

COMPOSITIONAL RELATIONS IN MINERALS
FROM KIMBERLITE AND RELATED ROCKS
IN THE MOSES ROCK DIKE, SAN
JUAN COUNTY, UTAH¹

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ABSTRACT

The Moses Rock dike, a well-exposed, kimberlite-bearing breccia intrusion, crops out in gently dipping beds of the Permian Cutler Formation, in eastern Monument Valley, Utah.

Petrographic, bulk chemical, and electron microprobe analyses of kimberlite and its constituent minerals reveal this highly serpentinized microbreccia contains a primary mineral assemblage consisting of olivine (Mg/Mg+Fe), 87 to 93), orthopyroxene and clinopyroxene (falling into two compositional ranges after correction for Na-pyroxene molecules—one with Al₂O₃ between 0.5 and 1 percent another, 2 to 5 percent), spinel, chrome-rich pyrope garnet, ilmenite-geikielite, titanoclinohumite and one or more micas. Diamonds are not known.

We conclude (1) mineral grains in kimberlite are unlike associated dense rock fragments, except rare lherzolite; (2) kimberlite was emplaced as discrete angular mineral clasts, not a silicate melt; (3) *P-T* assignments based on clinopyroxenes compositions suggest derivation over a depth range in the upper mantle extending to 150 km or more, at temperatures near or below the experimentally determined garnet-lherzolite solidus; (4) the kimberlite was derived by physical disaggregation of both Al-poor and Al-rich pyroxene bearing peridotite in the mantle (garnet- and spinel-lherzolite, respectively); (5) titanoclinohumite is present in both assemblages and may be an important mineralogical site for volatiles in the upper mantle; (6) dense rock fragments (except lherzolite) are unrelated to the kimberlite and are chunks of the vent wall from the crust and possibly the upper mantle sampled during the eruption.

INTRODUCTION

This report focuses on the mineral compositional data from kimberlite and related rock fragments. It discusses the implications of these observations with respect to the genesis of the kimberlite at Moses Rock dike and the composition and physical state of the upper mantle underlying the dike.

Pyroxenes, as a mineral group, are of particular interest in this investigation and to students of kimberlites and of the earth's interior in general. In part, this is because they are a quantitatively important phase but also because they contain significant information about the conditions of

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their genesis. In recent years, experimental petrologists have extended our knowledge of phase and mineral compositional relations to include ultramafic systems at pressures and temperatures existing in the earth's upper mantle. The electron microprobe permits the observational petrologist to efficiently examine the major element chemistry of mineral phases in rocks with precision and with spatial resolution. Some of the major conclusions reached in this report are based on electron microprobe analyses of natural pyroxenes and interpretation of the conditions of their genesis based on experiments on systems of similar composition.

Previous Work. Sterrett (1909) is the first geologist known to have observed the kimberlite diatremes on the Navajo Reservation. He visited Buell Park and the cluster of diatremes along Comb Ridge in eastern Monument Valley, described pyropic garnets collected at the Moses Rock dike, and suggested that the dike was a glacial deposit. He referred to rocks at Buell Park as peridotite agglomerate, similar to kimberlite. Woodruff (1912), after noting the abundance and rounded nature of the exotic rocks occupying the surface of the ground at the Moses Rock dike also suggested that it was glacial in origin. In his classical reconnaissance of the Navajo country, Gregory first recognized the kimberlite-bearing diatremes as volcanic features (Gregory, 1915). Williams (1936) briefly described the abundant and varied crystalline rock fragments contained in the kimberlite diatremes in his reconnaissance study of the volcanic rocks of the Navajo and Hopi Reservations.

The first geologist to identify the green tuff-like serpentine-microbreccia as "kimberlite" was Balk (1954), after detailed petrographic and chemical analysis of material from Buell Park. A geologic map of the Buell Park diatreme was completed by Balk (1954). Malde (1954) and Malde and Thaden (1963) mapped the geology of one of the two vents at Garnet Ridge, south of the Moses Rock dike and reported serpentine-rich breccia interspersed between large blocks of sedimentary rock. E. M. Shoemaker and H. J. Moore (unpublished map) mapped the geology of the Mule Ear diatreme during 1955 to 1957 and found tuff-like intrusive kimberlite.

Shoemaker (1956, 1962) and Shoemaker, Roach, and Byers (1962) have described the structure of kimberlite and minette diatremes of the central Navajo Reservation and monchiquite diatremes of the Hopi Reservation. The geology of the quadrangle in which the Moses Rock dike lies has been described by O'Sullivan (1965).

More detailed petrologic studies of the Colorado Plateau kimberlites have been undertaken recently. Watson (1960) described eclogites collected at Garnet Ridge. O'Hara and Mercy (1966) collected and described

peridotite, eclogite and garnets at Garnet Ridge and other diatremes. Among the garnets collected were chromium-rich pyrope-garnets characteristic of South African kimberlites. No diamonds have been observed as yet in any of the Colorado Plateau kimberlites. Watson recently summarized the Arizona pipes (in Wyllie, 1967). Gavasci and Kerr (1968) published a description of Garnet Ridge with emphasis on garnet compositions and uranium emplacement and Gavasci and Helmstaedt (1969) recently described a garnet lherzolite fragment collected at the Moses Rock dike.

GEOLOGY

Regional Setting. The Moses Rock dike lies in the eastern part of Monument Valley, about 5 miles southeast of Mexican Hat, Utah, near the center of the Colorado Plateau Province, where sedimentary rocks of Paleozoic and Mesozoic age are exposed. The Cutler Formation of Permian age is exposed over much of the Monument Valley area. Quaternary deposits occur locally.

The major structural elements of this part of the Colorado Plateau are the Monument uplift and the Comb Ridge monocline. The Monument uplift is a broad, north-south trending, flat, asymmetrical anticline approximately 50 miles wide by 100 miles long, upon which are developed a few minor folds (Baker, 1936; Shoemaker, 1954; Kelley, 1955). The eastern margin of the Monument uplift is defined by the Comb Ridge monocline. The Moses Rock dike occurs just west of this monocline. Eastward of the monocline, strata dip very gently across the Four Corners Platform.

Kimberlite-bearing dikes and diatremes occur at eight known localities scattered about the east-central Colorado Plateau (Figure 1). A cluster of vents occurs in the east part of the Monument Valley along the Comb Ridge monocline. The Mule Ear diatreme, the northern-most of the known Colorado Plateau kimberlite vents, is an elliptical pipe which occurs near the axis of the monocline just south of the San Juan River. Five miles southwest lies the Moses Rock dike. Two miles southwest of the Moses Rock dike is a roughly semi-circular collapse structure, the Cane Valley diatreme. Approximately six miles southeast of the Moses Rock dike, on the east side of the Comb Ridge monocline and just south of the Utah-Arizona border are two roughly elliptical diatremes at Garnet Ridge. Just north across the Utah border from Red Mesa, Arizona and approximately 20 miles east of Garnet Ridge is a solitary kimberlite-bearing dike which at one spot widens into a nearly circular diatreme. Another cluster of diatremes occurs on the east flank of the Defiance uplift, along the Defiance monocline near the Arizona-New Mexico border northwest of Gallup, New Mexico. The largest is a circular

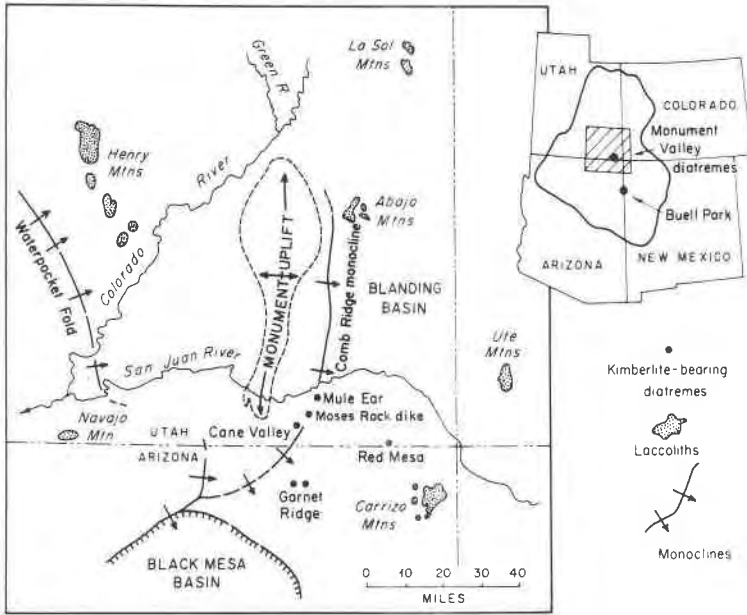


FIG. 1. Location map for the region near the Moses Rock dike.

kimberlite diatreme at Buell Park near Fort Defiance, Arizona. Two smaller kimberlite plugs occur at Green Knobs, approximately 5 miles northeast of Buell Park (Fig. 1).

Geology of the Moses Rock Dike. The Moses Rock dike (Fig. 2) is a north-trending, hook-shaped, breccia-filled diatreme about 4 miles long, cutting gently dipping red clastic strata of the Cutler Formation of Permian age. The dike is two miles west of the axis of Comb Ridge monocline. Contacts of the dike are vertical to steeply westward dipping, and rocks in the vent walls are generally undeformed and unaltered except for jointing parallel to the contact and some local bleaching and minor folding. Typically, beds are simply truncated abruptly at the contact.

The nature of the breccia filling the dike varies from place to place. Kimberlite (green to greenish-black, serpentine-rich, mica-bearing, peridotite microbreccia) occurs only locally. Most of the material within the dike consists of rubble composed of large blocks derived from the Cutler Formation exposed in the walls and mixed with (1) comminuted clastic debris ground from these blocks, (2) lesser amounts of rock fragments from the limestone units below, (3) well rounded rock fragments from the crystalline basement. The matrix between the blocks consists of fine grained rock debris mixed with mineral fragments from kimberlite.

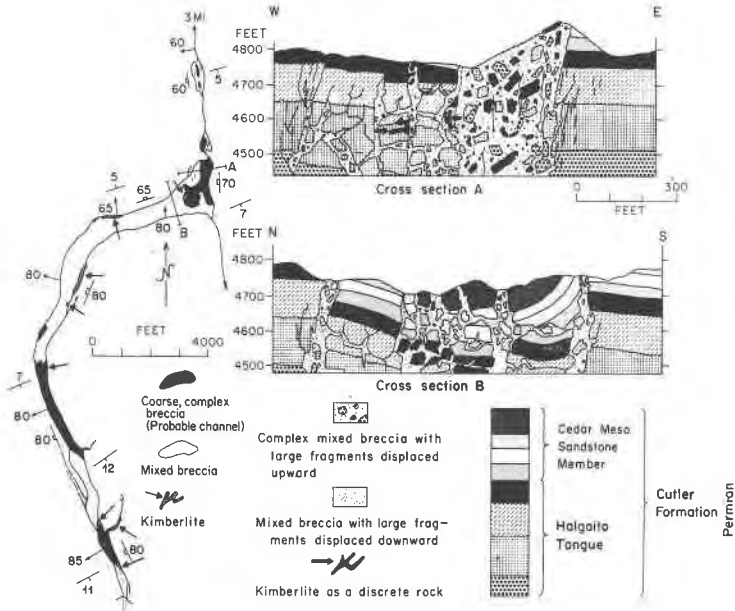


FIG. 2. Schematic geologic map of the Moses Rock dike, with two geologic cross sections based on detailed mapping at 1 in = 200 ft.

Approximately 72 percent of all material in the dike as presently exposed is derived from the Cutler Formation; only 12 percent is kimberlite or material derived directly from kimberlite. Most of the mineral fragments derived from kimberlite are finely dispersed through the various breccias; only 1 percent of the exposed area of the dike is occupied by kimberlite as a discrete mappable unit. About 12 percent of the breccia is composed of limestone fragments derived from underlying Paleozoic strata, and 3 percent are crystalline igneous and metamorphic rock fragments. In terms of size, about 12 percent of the area of the dike is occupied by blocks larger than 100 feet in maximum exposed dimension, 18 percent between 10 and 100 feet, 23 percent between 1 and 10 feet and 47 percent less than 1 foot. The size frequency distributions of the fragments collected in bulk samples are similar to distributions produced in comminution processes, such as mechanical grinding in a ball mill.

Kimberlite, as a rock unit, occurs as small dikes within large breccia blocks, as small sills emplaced in the vent walls, as small dikes outside the main dike, as small bodies plastered against the outside wall rocks at the contact, and as pods within the dike. In these occurrences of kimberlite, dilution by rock debris is very slight (by definition), about 1 part in 20.

In the rubble filling most of the dike, however, the minerals derived from kimberlite are found only in the matrix between the large blocks where they are mixed with debris derived largely from the comminuted surface of the blocks themselves. This dilution in the matrix reaches 7 parts rock debris to 1 part mineral fragments from kimberlite. This matrix is commonly light lime green, completely uncemented, and highly friable.

There are irregular pod-shaped areas within the dike which appear to have been channels in which the upward flow was concentrated during the eruption. In these areas crystalline rock fragments and limestone blocks derived from underlying strata are largest, and the degree of dilution of kimberlite with rock debris is a maximum. It is inferred that at the surface above these channels several craters of the maar type were present.

The age of the dike is bracketed geologically between 10 and 60 million years; two crustal fragments from the Mule Ear diatreme have been dated by the fission track method at 28 and 30 million years. (Naeser and Stuart-Alexander, 1969)

PETROLOGY

The rock fragments within the Moses Rock dike which have been transported upward from below the Paleozoic section include both the kimberlite and a diverse suite of crystalline rocks. These crystalline rocks occur as discrete, commonly spheroidal, unaltered fragments within the unconsolidated breccias. Because the reservoir from which part or all of the kimberlite originated apparently was located at great depth, probably within the upper mantle, these clasts represent thoroughly mixed samples derived from a very long vertical section through the crust and, possibly, through part of the upper mantle.

Igneous and metamorphic crystalline rock fragments constitute about 3 percent by volume of the intrusive material filling the Moses Rock dike. They range in size from silt-sized particles to very well rounded blocks up to 6 feet in diameter. Generally, all fragments are very well rounded. Comparison of the mineralogy at the edges and centers of fragments reveals no evidence that they have been affected by metamorphism after the fragmentation event. It is clear, however, that their spheroidal shape is the result of impact and abrasion during transport.

Approximately 75 percent of the crystalline igneous and metamorphic fragments are unfoliated rocks with igneous or modified igneous textures. The most common types are metabasalt gabbro and diorite; present but less abundant are rhyolite and granite. Approximately 25 percent of the fragments are foliated metamorphic rocks of greenschist, amphibolite and granulite grade. The most abundant metamorphic type is mafic amphibolite or granulite consisting of altered plagioclase, hornblende, some

remnant clinopyroxene, and with or without garnet. This rock is believed to be retrograded from rocks with the assemblages plagioclase-pyroxene or garnet-plagioclase-pyroxene. Acid granulite (garnet-quartz-alkali feldspar), amphibolite and greenschist grades of rocks are present but not abundant. Dense fragment types ($\rho > 3.2$ gm/cm³) composing less than 1 percent of the crystalline fragment population include, in decreasing relative abundance, 1) jadeite-pyroxenite, 2) eclogite, 3) spinel-bearing websterite, and 4) spinel-bearing lherzolite. Apparently the jadeite-rich clinopyroxenite rocks are low-garnet end members of an eclogite series. These rocks are under investigation at present. Antigorite-tremolite schist is not included in the suite of dense types, but if related, it is the most abundant of the possibly mantle-derived types.

Kimberlite. The mineral constituents of kimberlite make up about 12 percent of the breccia filling the Moses Rock dike; however, over 90 percent of these minerals are intricately mixed on a fine scale and dispersed throughout the various breccia units. Only in approximately 1 percent of the area within the dike is kimberlite present as a discrete mappable rock unit.

The best exposure of kimberlite in the Moses Rock dike occurs as a thin dike within a large breccia block of the Cedar Mesa Sandstone Member near the north-east end of the dike. Here it is a dark greenish-black microbreccia containing olivine, serpentine, rare brown layered-structure minerals, garnet, pyroxene, spinel, titancolinohumite and small lithic fragments. The greenish-black rock from the center of the dike was sampled in hand specimens and in bulk (MR-1416A, Table 1, Analysis 6). The descriptions and chemical and mineral analyses of kimberlite are from this occurrence. There is a thin contact zone about 1-2 cm thick between the kimberlite and overlying pale orangish-red sandstone which consists of lime-green powder. X-ray diffraction revealed this powder to be antigorite, with minor talc, no quartz, and no other mineral in significant abundance. The red sandstone at the contact shows only minor bleaching. The lower contact is against a similar light lime-green unit, consisting of kimberlite minerals apparently diluted with silt- and sand-sized sedimentary rock debris. The lower contact is not well exposed.

In thin section, kimberlite is composed of millimeter-size, discrete angular mineral fragments, originally mostly olivine, which exhibit varying degrees of alteration to serpentine (Fig. 3). These fragments are set in a fine-grained groundmass, apparently also serpentine, but of a clearly different texture than the alteration product of the angular fragments of olivine. Remnant patches of olivine are optically continuous. Other common mineral phases include pale yellowish-green orthopyroxene, red to

TABLE 1. CHEMICAL ANALYSES OF KIMBERLITE AND SELECTED ROCK FRAGMENTS FROM MOSES ROCK DIKE
SELECTED PUBLISHED SOURCES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SiO ₂	47.50	43.27	36.58	30.72	30.13	39.16	40.07	54.11	46.64	41.82	34.16	32.55	45.00	46.15	44.60	50.93	50.97	45.85	45.20
Al ₂ O ₃	1.38	3.49	7.15	4.04	8.72	3.38	2.73	1.57	3.76	8.17	4.49	5.10	1.82	3.14	3.90	3.85	8.65	2.05	3.54
FeO ₃	4.34	5.78	6.09	6.65	8.18	3.34	3.33	7.15	8.77	12.59	11.74	15.13	7.65	7.13	7.90	2.82	4.50	7.14	8.04
FeO	2.37	2.94	4.37	4.57	5.87	3.07	3.05	35.61	25.30	25.78	36.02	27.95	42.48	39.27	41.00	54.76	21.33	41.63	37.48
MgO	31.26	23.47	22.55	32.40	7.05	1.74	2.10	8.75	8.31	6.92	7.00	7.62	1.31	2.42	1.78	3.00	12.58	1.76	3.08
Na ₂ O	.05	1.08	6.28	6.10	7.45	.05	.08	.12	1.16	3.32	.19	.19	.06	.09	.13	.66	.54	.15	.57
CaO	.11	1.97	.47	1.00	1.96	.05	.08	.42	2.77	.54	1.11	1.04	.07	.09	.13	.01	.01	.08	.13
K ₂ O	10.88	4.55	8.51	8.90	6.96	11.20	11.50	---	---	---	---	---	---	---	---	---	---	---	---
H ₂ O	1.65	1.50	3.31	2.01	1.55	1.85	1.02	---	---	---	---	---	---	---	---	---	---	---	---
CO ₂	.08	1.70	2.67	1.81	5.32	1.20	1.27	.00	1.19	3.05	2.23	5.75	1.38	1.46	---	---	---	.41	.71
SO ₂	.02	.10	.38	.77	3.60	.09	.11	.09	1.83	3.43	2.01	3.89	.03	.05	.02	.04	.12	.03	.15
PO ₃	.02	.10	.38	.77	3.60	.09	.11	.09	1.83	3.43	2.01	3.89	.03	.05	.02	.04	.12	.03	.15
MnO	.12	.14	.34	.16	.12	.09	.10	.14	.15	.39	.18	.13	.15	.12	.15	.07	.13	.15	.14
Cl ₂ O ₃																			
NiO																			
Total	100.23	99.30	99.97	100.77	101.90	99.47	99.70	99.98	99.99	100.01	99.99	100.02	100.05	100.00	99.48	100.00	99.72	99.99	99.99

1. Kimberlite Tuft, Buell Park, R. Balk, 1954, New Mexico Mines and Mineral Res., N. Mex. Inst. of Tech., Bull. 36.

2. Average of 8 kimberlites So. Africa: quoted by Balk, 1954.

3. Basutland kimberlites; J. W. Dawson, 1902, G.S.A. Bull. 72, p. 545-560.

4. Kimberlite, Troynoga, Olenek district, U.S.S.R. (Krutojarsky, 1958).

5. Moses Rock kimberlite (Blackish-green-MR-1416A) } [McGetchin, 1968.]

6. Moses Rock kimberlite (Light lime-green-MR-1416B) }

7. Moses Rock kimberlite (Light lime-green-MR-1416B) }

8. Analyses 1 recalculated water free, Fe as FeO.

9. Analyses 2 recalculated water free, Fe as FeO.

10. Analyses 3 recalculated water free, Fe as FeO.

11. Analyses 4 recalculated water free, Fe as FeO.

12. Analyses 5 recalculated water free, Fe as FeO.

13. Analyses 6 recalculated water free, Fe as FeO.

14. Analyses 7 recalculated water free, Fe as FeO.

15. Calculated composition of spinel-hercynite fragment based on modal analysis and microprobe analyses of minerals, anhydrous basis (McGetchin, 1968).

16. Antigorite-tremolite schist fragment from Moses Rock dike, anhydrous basis (McGetchin, 1968).

17. Spinel-hercynite fragment, Moses Rock dike (McGetchin, 1968).

18. Garnet-hercynite (KA-64-16) from Duloitspan Mine, South Africa (Ito and Kennedy, 1967). Water free, Fe as FeO.

19. Pyrolyte III, Green and Ringwood, 1967.

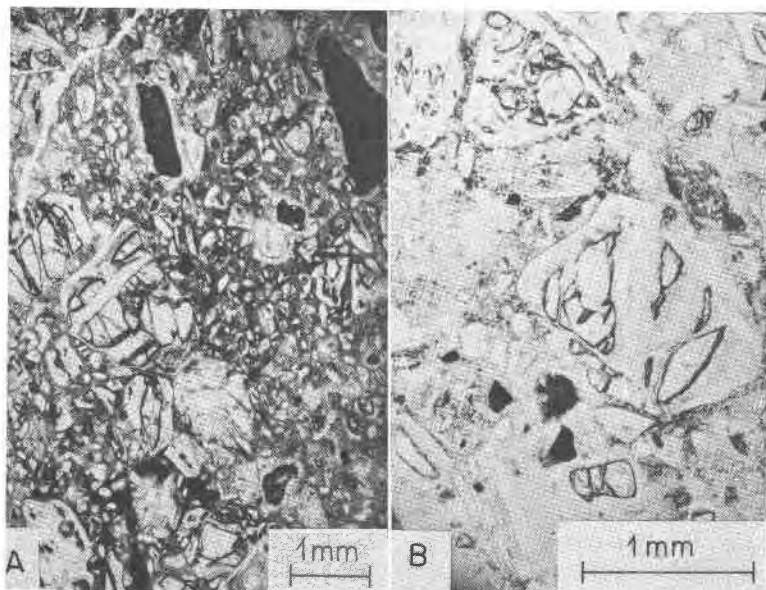


FIG. 3. Photomicrographs of kimberlite at the type locality. Rock is a blackish-green serpentine-rich, mica-bearing microbreccia consisting of about 50 percent angular crystal fragments of olivine (ol), orthopyroxene (opx), clinopyroxene (cpx), garnet, spinel, opaques, rare mica (m), and lithic fragments, set in a fine grained groundmass (SG) of serpentine and possibly chlorite and talc. Olivine grains are generally partially altered to serpentine (SO) but remnant olivine is optically continuous. Only minor amounts of carbonate, mica and opaque material is present.

to wine-colored garnet, grass-green clinopyroxene, and rare large grains of mica. Amphibole and calcite are present but are not common. Relatively rare are titanoclinohumite, opaques, green and brown spinel, plagioclase and zircon. Pyroxenes are unzoned and show no evidence of exsolution. Serpentinization of olivine grains is commonly pervasive; alteration of orthopyroxene is relatively slight. Lithic fragments, generally limestone and siltstone, show no apparent alteration in contact with the enclosing groundmass. Garnets commonly have thin kelyphitic rims of chlorite and magnetite(?). Small veins of fibrous carbonate are observed within the groundmass. Small platy chips of transverse-fiber carbonate are commonly observed in the breccias or on the surface of the ground within the dike. Microprobe analysis of these carbonate veins and chips in kimberlite revealed that this material is nearly pure CaCO_3 with less than weight 1 percent MgCO_3 present. Optical determinations showed that it is calcite, not aragonite.

Modal analysis of kimberlite (MR-1416A, Fig. 3) showed that the rock

is approximately 85 to 90 percent serpentine by volume. Serpentine-rich groundmass is 50 percent of the rock. Unaltered olivine is only 5 to 10 percent by volume. Approximately 35 percent of the rock is pseudomorphs after olivine. Large layered-structure minerals (mica and chlorite) form about 1 percent and orthopyroxene and altered orthopyroxene, about 2 percent by volume.

X-ray diffraction analysis of the pulverized rock revealed serpentine, subordinate talc and possible chlorite group peaks.

A search was made for the high-pressure phases diamond and coesite in the heavy mineral concentrate from a 200-pound sample of Moses Rock kimberlite (MR-1416A) sampled at the type locality. None were found. The dense, non-magnetic fraction contained a suite of heterogeneous zircons, subordinate barite, and an isotropic, transparent yellow mineral with very high relief and an apparent octahedral crystal form. X-ray diffraction (photograph by W. B. Kamb) and electron microprobe analysis revealed this mineral to be a nearly iron-free sphalerite.

Chemical analysis of two specimens of kimberlite from Moses Rock were obtained (Table 1, Analyses 6 and 7). Both specimens analyzed are from the type locality, however, MR-1416B (Analysis 7) is lighter in color and appears to be more altered than MR-1416A (Analysis 6).

Compared with other types of ultramafic rocks, kimberlites in general have unusually high contents of K_2O , Al_2O_3 , TiO_2 , CaO , CO_2 , P_2O_5 , and H_2O , low Mg/Fe ratios and high K/Na and Fe^{+3}/Fe^{+2} ratios (Dawson, 1967). Moses Rock kimberlite differs from most other kimberlites (Table 1, Analyses 2, 3, 4, 5) in its low K_2O , Al_2O_3 , TiO_2 , CaO , CO_2 , and P_2O_5 content and high MgO content. K_2O is low because phlogopite or mica is rare; TiO_2 may be low because perovskite is absent, although ilmenite-geikielite and titancolinohumite are present but not abundant; and P_2O_5 is low because apatite is rare.

Relative to the kimberlite at Buell Park, Arizona (Analysis 1), the Moses Rock kimberlite is depleted in silica, lime and alkalis and enriched in MgO. The kimberlite analyses recalculated on a volatile-free basis (13 and 14) are very similar to the calculated spinel-lherzolite composition (15). The analyzed antigorite-tremolite schist fragment is enriched in SiO_2 and Na_2O and depleted in MgO relative to kimberlite.

A reconnaissance microprobe investigation of the composition of the serpentine in each textural mode produced puzzling results. In a polished thin section of kimberlite, partial chemical analyses were obtained from a relict olivine grain and pseudomorphous serpentine derived from this grain and a nearby orthopyroxene grain, pseudomorphous serpentine after this pyroxene grain. Several differences between the orthopyroxene and olivine are useful in considering the serpentine compositions. First,

the orthopyroxene not only contains more silica but also has a significant Al_2O_3 content, about 4.4 weight percent. If serpentinization had occurred without significant chemical exchange, there should be a significant difference in the composition of the serpentine produced from olivine as opposed to that formed from the orthopyroxene. The data suggest no such difference exists. Serpentine produced from the same olivine grain, however, is by no means homogeneous; rather, it varies widely in its alumina and silica content. It appears that silica and alumina were highly mobile in the system because the serpentines differ so drastically from the parent minerals from which they were produced (in Al_2O_3 and SiO_2 content and Mg/Fe ratio). Because the serpentine compositions are so variable, there is no suggestion of chemical equilibrium. The anhydrous groundmass composition is consistent with serpentine produced from a pyroxene-olivine ratio, of about 3:1 to about 5:1. The kimberlite whole-rock chemical analyses and the serpentine-rich schist also are intermediate between olivine and orthopyroxene in bulk composition.

Microprobe Investigations of Kimberlite Minerals. Chemical analyses of mineral grains in kimberlite and other rocks permit some discussion of their origin and relationship to each other. About 400 analyses for 9 major elements were obtained for olivine, orthopyroxene, clinopyroxene, garnet, spinel, titanoclinohumite, ilmenite, geikielite and several others. A representative sample of these analyses is presented in Table 2. Of particular interest are comparisons between individual mineral grains in kimberlite and (1) minerals in the dense rock fragments and (2) mineral inclusions in pyropic garnets.

All ratios of elemental compositions which follow are atom ratios; all concentration figures are in weight percent.

Garnets occur in the breccia and in rock fragments. Garnets from coarse lag concentrates in the ejecta apron around ant hills include abundant deep wine-colored, gem quality, chrome-rich pyropes. These pyropes have not been found in any rock fragment. Orange almandine-rich garnets, similar to those found in schists and gneiss fragments, are also abundant.

Small mineral grains, generally less than 500 μm in diameter, observed within pyropic garnets include olivine, orthopyroxene, clinopyroxene, ilmenite, geikielite, rutile, titanoclinohumite, and possible mica. Before proceeding to a description of the compositions of minerals in kimberlite, compositions of these garnets and their inclusions will be presented.

Compositions of individual minerals in kimberlite appear to be closely related either to minerals observed in a spinel-lherzolite fragment in the Moses Rock dike (MRX-2, Table 1, Analysis 15) or to the mineral inclu-

TABLE 2. MICROPROBE ANALYSES OF MINERALS FROM MOSES ROCK KIMBERLITE (MR-1416A)

	Garnet				Olivine				Orthopyroxene				Clinopyroxene				Spinel		Titanoclinohumite	Ilmenite
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
SiO ₂	43.1	41.0	39.9	38.7	40.2	41.3	41.3	56.7	56.2	55.9	54.7	54.7	54.6	53.7	52.1	.12	.01	36.1	.01	
TiO ₂	.18	.08	.01	.04	.00	.00	.00	.03	.03	.02	.03	.04	.14	.34	.24	.06	—	5.0	54.6	
Al ₂ O ₃	23.4	21.5	18.2	21.8	n.d.	n.d.	.70	2.02	3.32	4.92	1.54	1.54	2.32	4.40	6.39	36.2	52.3	.00	.08	
Cr ₂ O ₃	1.73	2.99	6.95	.00	.01	.01	.28	.52	.72	.55	1.44	2.29	2.29	1.37	1.01	32.1	16.0	.05	.04	
FeO	8.9	8.4	11.3	25.7	10.31	7.57	6.09	6.67	5.29	5.01	6.22	1.45	1.88	1.97	1.97	16.4	13.2	9.3	35.7	
MgO	20.5	20.5	16.1	10.9	49.90	50.6	51.83	35.5	35.9	34.8	33.8	16.8	15.8	14.8	14.5	14.4	17.8	48.1	10.1	
CaO	4.7	5.22	7.83	1.07	n.d.	n.d.	.11	.31	.70	.36	22.5	21.0	20.6	21.4	.02	.02	—	n.d.	.22	
Na ₂ O	.06	.02	.03	.02	.02	.01	.02	.03	.03	.02	1.36	2.11	2.36	1.92	.29	.15	.13	.21	.21	
K ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.04	
MnO	.39	.41	.76	2.76	.15	.00	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.04	
Σ	103.0	100.1	101.1	101.0	100.6	99.5	99.2	100.0	100.3	100.5	100.6	99.8	100.1	99.5	99.5	99.6	99.5	98.68	101.03	
Si	2.943	2.945	2.954	2.954	.982	1.000	.997	1.959	1.928	1.913	1.878	1.983	1.974	1.949	1.893	.007	.001	.005	.005	
Ti	.004	.001	.002	.002	.000	.000	.000	.001	.001	.000	.001	.001	.004	.009	.007	.003	.003	.003	1.926	
Al	1.818	1.580	1.959	1.959	—	—	.029	.081	.134	.200	.200	.066	.069	.188	.274	2.477	3.305	.004	.004	
Cr	.170	.405	.000	.000	.000	.000	.008	.014	.019	.015	.041	.041	.066	.039	.029	1.474	.679	.001	.001	
Fe	.503	.694	1.641	1.641	.211	.154	.124	.193	.151	.143	.179	.044	.055	.060	.060	.795	.592	1.402	1.402	
Mg	2.192	1.768	1.241	1.241	1.819	1.842	1.880	1.829	1.834	1.773	1.728	.906	.854	.801	.786	1.243	1.424	.706	.706	
Ca	.402	.618	.087	.087	—	—	.004	.012	.026	.013	.073	.873	.814	.800	.833	.001	—	.011	.011	
Na	.003	.004	.003	.003	.001	.001	.000	.001	.002	.002	.002	.006	.148	.166	.136	—	—	.004	.004	
K	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	.008	
Mn	.025	.047	.179	.179	.003	.003	.002	—	—	—	—	—	—	—	—	.014	.007	—	.008	
Σ Cations	8.060	8.062	8.066	8.066	3.016	3.000	3.003	4.024	4.023	4.010	4.016	4.010	4.014	4.012	4.018	6.014	6.008	4.067	4.067	
O	12	12	12	12	4	4	4	6	6	6	6	6	6	6	6	8	8	8	8	
(Mg+Me)/Fe	.805				.806	.923	.938	.905	.924	.925	.906	.954	.939	.930	.929					
C ₃ /(C ₃ +Mg)												.491	.488	.500	.515					
Grain Mount	PG-2	61-3-3	61-2-1	61-1-4	62-4-5	62-6-4	62-4-8	63-7-2-1	63-8-8-1	63-8-5	63-8-11-1	63-2-3-1	63-1-2-1	63-3-3-1	63-2-2-1	K-1-8-2K-1-9-1	61-6-4	MR-SP-1		

(Fig. 2)

sions within pyropic garnets. It appears that kimberlite minerals are closely related to two distinct, but possibly overlapping assemblages, spinel-lherzolite, and garnet-lherzolite.

Table 2 contains a representative selection of the mineral analyses chosen to illustrate typical compositions and ranges observed. In the analyses, Fe is expressed as FeO. Iron probably exists in ferric state in both garnet and clinopyroxene. Mineral structure formulae were calculated to an appropriate number of oxygen atoms assuming Fe was present as FeO and Al as Al₂O₃. Results are shown to one oxide weight percent although never more than three figures are significant. Analytical error for the major elements is believed to be about two relative percent of the amount shown; it is somewhat larger for the minor and trace elements.

Garnet. The garnet population in the kimberlite is heterogeneous. The heterogeneity is visible both among garnets separated from massive Moses Rock kimberlite (Mr 1416A) and among large brilliant specimens commonly concentrated as lag materials around ant hills. They vary in color from orange to pink to deep burgundy. Refractive index data are in agreement with published results on garnets from Green Knobs (O'Hara and Mercy, 1966) and Garnet Ridge (Gavasci and Kerr, 1968).

Partial microprobe analyses of 35 selected grains confirm heterogeneity. Some garnets show clear affinity to garnets in eclogite xenoliths and in other metamorphic rock fragments. The most abundant garnet grains are wine-colored pyrope-rich specimens. The compositions of the garnet populations in the kimberlite and in the crystalline rock fragments are seen in Figure 4. The chrome-rich pyropic garnets appear to belong uniquely to the kimberlite.

Inclusions in Pyrope. A representative suite of the inclusions found in pyropic garnets, shown in their typical form and setting, are illustrated in Figure 5. The grains generally have ellipsoidal shapes, and commonly are surrounded by a radiating curved array of fractures of a birefringent halo. Both peripheral effects apparently result from stresses produced by differential volume changes of inclusions and host in response to transport to near-surface pressure and temperature conditions from the conditions at depth in which they were in physical equilibrium. Stresses arise from the differences in thermal expansion coefficients and compressibilities of the two phases. This problem has been discussed by Rosenfeld and Chase (1961) and by Richey (1968).

The garnets, typically homogeneous within 5 weight percent for any oxide, are typically unzoned (Figure 6).

The compositions of the host garnets and the inclusions are rather uniform from grain to grain. Compositional data on these mineral in-

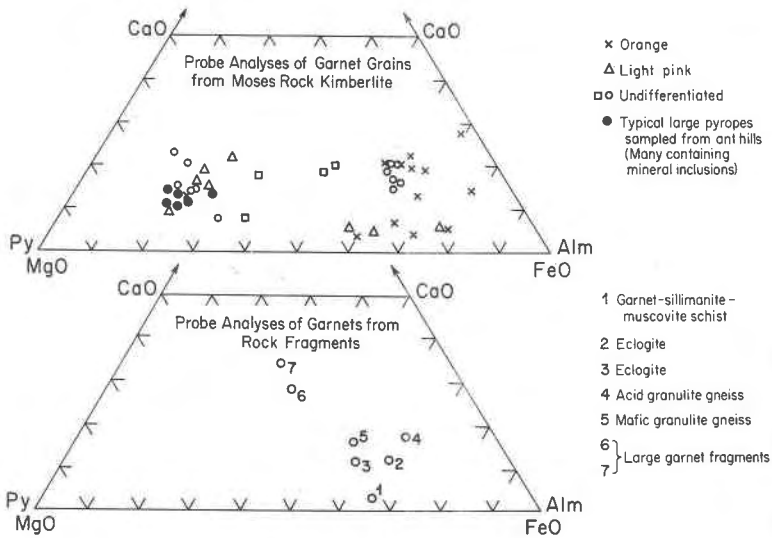


FIG. 4. Comparison of garnet compositions from Moses Rock kimberlite (MR-1416A) and from various crystalline rock fragment types.

clusions are summarized in Table 3. The garnets are near the composition $Mg:Fe:Ca=69:19:12$ and have Cr_2O_3 contents between 1 and 7 weight percent. Olivine, orthopyroxene, and titanoclinohumite have $Mg/(Mg+Fe)$ atom ratios near 94; clinopyroxene ranges from 91 to 96. The alumina content of the orthopyroxene is low, between 0.5 and 1.1 weight percent; in the clinopyroxenes, the alumina (or combined R_2O_3) in excess of jadeite-type ($NaRSi_2O_6$) molecules is modest. The clinopyroxenes are chrome diopsides, Cr_2O_3 between 1.5 and 2 percent with some jadeite and R_2O_3 (Tschermak) solid solution. Soda varies between 0.4 and 2.6 percent. The total iron content of the clinopyroxenes is less than 2 percent. Rutile is a common inclusion, but it does not occur as commonly as in the abundant needle-like exsolution rods so well developed in more iron-rich garnets and in the eclogite garnets. Analyses of the rutile commonly contain several percent Cr, Fe and Mg. An opaque phase, ilmenite, is present which contains a considerable amount of Mg (as geikielite). Finally, titanoclinohumite is present *within* pyropes, a textural setting which virtually precludes it origin as a near surface alteration mineral.

Inclusions of clinopyroxene were observed in two orange garnets. These garnets are more iron-rich and contained very little chromium. The clinopyroxenes were also chrome-poor. These garnets may be gradational to eclogitic types and are not considered to be part of the pyrope population provisionally assigned to kimberlite.

The suite of inclusions found in pyrope garnets described above

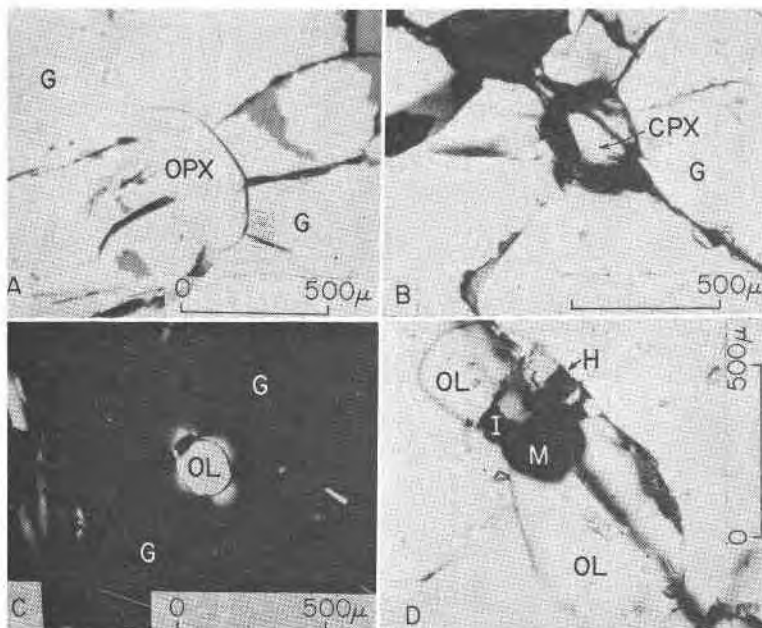


FIG. 5. Photomicrographs of inclusions in pyrope-garnets. A. Orthopyroxene, ordinary light (PG1B67) B. Chrome-diopside, ordinary light (PG-9) C. Olivine, polarized light (PG-24) D. Olivine with clinohumite, geikielite, and mica (?) below surface of the grain, ordinary light (PG-2). Compositional data on host garnet and included minerals is summarized in Table 2.

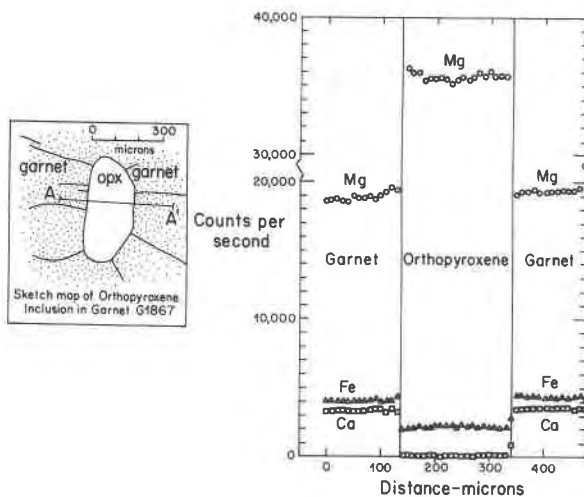


FIG. 6. Microprobe traverse across orthopyroxene inclusion in garnet (PG1B67) showing absence of significant zoning.

TABLE 3. SUMMARY OF COMPOSITIONAL DATA ON INCLUSIONS OBSERVED IN PYROPIC GARNETS FROM THE MOSES ROCK DIKE

Host Garnet*			Inclusions*					
	Mg:Fe:Ca	Cr ₂ O ₃						
PG-2	70:18:12	1.7	{ olivine clinohumite ilmenite mica or chlorite (not exposed at surface)	Mg/(Mg+Fe)=94				
PG-24	68:19:13	1.5		olivine	Mg/(Mg+Fe)=93			
PG1B67	68:18:13	2.0		orthopyroxene	Mg/(Mg+Fe)=94; Al ₂ O ₃ =1.1; Cr ₂ O ₃ =0.3			
PG-23	69:19:12			orthopyroxene	Mg/(Mg+Fe)=94; Al ₂ O ₃ =0.5; Cr ₂ O ₃ =0.1			
			{ ilmenite (geikielite)	TiO ₂ =56; FeO=27; MgO=15; Cr ₂ O ₃ =1				
				rutile	TiO ₂ =95.0; Cr ₂ O ₃ =2.7; FeO=1.5; MgO=0.9			
PG-6	65:24:11	1.4	ilmenite	TiO ₂ =57; FeO=33; MgO=12; Cr ₂ O ₃ =1				
PG-3	69:19:12	3.0	rutile	TiO ₂ =93.3; Cr ₂ O ₃ =5.3; FeO=1.1				
Ca-Rich Pyroxene Inclusions*								
			Ca/ (Ca+Mg)	Al ₂ O ₃	Cr ₂ O ₃	Na ₂ O	FeO	Fe/ (Fe+Mg)
PG-4	68:18:14	2.4	.498	2.3	1.3	1.2	1.3	.959
PG-5	68:20:12	1.6	.495	3.0	1.2	2.4	2.6	.917
PG-9	69:19:12	2.7	.481	2.6	1.7	2.3	1.8	.941

* All ratios are on atom basis; all concentrations are in oxide wt. %.

constitutes the mineral assemblage of a garnet-lherzolite, which led Richey (1968) and us (McGetchin and Silver, 1968) to independently suggest that a garnet peridotite assemblage existed at depth. This was confirmed by the recent reported discoveries of garnet lherzolite as discrete rock fragments at Moses Rock (Gavasci and Helmstaedt, 1969), and Mule Ear (H. G. Wilshire, 1969, pers. commun.).

Olivine. Partial chemical analyses of 40 olivine grains in kimberlite were obtained. The Mg/(Fe+Mg) atom ratios range from 89 to 95, with modal values being about 92 (Fig. 7). Traverses of grains revealed Ca, Mg, and Fe variations of only about 2 relative percent across millimeter-sized grains, showing the olivine to be essentially unzoned.

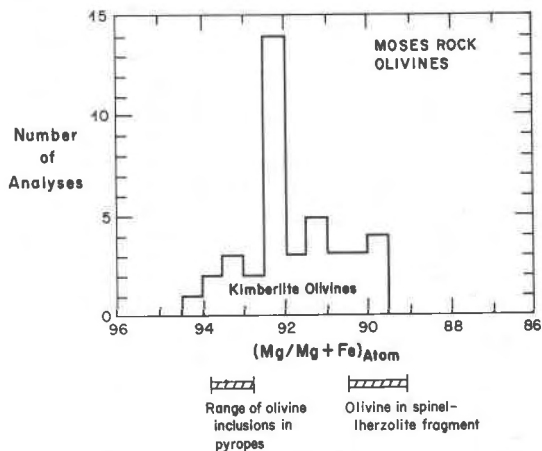


Fig. 7. Mg/(Mg+Fe) ratios of kimberlite olivine grains, olivines from spinel-lherzolite fragment and olivine inclusions in pyropic garnets.

Olivine grains in the Moses Rock kimberlite range from f_{083} to f_{095} . Olivine in the spinel-lherzolite fragment (MRX-2) is f_{090} ; olivine inclusions in the pyrope-rich garnets are f_{093-94} . The olivine population in kimberlite spans the compositional range between the olivines observed to coexist with spinel and garnet in the Moses Rock dike.

Olivines from South African kimberlites have similar compositions to those in the Moses Rock kimberlite. Dawson (1962) reports f_{089-92} from Basutoland pipes; Nixon, von Knorring and Rooke (1963) report kimberlite olivines of composition f_{090} or more, in the ultrabasic inclusions in the South African pipes. Olivines of higher Fe/Mg ratio commonly are found in the South African kimberlite.

Orthopyroxene. Partial chemical analyses of 39 orthopyroxene grains separated from kimberlite (MR-1416A) show that the range of Mg/(Mg+Fe) atom ratios is 90 to 93 (Figure 8). The Al_2O_3 content ranges up to about 5 percent by weight. There appears to be little apparent correlation between Mg/(Mg+Fe) ratio and Al_2O_3 content.

Orthopyroxenes similar in composition to those in spinel-lherzolite (MRX-2) are common; kimberlite orthopyroxenes similar to the orthopyroxene inclusions in the pyropic garnets are *not* common. Thus, nearly all the orthopyroxenes have a compositional affinity to spinel-lherzolite, *i.e.* higher alumina contents and slightly lower Mg/(Mg+Fe) ratios. This suggests that if a garnet peridotite does exist at depth, it may be depleted in orthopyroxene.

Minerals analyzed were selected from 4 different separations to cover the spread of high and low density and magnetic susceptibility, so it is

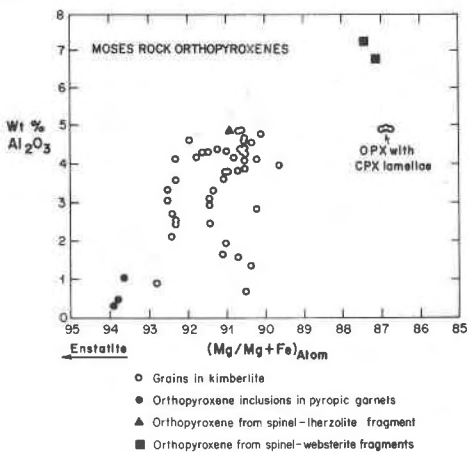


FIG. 8. Plot of $Mg/(Mg+Fe)$ ratio against Al_2O_3 content for kimberlite orthopyroxenes, orthopyroxenes from associated rocks and orthopyroxene inclusions in pyropic garnets.

believed that no masking of certain compositions was introduced artificially. In order to confirm this, 10 additional grains were picked from the most magnesian fraction (which in this case was the *most* magnetic because of the compensating effect of chromium). No low-aluminum specimens were observed. Furthermore, exsolved calcium-rich pyroxene lamellae of the order of $10 \mu m$ wide were observed in several grains. Their compositions were similar to the spinel-lherzolite type clinopyroxenes, and virtually no zoning was observed in traverses, taking $3 \mu m$ steps. More iron-rich grains were observed, however, extending the $Mg/(Mg+Fe)$ range to 0.87.

Clinopyroxene. Partial chemical analyses of 37 calcium-rich pyroxenes from kimberlite (MR-1416A) were obtained. If the data are plotted on a diagram with Al_2O_3 against $Ca/(Ca+Mg)$ ratio, it is immediately apparent that these minerals fall into two groups (Figure 9). One group, characterized by high alumina contents and $Ca/(Ca+Mg)$ ratios commonly greater than 0.50, is similar in composition to clinopyroxenes in the spinel-lherzolite fragment (MRX-2), and also to a clinopyroxene grain observed intergrown with a spinel. The other group, with low alumina contents and $Ca/(Ca+Mg)$ ratios below 0.50, is similar to these clinopyroxene inclusions in pyropic garnets. The ratio of clinopyroxenes similar to those associated with spinel relative to those with garnet is about 2 to 1.

Compared to clinopyroxenes in the websterite, eclogite and clinopy-

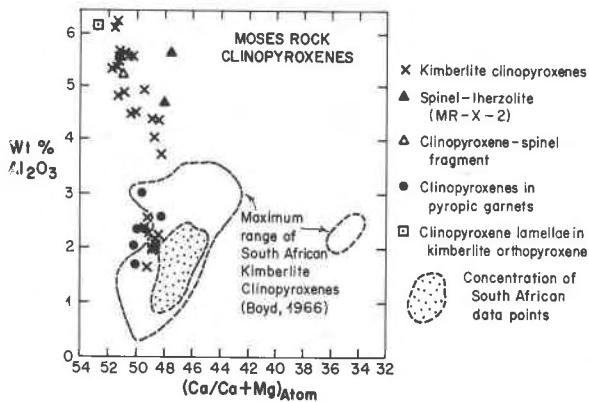


Fig. 9. Plot $Ca/(Ca+Mg)$ ratio against Al_2O_3 content for kimberlite clinopyroxenes, clinopyroxenes from associated rocks and clinopyroxene inclusions in pyropic garnets.

roxenite, the clinopyroxenes in the kimberlite have *much* lower solid solution of jadeite or tschermak component.

Compared to the South African kimberlite clinopyroxenes, those from the Moses Rock kimberlite are not as iron-rich, although the comparison is complicated by the uncertainty in Fe^{+3}/Fe^{+2} ratio. Some of the Moses Rock kimberlite clinopyroxenes are much more aluminous than the South African ones (Figure 9).

Chrome and soda variations differ in the two aluminum groups within the clinopyroxenes (Figure 10). In the high aluminum group (squares) the chrome has a restricted compositional range while the soda varies more widely. In the low aluminum group (circles) the chromium content is positively correlated with soda suggesting variable solid solution of ureyite ($NaCrSi_2O_6$) component. Furthermore, as soda content approaches zero, chromium also approaches zero implying that no chromium exists in tschermak form in the low-alumina group pyroxenes. In the high alumina group pyroxenes it appears that about 1 percent by weight Cr_2O_3 exists as tschermak component.

The $Ca/(Ca+Mg)$ ratio of the kimberlite clinopyroxenes is of particular interest because of the geothermometer provided by the enstatite-diopside solvus (Boyd and Schairer, 1964; Davis and Boyd, 1966). In order to use these diagrams, it is necessary to assume that clinopyroxene coexisted in equilibrium with orthopyroxene. Boyd had noted in the South African occurrences of ultrabasic fragments in kimberlite, that orthopyroxene is commonly found without clinopyroxene, but clinopyroxene is essentially always accompanied by orthopyroxene. In the suite of heavy minerals separated from the kimberlite at Moses Rock, ortho-

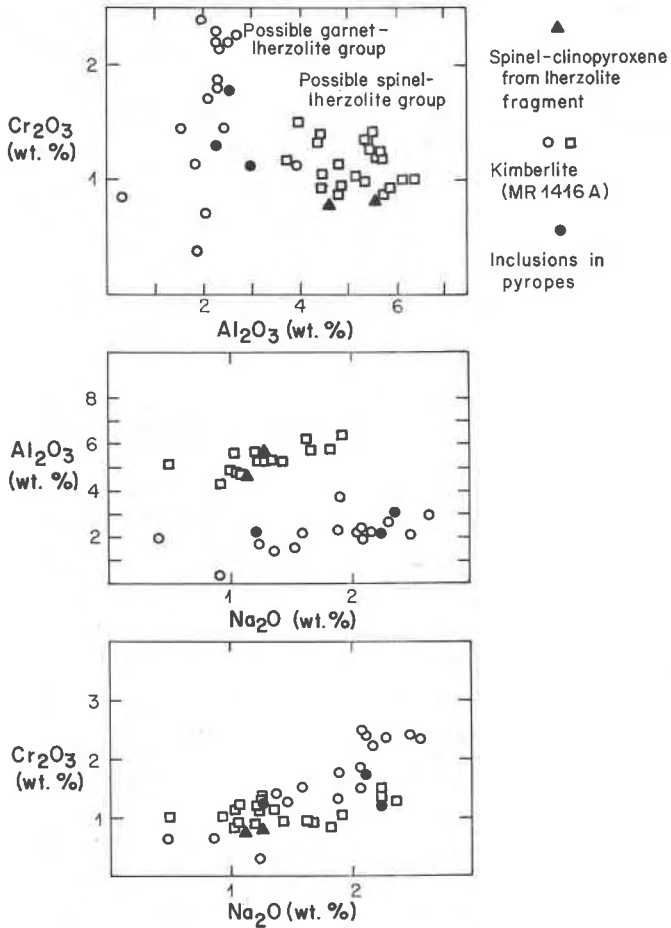


FIG. 10. Relationships among chrome-alumina-soda in clinopyroxenes from Moses Rock kimberlite, associated rock fragments and pyropic garnets.

pyroxene is more abundant than the clinopyroxene by about a factor of 5. It is difficult to assess preferential alteration of orthopyroxene versus clinopyroxenes.

A comparison of $\text{Ca}/(\text{Ca} + \text{Mg})$ ratios of the South African and Moses Rock clinopyroxenes (Figure 9) suggests that most of the Moses Rock kimberlite clinopyroxenes formed at somewhat lower temperatures than most of those from South Africa. The maximum temperature of formation suggested for the Moses Rock clinopyroxene is approximately 950°C . However, since their alumina content is fairly high, this temperature estimate may be too low because O'Hara has shown that Al_2O_3 extends

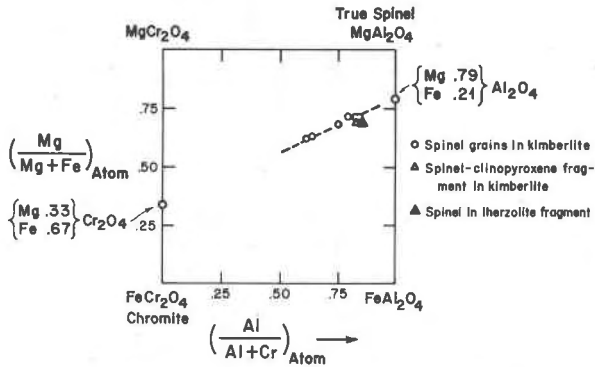


FIG. 11. Compositions of spinel grains in kimberlite and associated rock fragments.

the miscibility gap in the enstatite-diopside system (Boyd, 1966). This result however, is contradicted by more recent experiments (Boyd, 1969). The presence of Fe however, closes the miscibility gap between the pyroxenes, hence has a compensating effect. The Mg/(Mg+Fe) ratio in the clinopyroxenes ranges between 0.91 and 0.95. Probably, the crystallization of these clinopyroxenes occurred over a range of temperatures, with a maximum at perhaps 1000°C. This interpretation will be discussed later.

To sum up, at Moses Rock the kimberlite clinopyroxenes fall neatly into two groups, one like spinel-lherzolite clinopyroxenes, the other like inclusions in pyrope garnet. They are compositionally distinct from clinopyroxenes in eclogite, websterite and clinopyroxenite fragments.

Spinel. Brown spinel is present in accessory abundance in the kimberlite, and in one instance was observed intergrown with a clinopyroxene fragment. Microprobe analyses of 6 grains showed compositions ranging between $(\text{Mg}_{1.2}\text{Fe}_{0.8})(\text{Al}_{2.4}\text{Cr}_{1.6})\text{O}_8$ and $(\text{Mg}_{1.4}\text{Fe}_{0.6})(\text{Al}_{3.5}\text{Cr}_{0.5})\text{O}_8$. The variation in composition is systematic (Figure 11), and individual spinel analyses fall along a line connecting these compositions. The Al and Mg rich specimens are similar to those in the spinel-lherzolite fragment (MRX-2).

Titanoclinohumite. Titanoclinohumite has been observed in polished sections as discrete grains and in grains coexisting with olivine in kimberlite and also as an inclusion in pyrope garnet (PG-2). It has a bright yellow color in ordinary light which permits easy distinction from olivine, optically. Its textural relationships with olivine in the kimberlite and as an inclusion within pyrope (Fig. 5) virtually preclude its origin as a near-

surface alteration product, therefore it must have been an integral part of an olivine-pyroxene bearing assemblage at depth, probably garnet-peridotite.

Analyses of nine major elements for four grains from the mineral separates are presented elsewhere (McGetchin, Silver and Chodos, 1970). Grains from these same separates were powdered and identified as clinohumite by X-ray diffraction. TiO_2 contents are 4.7, 5.0, and 5.6; $\text{Mg}/(\text{Mg} + \text{Fe})$ ratios 0.93, 0.92, 0.90, and 0.89. All grains contained trace amounts of Cr and Mn.

Data on coexisting olivine and titanoclinohumite indicate that the Mg/Fe ratio of the coexisting phases are virtually equal and range from values typical of those in spinel-bearing assemblages up to those typical of garnet-bearing assemblages.

Density of the titanoclinohumite grains is approximately 3.27 gm/cm^3 .

Humite group minerals are not commonly reported members of kimberlite assemblages, although Balk has reported titanoclinohumite at Buell Park (Allen and Balk, 1964).

Although titanoclinohumite is not quantitatively important in the kimberlite assemblage at Moses Rock (about 1%), the possible significance of this phase is great (McGetchin and Silver, 1968; Jones, Ribbe and Gibbs, 1969; McGetchin, Silver and Chodos, 1970). It is a dense *hydrous* phase in the system $\text{MgO}-\text{SiO}_2-\text{H}_2\text{O}$, and could be one site where water may reside in the lower parts of the upper mantle. Kitahara, Takenouchi and Kennedy (1966) studied the system $\text{MgO}-\text{SiO}_2-\text{H}_2\text{O}$ to 30 kbar and observed no humite group minerals. Sclar *et al.* (1967) have reported hydrous pyroxenes at pressures near 50 kbars in the system $\text{MgO}-\text{SiO}_2-\text{H}_2\text{O}$, and between 1000°C and the liquidus. The high pressure stability field of clinohumite, particularly in Ti-rich systems, has not been investigated.

The presence of a *hydrous*, magnesian, titanium-rich phase in the upper mantle may be important from the point of view of petrogenesis of kimberlite, and basaltic melt as well, because *dehydration* of this mineral could release volatiles and titanium minerals. The stability of titanoclinohumite at mantle conditions is of considerable interest.

Other Coexisting Minerals. In polished thin sections of kimberlite, bi-mineralic or polyminerally fragments are occasionally observed. Of particular interest are spinel-clinopyroxene, orthopyroxene-clinopyroxene, and orthopyroxene-olivine pairs. The compositions of each mineral in all three mineral pairs are similar in composition to similar species in the spinel-lherzolite.

Four examples of bastite-clinopyroxene intergrowths were observed. The serpentine pseudomorphs after orthopyroxene appear to have little correlation with the compositions of the coexisting clinopyroxene suggesting that the alteration of the orthopyroxene has disrupted any possible prior systematic relationships.

Opaques. No systematic investigation of the opaque mineral phases has been attempted, although ilmenite-geikielite has been observed. Two opaque grains observed in the polished sections of kimberlite contained TiO_2 , 13.7 and 21.2 weight percent and FeO, 80.0 and 73.1 weight percent respectively. Titanium-rich opaque phases appear to be typical.

Other Minerals: Carbonate, Mica (?) Carbonate and micaeous minerals are also present in the kimberlite assemblage. Commonly, small veins of carbonate are observed running through the kimberlite, which cut across grains in some instances. Microprobe analyses of these carbonate veins revealed that they are nearly pure CaCO_3 , almost free of Mg. Analysis of a $\frac{1}{2}$ " thick fibrous carbonate plate, fragments of which are a common constituent in the breccia, was also found to be nearly free of Mg. Lithic fragments of limey siltstone (Cutler or Rico Formation) in the kimberlite contained carbonate with appreciable Mg. Therefore, it appears that this magnesium-free carbonate is typical of the kimberlite at the Moses Rock dike and probably is not remobilized sedimentary carbonate.

A diverse suite of layered structure minerals, apparently including micas, serpentine and chlorite is observed. Brown and black mica and light purple coarse chlorite (pseudomorphs?) are common constituents of the kimberlite at Moses Rock, and form approximately 1 percent of the rock. A systematic investigation of the compositions of these phases with the microprobe is in progress. One mica from kimberlite was analyzed during reconnaissance investigations. It is quite iron-rich (FeO, 14%; MgO, 14%) and is highly zoned.

DISCUSSION

Relationship of Kimberlite and Dense Inclusions. There are striking chemical differences between minerals observed in the crystalline rock fragments compared to minerals from the kimberlite. The Al_2O_3 content or clinopyroxene in eclogite, websterite and jadeite-clinopyroxenite are out of the range of the kimberlite clinopyroxenes. The kimberlite clinopyroxenes form two distinct compositional groups; one group resembles the spinel-lherzolite clinopyroxenes, the other the clinopyroxene inclusions in pyrope. The websterite pyroxenes are much more aluminous

than kimberlite ones. The spinel-lherzolite is the only olivine-bearing inclusion collected and the composition of its olivine is just within the kimberlite range, on the iron-rich end. Pyroxenes in spinel-lherzolite are within the compositional ranges defined by kimberlite pyroxenes. Garnets, like those from eclogite and metamorphic rock fragments are observed in the kimberlite garnet suite, but the abundant chrome-rich pyropes in the kimberlite were not observed in any crystalline fragment type.

It is believed that eclogite, clinopyroxenite, websterite and serpentine schist fragments were derived from the vent walls during the eruption of the kimberlite and transported to the surface as "accidental" xenolithic fragments, unrelated to the kimberlite in any direct way. The spinel-lherzolite, however, could represent a direct parent for *some* but not all of the kimberlite mineral phases.

Source Rocks and Genesis of the Moses Rock Kimberlite. The observations of the occurrence of kimberlite in the Moses Rock dike indicate it was *not* a silicate melt when emplaced but a fluidized system consisting of gas (or very low density fluid phase, apparently mainly water) and particulate solids. (McGetchin, 1968a, 1968b).

It has been established that the great majority of mineral fragments in kimberlite are compositionally similar to those in (1) the spinel-lherzolite fragment *or* (2) mineral inclusions in pyropic garnets, and *not* like those in pyroxenite and eclogite rock fragments. Hence, it appears that kimberlite represents a *physical* mixture of mineral grains derived from spinel-bearing and garnet-bearing lherzolite. The possibility that the pyropic garnets originate magmatically cannot be discounted completely, since pyrope melts on the solidus in ultramafic systems at high pressures (Green and Ringwood, 1967; Ito and Kennedy, 1968). However, the petrographic character and field occurrence of the kimberlite suggest its emplacement as a crystal-breccia blown in by a low density fluid phase, gaseous near the surface. Mica, carbonate and opaque phases so abundant in other kimberlites are not abundant in kimberlite at Moses Rock.

The simplest interpretation of the mineral data suggests that Moses Rock kimberlite was emplaced as crystal and rock fragments entrained by a volatile-rich fluid phase predominantly H₂O but with possible CO₂. The pervasive serpentinization probably occurred as the crystal breccia "stewed in its own juice" during and immediately after emplacement.

Proceeding with the hypothesis that Moses Rock kimberlite is a physical mixture of mineral assemblages derived from mantle rocks, it is possible to place some constraints on the modal abundances of minerals constituting these assemblages, with the data at hand. Material balance

considerations permit crude estimates of the relative contributions of each of the two assemblages because the *mode* of the postulated garnet-bearing assemblage is constrained by (1) the relative proportion of kimberlite minerals with affinities to spinel or garnet assemblages, and (2) the observed modes of the kimberlite and of the spinel-lherzolite fragment. This assumes that all garnet bearing assemblages are lherzolite—not harzburgite or wehrlite.

Two simultaneous equations can be written for *each mineral* involving the two unknowns, volume fraction of garnet-lherzolite (X_g) in the kimberlite, and the modal abundance of each mineral in the postulated garnet-lherzolite assemblage (M_g).

$$M_k = M_s(1 - X_g) + M_g X_g \quad (1)$$

$$R_0 = M_s(1 - X_g)/M_g X_g \quad (2)$$

where

M_k = observed modal abundance of minerals in kimberlite

M_s = observed modal abundance of minerals in spinel-lherzolite

M_g = unknown modal abundance of minerals in garnet-lherzolite

X_g = volume fraction of garnet-lherzolite in kimberlite

$1 - X_g$ = volume fraction of spinel-lherzolite in kimberlite

R_0 = observed ratio of minerals in kimberlite with affinities to spinel-lherzolite minerals/minerals with affinities to minerals associated with garnet (see Fig. 7, 8, 9).

In the above equations only X_g and M_g are unknown. The other quantities are observed or can be estimated from observations. The quantities used in the calculations and results for X_g are shown below:

	Kimberlite Mode M_k	Spinel-Lherzolite Mode M_s	R_0	Range of solutions for X_g
Olivine	80	54	1/3 and 1	.26 to .63
Orthopyroxene	12	37	20 and 40	.68 to .69
Clinopyroxene	1 and 3	7	1/2	.71 to .90

The calculations show that $X_g \sim 0.70$ is in best agreement with the available data suggesting that the kimberlite composition can be considered as a physical mixture of spinel- and garnet-bearing assemblages in the approximate ratio 30 to 70.

The modal abundances of the major mineral phases in the postulated garnet-lherzolite can be calculated by substituting $X = 0.70$ into equation (1). This calculated mode is olivine 91, orthopyroxene 1, clinopyroxene 1, and on a similar basis, garnet 4, others 3. This rock approaches garnet

TABLE 4. Calculated Modal Composition and Relative Abundances of Assemblages from which the Moses Rock Kimberlite Formed Based on a Simple Mixing of Spinel-Lherzolite and Inferred Garnet-Lherzolite

<i>Spinel-Lherzolite^a</i>	
54 Olivine	Mg/(Mg+Fe) = 90
37 Orthopyroxene	Mg/(Mg+Fe) = 91; Al ₂ O ₃ = 2.5 to 5%
7 Clinopyroxene	Ca/(Ca+Mg) = 48 to 52; Al ₂ O ₃ = 4 to 6.5% Cr ₂ O ₃ = .8; Mg/Mg+Fe = 94; Na ₂ O = 1.2; FeO = 1.8
2 Spinel	Mg/(Mg+Fe) = 60 to 70; Al/Al+Cr = 60 to 80
Titanoclinohumite	Mg/(Mg+Fe) = 90
<i>Garnet-Lherzolite^a</i>	
91 Olivine	Mg/(Mg+Fe) = 94
1 Orthopyroxene	Mg/(Mg+Fe) = 94; Al ₂ O ₃ = 0.5 to 1%
1 Clinopyroxene	Ca/(Ca+Mg) = 48 to 50; Al ₂ O ₃ = 1.5 to 3.0; Cr ₂ O ₃ = 1.5; Mg/(Mg+Fe) = 92 to 96; Na ₂ O = 1.2 to 2.5; FeO = 1.3 to 2.5
4 Garnet	Mg:Fe:Ca = 69:19:12; Cr ₂ O ₃ = 1.4 to 2.5
{ Ilmenite (Geikielite)	TiO ₂ = 58; FeO = 33; MgO = 12
{ Rutile	Some Cr, Fe, Mg in solid solution
3 Titanoclinohumite	Mg/(Fe+Mg) = 93; TiO ₂ = 4 to 6%
{ Mica or Chlorite	
Kimberlite	{ 7 Part Garnet-Lherzolite + Volatiles 3 Part Spinel-Lherzolite

^a All ratios are on atom basis; all concentrations are oxide weight percent

dunite in composition. However, numerous assumptions make this an approximation.

Table 4 summarizes the inferred relative abundances, and modal and mineralogical compositions of the two assemblages from which the Moses Rock kimberlite was derived.

Location of the Reservoir Inferred from Clinopyroxene Compositions. Minerals in natural four-phase peridotites (rocks containing plagioclase, spinel or garnet in addition to olivine and two pyroxenes) consist of complex solid solutions whose compositions are variable depending on the conditions of their genesis. Calcium-rich pyroxenes are especially sensitive to conditions of formation, because of solid solution relationships with garnet or spinel and also with calcium-poor pyroxene. In the system MgO—CaO—Al₂O₃—SiO₂, at a given temperature and pressure, the composition of a clinopyroxene coexisting with orthopyroxene, olivine and spinel or garnet is uniquely determined.

Specific *P-T* assignments can be made to individual clinopyroxenes in

four-phase peridotite assemblages on the basis of their $\text{Ca}/(\text{Ca}+\text{Mg})$ ratio and Al_2O_3 content (in excess of jadeitic ($\text{NaR}_2\text{Si}_2\text{O}_6$) component). The $\text{Mg}/(\text{Ca}+\text{Mg})$ ratio is a measure of the amount of enstatite solid solution in the clinopyroxene; the alumina content (or rather $\text{R}_2\text{O}_3 = \text{Al}_2\text{O}_3 + \text{Cr}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) is a measure of the "garnet" solid solution. Both solid solution relations have different functional relations to P and T . As a result, the composition of clinopyroxenes existing in equilibrium within the stability field of a given four-phase peridotite assemblage is unique, at least in theory. Experimentally determined phase diagrams on synthetic and natural systems are the basis of these interpretations. O'Hara (1967) has recently summarized the experimental and observational work of many authors on mineral relationships in the system $\text{CaO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ and natural systems which approach this compositional tetrahedron.

It is important to point out that the effects of additional components on the behavior of these systems is significant (MacGregor, 1969). The most important substitutions quantitatively are Cr and Fe^{+3} for Al, Fe^{+2} for Mg and the addition of TiO_2 , Na_2O , and K_2O . Trace amounts of other constituents such as MnO, and NiO are probably relatively unimportant.

Before P - T assignments were made from the microprobe analyses of clinopyroxene analyses from the Moses Rock dike it was necessary to make some estimate of the $\text{Fe}^{+3}/\text{Fe}^{+2}$ ratio because the microprobe does not distinguish between oxidation states. This was done by assuming that the ratio ferric iron to total iron has a linear relationship with soda similar to that in chemically analyzed clinopyroxenes in peridotites (Ross, Foster, and Myers, 1954; Nixon, von Knorring, and Rooke, 1963). The curve used in estimating the iron oxidation state is shown in Figure 12.

After calculating the ferric-ferrous ratio, two compositional parameters were determined from each clinopyroxene analysis. The first was the atom ratio $\text{Ca}/(\text{Ca}+M)$ where M represents all octahedrally coordinated cations including Mg, Fe^{+2} and Mn. This quantity was used to assign provisional temperatures by comparison with $\text{Ca}/(\text{Ca}+\text{Mg})$ ratios on the diopside-enstatite solvus at 30 kilobars (Davis and Boyd, 1966). The location of this solvus is relatively insensitive to pressure. This parameter is similar to α as defined by O'Hara (1967) except we assume α to be a function of temperature only, consistent with Boyd (1969).

Next the solid solution of "garnet" component in the pyroxene was determined by examining the amount of R_2O_3 group elements in excess of jadeite component. This was done from the structure formula by recalculating the atom quantity $(\text{Al}^{+3} + \text{Cr}^{+3} + \text{Fe}^{+3} - \text{Na}^+)$ in terms of

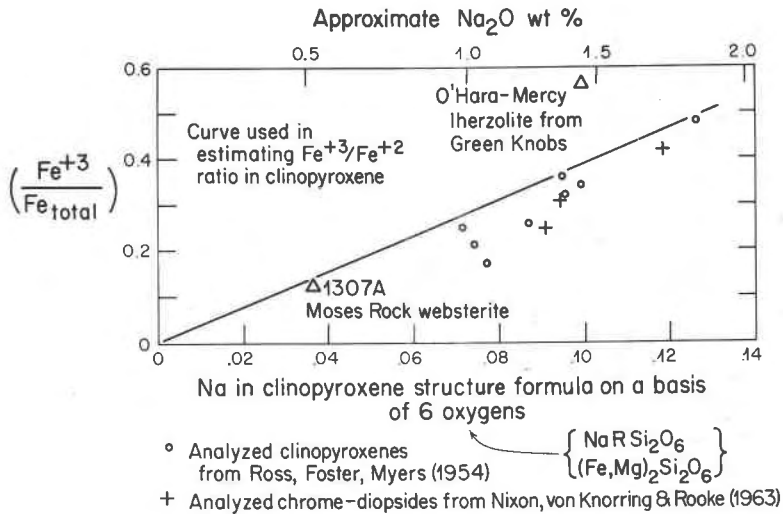


FIG. 12. Relationship between Fe^{3+}/Fe (total) and Na content of analysed clinopyroxenes from ultramafic rocks, taken from the literature. Indicated curve was used to estimate ferric/ferrous ratio in the clinopyroxenes.

equivalent weight Al_2O_3 . Al_2O_3 content of pyroxene in equilibrium with pyrope has been investigated by Boyd and MacGregor (1964) and Green and Ringwood (1967). These investigations have shown that Al_2O_3 content is a function of both P and T (see for example, Green and Ringwood, 1967, *p.* 155). The data of Green and Ringwood (1967) on natural peridotites was used in making the P - T assignments but the results would be very similar using Boyd and MacGregor's data. In the garnet peridotite field, intersections of $\text{Ca}/(\text{Ca} + \text{Mg})$ ratio and Al_2O_3 isopleths provide a means of estimating pressures and temperatures of formation for clinopyroxenes from lherzolite assemblages, under the assumption that the mineral phases, clinopyroxene, orthopyroxene and garnet, coexisted in equilibrium.

Provisional P - T assignments on clinopyroxenes from the Moses Rock dike are in the ranges 10–60 kbar and 900–1000°C and are shown in Figure 13. Similar schemes exist in the literature, most notably that of O'Hara (1967). Figure 13 differs in that the temperature assignments were made directly from the diopside-enstatite solvus, with no correction for the effect of minor constituents on the solvus. Recent experiments by Boyd (1969) suggest that temperature assignments based directly on the diopside-enstatite diagram appear to be reasonable approximations for peridotite systems and, at present, are probably as effective as schemes in which a correction for Al_2O_3 is made.

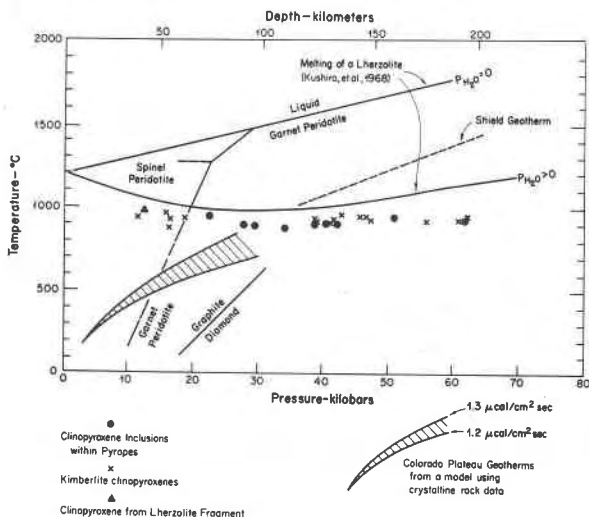


FIG. 13. Provisional assignment of equilibrium conditions of formation of clinopyroxenes from kimberlite, associated rocks and inclusions in pyropic garnets from the Moses Rock dike.

The results, shown in Figure 13 suggest if the clinopyroxenes found as fragments in the Moses Rock kimberlite and as inclusions in associated pyropes were in equilibrium with four-phase peridotite assemblages, they formed over a range of depths extending from the base of the crust to about 200 km. Indicated temperatures at depth are modest, possibly below solidus temperatures in ultramafic systems of low K_2O content. They are nearly constant, parallel to and nearly coincident with the wet melting curve of a natural garnet lherzolite (Kushiro, *et al.*, 1968), suggesting an upper mantle geotherm buffered against a lherzolite solidus. It has been suggested that if the Al_2O_3 isopleths have a positive slope in the spinel-peridotite field, the P - T assignments for spinel-bearing assemblages will be at higher temperatures therefore, even closer to the lherzolite solidus (MacGregor, personal communication, 1970). Also, this array crosses geotherms calculated for a plausible crustal-upper mantle model developed from an investigation of the crystalline rock fragments in the Moses Rock dike (see McGetchin, 1968). The suggested geothermal gradient is essentially flat between 50 and 150 kilometers. Calculated temperatures at depth are significantly lower than those shown by Clark and Ringwood (1964) for shield regions.

Phase Transformations in Lherzolite with Depth in the Upper Mantle.
The transition from spinel-lherzolite to garnet-lherzolite with increasing

depth in the oceanic upper mantle as suggested by Boyd, Ringwood, MacGregor, and also recently by Ito and Kennedy (1967) and Green and Ringwood (1967), appears to be consistent with the observations here. The paucity of garnet-lherzolite as discrete rock fragments may be due to comminution to millimeter size fragments (a view consistent with a very deep-seated origin). Also, the conditions inferred for the reservoir (a region in the mantle where volatiles may be collecting along grain boundaries) may reduce rock resistance to comminution. After observing the stress-induced birefringence, radial cracks and cratering around mineral inclusions in pyropes from the Colorado Plateau kimberlites Richey (1968) has concluded independently that the pyropes originated from garnet-peridotite at great depth and suggested that the parent garnet-peridotite experienced auto-destruction due to differential expansion of mineral phases during transport to the surface.

Possible Significance of Titanoclinohumite. The titanoclinohumite found with pyropes and intergrown with forsteritic olivine may play an essential role in the genesis of the kimberlite (McGetchin, Silver and Chodos, 1970). If this phase is quantitatively important at pressures above 50 kbar then it could have great geophysical importance. Dehydration at lower (or very high) pressures may provide the volatile phase responsible for the eruption. The release of bound water near 50 kbar (150 km) could aid partial melting of mantle rocks to produce basaltic melts, provide an alternate explanation to partial melting for the low velocity zone in regions of low geothermal gradient such as the Colorado Plateau. This process could also account for serpentinization of the upper mantle under the Colorado Plateau as suggested by Hess (1954) and part of the epeirogenic uplift of the region.

SUMMARY

1. The primary mineral suite of the kimberlite breccia at Moses Rock dike includes olivine, pyrope, spinel, clinopyroxene, orthopyroxene, titanoclinohumite, ilmenite-geikielite, and possible mica. These can be explained as a mixture of two dominant lherzolite assemblages; garnet-lherzolite and spinel-lherzolite in the approximate ratio 70:30. This is distinctly different from the observed relative abundance of lherzolite xenoliths in South African kimberlites, estimated by MacGregor (personal communication, 1970) to be about 95:5, garnet- to spinel-bearing types.

2. Microprobe investigations of mineral grains in kimberlite have shown that they are compositionally unlike those found in almost all associated xenoliths: the known exceptions are a spinel lherzolite fragment and small mineral inclusions in pyrope fragments. All of the other

dense and ultramafic xenolithic fragments are apparently unrelated to the kimberlite and are considered to be accidental inclusions derived from the vent walls during the eruption.

3. Tentative *P-T* assignments to kimberlite clinopyroxene grains suggest their derivation over a significant depth range in the upper mantle, from about 35 to nearly 200 km depth. Indicated temperatures are remarkably constant in the range 900 to 1000°C.

4. The unzoned character of the mineral inclusions and associated pyropes suggests these assemblages formed in chemical equilibrium, consistent with the conditions indicated above. This view is in accord with the observable strain effects in the garnet surrounding the mineral inclusions, which argues that the assemblages existed as discrete crystalline entities in a *P-T* environment far removed from the surface before their incorporation in the erupting kimberlite and transport to the surface.

5. Titanoclinohumite may be considered among possible hydrous phases in the upper mantle and its decomposition may play a role in providing volatiles involved in the emplacement of kimberlite.

6. To sum up, the observations at the Moses Rock dike are consistent with the view that the kimberlite was derived from the upper mantle, at depths extending to 150 kilometers or more, from a reservoir of unknown extent and geometry which contained a free volatile (water-rich?) phase, and that the erupting kimberlite consists of this volatile phase plus the products of physical disaggregation of spinel-lherzolite and garnet-lherzolite. The locus of temperatures indicated by clinopyroxenes are below and parallel to the solidus curve for wet ultramafic systems compositionally similar to kimberlite at Moses Rock (Kushiro, *et al.*, 1968). This suggests the possibility of a geotherm (or fossil geotherm) buffered against the garnet lherzolite solidus boundary.

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APPENDIX. ANALYTICAL TECHNIQUES

Whole Rock Chemical Analyses. The Analytical Branch, U. S. Geological Survey, Denver, Colorado, provided the major and trace element analyses by gravimetric and spectrographic methods. Specimens selected for chemical analysis were taken from a suite of crystalline rock fragments collected at the Moses Rock dike on the basis of hand specimen and thin section petrography. Rocks were selected to represent the range of chemical and petrographic types on the basis of reconnaissance and some detailed petrography. Selected specimens were powdered to -200 mesh with a "Diamonite" mortar and pestle.

Electron Microprobe. Partial chemical analyses were made with an Applied Research Laboratory three-channel electron microprobe (EMX) equipped with pulse height analysers on each channel. Two channels had sealed proportional gas-counter detectors; the third a gas flow counter. Analyses were made at an operating voltage of 15 kV and a sample current of 0.05 μ A; rarely sample currents of 0.10 μ A was used. The size of the spot produced by the electron beam ranged from 2 to about 10 μ m. Volatilization of specimens was not an analytical problem. Sample current readings were made on brass mounts or currents measured on specimen surfaces were calibrated to brass. Dead time correction was included for high counting rates. Background counts were taken routinely on all analyses of both standard and unknown minerals. Counts on unknowns generally ranged between 10^4 and 10^5 counts for runs of 10 seconds on each spot.

Analyses of unknowns were obtained by direct reduction of counts to oxide weight percent calibrated against analysed mineral standards, generally end-member compositions, and by the technique of Bence and Albee (1968). A CITRAN computer program developed by Drs. Alfred Bence, Arden L. Albee and Richard Naylor was used in the data reduction. Discrepancies between the two methods were usually negligible or attributable to doubtful results of wet chemical analyses of the standards.

Two types of samples were prepared for electron microprobe analysis: (1) polished thin sections of rocks, and (2) grains mounted in epoxy.