$ versus $Na/(Na + K)$ plot showing negative correlation for the chayesite and roedderite analyses of Fig. 1.

roedderite crystals from the Eifel, Germany, in order to explain their observed alkali deficiencies. The microprobe analyses of these crystals are also included in Table 1 and Figure 1, as C and D, respectively, after recalculation according to the above scheme. Figure 1 shows quite impressively that there may be a complete solid solution between roedderite and chayesite. Thus roedderites D and C have some 25 and 40 mol% of chayesite component, respectively, in solid solution, and the Moon Canyon chayesite crystals are not of ideal end-member composition, but contain up to about 40% of the roedderite end-member. The systematic deviations of the analyses plotted in Figure 1 from the ideal solid-solution line can probably be explained by very small analytical errors in the microprobe analyses, because—except for the alkalis—all the elements determined, and even the presence of trace elements not analyzed so far, contribute to errors in the calculated Fe^{3+} values.

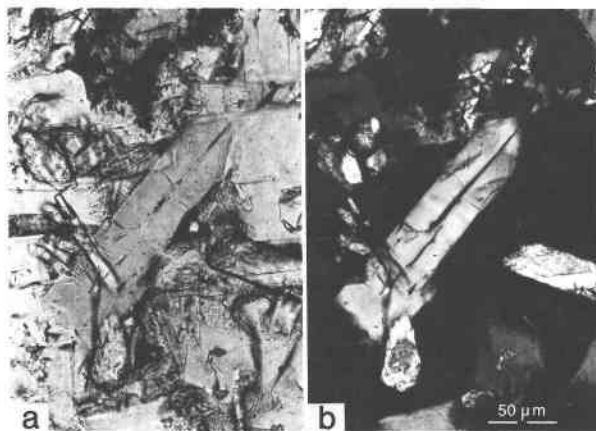


Fig. 3. Tabular, euhedral chayesite crystal coexisting with K-feldspar in the groundmass of Moon Canyon, Utah, lamproite, sample MC7. (a) Plane-polarized light. (b) Crossed Nicols.

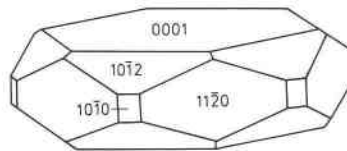


Fig. 4. Idealized sketch of chayesite morphology (compare Fig. 3).

It is interesting to note in this connection that the substitution $Fe^{3+} + \square = Fe^{2+} + Na^+$ linking chayesite and roedderite was also shown to occur in osumilite itself, where it is responsible for alkali deficiencies below 1.00 per formula unit (Schreyer et al., 1983).

As the new mineral chayesite contains Fe^{3+} as an essential component, minimum amounts of Fe are present in the solid-solution series from roedderite to chayesite, increasing from zero for pure roedderite to one Fe^{3+} per formula unit for the chayesite end-member (see Fig. 1). Figure 2 actually indicates that the degree of chayesite substitution is correlated with the total Fe content of the crystals. Table 1 shows that there is always an excess of total Fe over the required amount, so that significant amounts of Fe^{2+} are present as well. Figure 2 also confirms that it is mainly Na—rather than K—that varies in the roedderite to chayesite series.

PHYSICAL PROPERTIES

In the Moon Canyon sample studied, chayesite forms very small (mostly less than 50 μm , rarely up to more than 100 μm) euhedral to subhedral crystals (Fig. 3). Even in thin section, the mineral exhibits a decidedly blue color. The habit is tabular with the dominant faces $\{0001\}$, $\{10\bar{1}0\}$, $\{11\bar{2}0\}$, and $\{10\bar{1}2\}$, which are also common for other milarite-type minerals (Fig. 4). No twinning has been observed. The mineral is transparent with a vitreous luster and a marked pleochroism with $O =$ sky blue and $E =$ colorless. The crystals are brittle with no apparent cleavage. Hardness and density could not be measured because of the small grain size. The calculated density is 2.68 g/cm^3 .

Chayesite is uniaxial positive, with $\omega = 1.575(1)$ and $\epsilon = 1.578(1)$, measured in Na light ($\lambda = 589$ nm) on isolated small grains. In thin sections, a slightly higher birefringence than 0.003 was suspected for some chayesite crystals. The compatibility index is excellent with $1 - (K_p/K_C) = -0.034$ according to the classification of Mandarino (1981).

Optical properties do not differ significantly between the members of the osumilite-type minerals. For example, blue color and a positive optical sign are exhibited by many osumilites (Schreyer et al., 1983) and some roedderites (Abraham et al., 1983). Given these similarities and the nearly identical X-ray pattern (see below), only chemical analyses can lead to a proper identification.

TABLE 1. Selected results of microprobe analyses of chayesite compared with analyses of roedderite

	Chayesite					Roedderite		
	1	2	3	4	5	C	D	A
SiO ₂	69.95	69.86	69.47	69.35	69.68	70.60	71.10	71.10
TiO ₂	0.21	0.21	0.36	0.23	0.17	0.07	0.10	0.07
Al ₂ O ₃	0.24	0.17	0.34	0.21	0.16	0.50	0.27	0.61
Cr ₂ O ₃	—	—	—	—	—	0.05	0.00	0.00
Fe ₂ O ₃ *	5.28	6.17	5.62	3.30	4.51	2.55	0.68	0.21
FeO*	5.40	4.27	5.25	9.32	7.68	3.50	3.84	0.78
MnO	0.23	0.21	0.23	0.35	0.39	0.21	0.26	0.37
MgO	13.64	13.90	13.39	11.61	12.30	15.70	16.50	18.85
CuO	—	—	—	—	—	0.03	0.00	0.13
ZnO	—	—	—	—	—	0.15	0.00	0.34
Na ₂ O	0.45	0.25	0.29	0.43	0.33	1.80	2.24	3.32
K ₂ O	5.24	5.14	5.18	5.28	5.31	4.20	4.28	4.33
Σ	100.64	100.19	100.13	100.08	100.53	99.11	99.20	100.09
Structural formulae on the basis of 30 oxygens								
Si	11.96	11.96	11.94	12.07	12.03	12.02	12.08	11.92
Al	0.04	0.03	0.06	0.00	0.00	0.00	0.00	0.08
Σ	12.00	11.99	12.00	12.07	12.03	12.02	12.08	12.00
Ti	0.03	0.03	0.05	0.03	0.02	0.01	0.01	0.01
Al	0.01	0.00	0.01	0.04	0.03	0.10	0.05	0.04
Cr	—	—	—	—	—	0.01	0.00	0.00
Fe ³⁺	0.68	0.80	0.73	0.43	0.59	0.33	0.09	0.03
Fe ²⁺	0.77	0.61	0.75	1.36	1.11	0.50	0.55	0.11
Mn	0.03	0.03	0.03	0.05	0.06	0.03	0.04	0.05
Mg	3.48	3.54	3.43	3.02	3.16	3.98	4.18	4.70
Cu	—	—	—	—	—	0.00	0.00	0.02
Zn	—	—	—	—	—	0.02	0.00	0.04
Σ	5.00	5.01	5.00	4.93	4.97	4.98	4.92	5.00
K	1.14	1.12	1.14	1.17	1.17	0.91	0.93	0.93
Na	0.15	0.08	0.10	0.15	0.11	0.59	0.74	1.08
Σ	1.29	1.20	1.24	1.32	1.28	1.50	1.67	2.01

Note: Chayesite analyses from sample MC7, Moon Canyon, Utah. Roedderite analyses from Hentschel et al. (1980) (cols. A and C) and Abraham et al. (1983) (col. D).

* For method of recalculation, see text.

CRYSTALLOGRAPHY

Single-crystal studies could not be carried out because of the small size of the isolated crystals. Thus the unit-cell parameters were refined from X-ray powder-diffraction data of several of these very small single crystals obtained with a Gandolfi camera with CuK α (Ni-filtered) radiation. The refined unit-cell parameters are $a = 10.153(4)$ Å, $c = 14.388(6)$ Å, and $V = 1284.4$ Å³ (Table 2). The c/a ratio calculated from unit-cell parameters is 1.4171.

The crystals are hexagonal and probably belong to space group $P6/mcc$ (by analogy with the osumilite-type minerals); $Z = 2$.

The X-ray powder-diffraction pattern was indexed in analogy to that of osumilite (Table 3). The chayesite pattern shows three very strong reflections with $d = 5.08$, 3.75, and 3.24 Å. These are also strong reflections in the pattern of the synthetic Mg-osumilite end-member (Schreyer and Seifert, 1968) with $d = 5.04$, 3.73, and 3.21 Å respectively. The X-ray patterns for other osumilite-group minerals, i.e., merrihueite (Dodd et al., 1965), roedderite (Olsen, 1967), yagiite (Bunch and Fuchs, 1969), and even the new B-bearing member poudretteite (Grice et al., 1987), have their strongest reflections at similar d values.

A SECOND OCCURRENCE OF CHAYESITE

Although not confirmed by X-ray data, chayesite most probably occurs also in a lamproite from Cancarix, Albacete, Spain, where it has already been mentioned as a new phase by Wagner and Velde (1986, p. 27–28) as well. In this rock, the mineral has been detected as a rare accessory phase of minute crystal size only in one thin section, whereas other sections from the same sample and from other specimens of this locality appear to be devoid of it. Such sporadic occurrence is reminiscent of the Moon Canyon locality—where chayesite has been found in only

TABLE 2. Lattice constants and some physical properties of chayesite from Moon Canyon and other minerals of the osumilite group

	1	2	3	4
a (Å)	10.078	10.138	10.14–10.15	10.153(4)
c (Å)	14.317	14.302	14.22	14.388(6)
D (g/cm ³)	2.624	2.629	2.67	2.69
ω	1.539	1.543	1.543	1.575(1)
ϵ	—	1.548	1.544	1.578(1)

Note: (1) Osumilite, KMg₂Al₃(Si₁₀Al₂O₃₀), Schreyer and Seifert, 1968 (ASTM/29-1016). (2) Roedderite, Hentschel et al., 1980. (3) Eifelite, Abraham et al., 1983. (4) Chayesite, refined from 19 reflections (Gandolfi pattern, CuK α , camera diameter: 114.6 mm).

TABLE 3. X-ray powder-diffraction data for synthetic osumilite and for chayesite from Moon Canyon

Osumilite*			Chayesite**		
d_{meas}	hkl_0	d_{meas}	d_{calc}	$h\bar{k}l$	hkl
8.72	3	—	—	—	—
7.18	50	7.14	7.194	st	002
5.54	15	5.56	5.568	w	102
5.04	60	5.08	5.076	vst	110
4.36	14	4.38	4.396	vw	200
4.12	40	4.14	4.148	m	112
3.73	45	3.75	3.751	vst	202
3.58	50	3.61	3.597	w	004
3.31	30	3.35	3.329	m	104
3.21	100	3.24	3.238	vst	121
2.995	11	3.01	3.017	w	122
2.919	60	2.933	2.9350	m	114
2.768	65	2.782	2.7840	st	204
2.712	12	2.736	2.7316	w	213
2.518	14	2.542	2.5382	m	220
2.412	11	—	—	—	—
2.388	3b	2.398	2.3981	vw	006
2.377	6	—	—	—	—
2.159	12	2.176	2.1754	w	215
2.088	4	2.103	2.1022	w	402
—	—	2.071	2.0739	vw	224
2.004	15	2.019	2.0185	w	314
1.904	2	—	—	—	—
1.888	10	1.903	1.9018	w	411
1.850	20	1.859	1.8604	w	315
1.793	14	1.799	1.7992	w	008
1.755	2	—	—	—	—
1.746	6	—	—	—	—
1.734	18	1.742	1.7431	m	226
1.689	4	1.695	1.6953	w	118
—	—	1.570	1.5701/1.5698	w	423/511
—	—	1.439	1.4390/1.4388	w	425/00.10

* From Schreyer and Seifert (1968) (ASTM/29-1016).

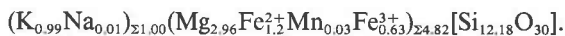
** Gandolfi pattern, CuK α , camera diameter 114.6 mm.

† Abbreviations are vst = very strong, st = strong, m = medium, w = weak, vw = very weak, b = broad.

one rock sample thus far—and may be indicative of a nonuniform distribution of chayesite in lamproites as a whole. Nonuniform distribution would certainly account for the fact that chayesite was overlooked in two well-studied localities for such a long time.

A representative microprobe analysis of the Cancarix mineral yielded the following results: SiO₂ 70.29; TiO₂ 0.02; Al₂O₃ 0.00; FeO (= Fe_{tot}) 12.60; MnO 0.23; MgO 11.44; Na₂O 0.04; K₂O 4.48. Thus this mineral has a considerably higher Fe/Mg ratio than the chayesite from Moon Canyon.

Employing the recalculation method for Fe³⁺ introduced earlier, the structural formula of the Cancarix mineral becomes



This is certainly close to the chayesite formula, if compared with the formulas of Table 1. However, there is a disturbing excess of Si over 12.00 that is most unlikely for a double-ring silicate. The deficiency against 5.00 in the remaining tetrahedral and octahedral sites may indicate the presence of additional elements although none were detected, but the sample was not analyzed for Li.

This situation also affects the Fe³⁺ calculation and results in too low a value. Thus, the Cancarix analysis plots in Figure 1 along the ordinate, although on the basis of its alkali content, it is actually closer to the ideal chayesite end-member, K(Mg,Fe²⁺)₄Fe³⁺[Si₁₂O₃₀], than the Moon Canyon phases. In Figure 2, the Cancarix mineral also plots along the ordinate near the Fe_{tot}/(Fe_{tot} + Mg + Mn) value of 0.4, thus extending the trend from roedderite to chayesite to a practically Na-free and most ferruginous member.

The above chemical features seem to confirm that the Cancarix phase represents chayesite as well, probably the purest one yet found. However, owing to its extreme rarity and the minute crystal size, the necessary supporting data have not been obtained thus far.

PETROLOGIC DISCUSSION

The mineral most closely related to chayesite, i.e., roedderite, was first reported from meteorites, where it occurs either with enstatite, albite, and tridymite (Fuchs et al., 1966) or with forsterite, F-richterite, albite, and krinovite (Olsen, 1967; Olsen and Fuchs, 1968). In terrestrial rocks, roedderite and the more sodic mineral eifelite occur in melt-coated cavities within gneiss xenoliths ejected by tephritic lavas of the Eifel province (Hentschel et al., 1980; Abraham et al., 1983). They are interpreted as precipitates from alkaline, Mg- and Si-rich, but Al-deficient gas phases. Unlike these two minerals, chayesite occurs in the igneous groundmass and must have crystallized from the lamproite melts. It is associated with the late-crystallizing phases K-feldspar, minute crystals of diopside, and an unidentified Ti-rich phase, but is slightly later than K-richterite. There is no petrographic observation that could indicate that richterite had become unstable. The only phases unstable at this stage of the solidification were olivine and Ti-rich phlogopite.

Forbes (1971) and Charles (1975) have shown that roedderite, associated with forsterite, diopside, melt, and vapor, is a low-pressure breakdown product of richterite (between 930 °C and 970 °C at 50 bars and 150 bars, respectively). Fe-bearing roedderite is also a decomposition product of the sodic amphibole riebeckite, forming at pressures below 500 bars (Ernst, 1968). Since in the two lamproites from Moon Canyon and Cancarix, the potassic assemblage chayesite + K-richterite is found instead of roedderite and Na-richterite, we may consider that chayesite belongs to a low-pressure assemblage formed from melt with a composition close to K-richterite.

Chayesite has so far not been synthesized, and thus no direct experimental information is available on its thermal stability. However, attempts to estimate the temperature of crystallization of lamproites have been made in many cases and give temperatures below 965 °C for the latest phases to crystallize (Wagner and Velde, 1986).

The presence of chayesite in the two lamproites testifies for the strong potassic peralkaline character of these rocks

as well as for progressive Fe enrichment with the crystallization of these Mg-rich lavas.

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