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ECLOGITE INCLUSIONS IN KIMBERLITE PIPES AT GARNET RIDGE, NORTHEASTERN ARIZONA

K. D. WATSON, *Department of Geology, Univerity of California, Los Angeles, California 90024*

AND

D. M. MORTON, *Calfornia Division of Mines and Geology, Los Angeles, California.*

ABSTRACT

Pyroxene in eclogite inclusions from kimberlite pipes at Garnet Ridge, northeastern Arizona, is essentially diopsidic jadeite (58 to 73 percent $NaAlSi_2O_6$) with an appreciable proportion of acmite. The coexisting garnet is pyropic almandine (62 to 70 percent $Fe_3Al_2Si_3O_{12}$ and 12 to 23 percent $Mg_3Al_2Si_3O_{12}$) with an appreciable content of grossularite.

Chemically, the eclogite at Garnet Ridge differs markedly from those found elsewhere as inclusions in kimberlite. Although the compositions of pyroxene and garnet in eclogite from Garnet Ridge resemble those of pyroxene and garnet in eclogite occurring as lenses in glaucophane schist terrains, there is no geological evidence at Garnet Ridge suggesting derivation from such a basement. The association of sparse eclogite inclusions with abundant xenoliths of granite gneiss and granite at Garnet Ridge may suggest that the garnet-pyroxene rocks were derived from eclogite lenses occurring in a migmatitic granite gneiss basement. However, the presence of similar granitic inclusions in abundance without eclogite in nearby minette diatremes does not favor this idea.

The fact that soda-rich eclogite occurs at Garnet Ridge in the same general region as the Hopi Buttes soda-rich volcanic province raises the question as to whether there may be some genetic significance to this association.

INTRODUCTION

The occurrence of eclogite inclusions in the kimberlite pipes of Africa has long been known, and the ones in both African and Siberian pipes have become quite familiar to many geologists from the descriptions published during the past several years. Not until a few years ago, however, was a somewhat similar occurrence in North America—the eclogite inclusions in kimberlite pipes at Garnet Ridge—first reported (Watson, 1960). In a recent paper, O'Hara and Mercy include a petrographic description of an eclogite fragment from Garnet Ridge along with a chemical analysis of the rock and of its constituent clinopyroxene and garnet (1966, p. 342). We have meanwhile continued investigation of the eclogite inclusions occurring at Garnet Ridge and have obtained mineralogical and chemical data essentially in agreement with the results of O'Hara and Mercy. Since a greater variety of eclogitic material was included in the present study, our observations and interpretation may also be of interest.

Many diatremes, dikes, and flows consisting of monchiquite, minette, limburgite, and trachybasalt occur in the part of the Colorado Plateau

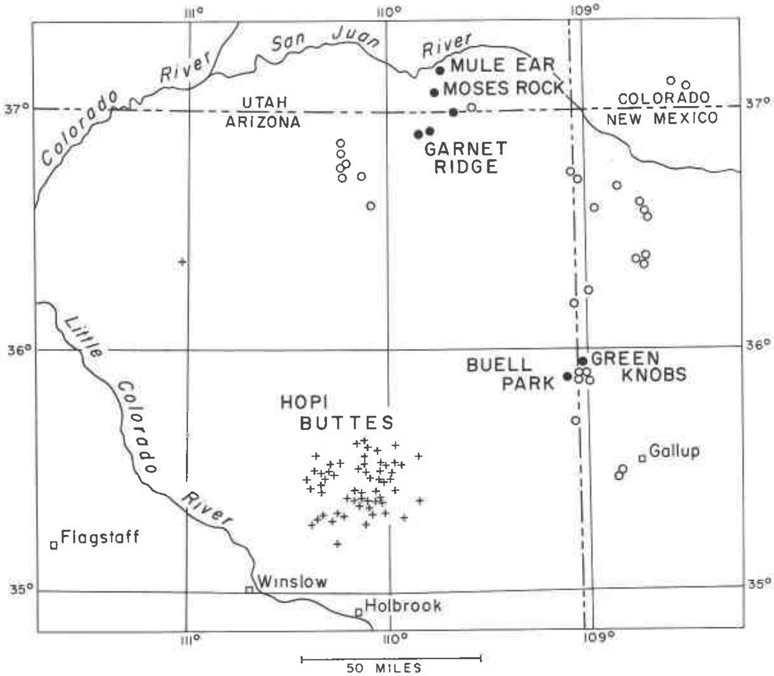

FIG. 1. Map of northeastern Arizona and adjacent parts of New Mexico, Utah, and Colorado showing distribution of kimberlite (black circles); minette and trachybasalt (open circles); monchiquite and limburgite (crosses). Mainly after Shoemaker (1956) and Shoemaker, Roach, and Byers (1962).

lying within northeastern Arizona and adjacent parts of Utah, New Mexico, and Colorado (Fig. 1). They have been described by Williams (1936), Hack (1942), Balk and Sun (1954), Shoemaker (1956), Shoemaker, Roach, and Byers (1962), and by others. As shown in Figure 1, the bodies in the Hopi Buttes area consist of monchiquite and limburgite, whereas most of those occurring elsewhere are minette and trachybasalt. There are within this region, in addition, nine diatremes that consist of an exceedingly abundant, closely packed, heterogeneous assemblage of sedimentary and crystalline xenoliths contained in a matrix rich in serpentine and/or olivine. These include the four kimberlite pipes occurring at Garnet Ridge. Since detailed descriptions of these, accompained by geological maps, have been published recently (Malde and Thaden, 1963; Watson, 1967), an account is not given here.

XENOLITHS AT GARNET RIDGE

The largest xenolithic blocks are Jurassic sedimentary rocks, many of which measure several tens of feet to a few hundreds of feet in length.

These blocks, which now are in juxtaposition, belong to the Morrison Formation and to the San Rafael Group and once were far apart stratigraphically. All have subsided to their present positions. One pipe includes a few blocks of shale containing "species of pelagic Foraminifera such as are found in the Mancos shale (Late Cretaceous) stratigraphically about 1200 feet higher" (Malde and Thaden, 1963, p. 57).

The kimberlite between the large Mesozoic blocks contains innumerable granule- to boulder-sized inclusions derived from the Paleozoic sedimentary section and the Precambrian igneous and metamorphic basement below. Most of these xenoliths are pebble-sized and subangular but the larger ones are well rounded and reach 10 feet in diameter. The surfaces of most xenoliths in contact with kimberlite are smooth or polished and the surfaces of a few even are striated. Inclusions of fossiliferous Paleozoic limestone show no metamorphism whatsoever, but a few inclusions of black shale and red sandstone have been slightly bleached. The fragments derived from the crystalline basement have ascended at least 4000 feet (Malde and Thaden, 1963, p. 56). These are mainly granites and granite gneisses; they include in addition, amphibolites, pyroxene granulites, peridotites, serpentine-actinolite-carbonate rocks, pyroxenites, eclogites and a great variety of other kinds of igneous and metamorphic rocks. None of the eclogite inclusions found have other kinds of rock attached to them; hence, they provide no direct evidence of their associations in the crystalline basement.

Eclogite

The eclogite inclusions at Garnet Ridge are sparse and, for the most part, small in size. They constitute far less than one percent of the total xenolith population and, although a few slightly exceed 15 cm in diameter, most are less than 5 cm. Similar eclogite fragments have been seen by the writers among the xenoliths at Moses Rock and Mule Ear in Utah and a related pyroxene-rich eclogite has been described by O'Hara and Mercy (1966, p. 341) from Green Knobs in New Mexico (Fig. 1). However, eclogite has not been found in the kimberlite diatreme at Buell Park.

The eclogites are medium-to fine-grained rocks in which bright green pyroxene and pink to red garnet can easily be seen macroscopically. Many of the nodules also contain megascopic white lawsonite or an extremely fine-grained white aggregate composed mainly of zoisite derived therefrom. A few also have megascopically discernible white mica, rutile, and pyrite. Modes of nine inclusions are recorded in Table 1. Although some inclusions contain almost as much garnet as pyroxene, most have considerably more pyroxene than garnet, and some contain so much pyroxene (*e.g.* 2 and 3, Table 1) that they could be called py-

TABLE 1. MINERALOGICAL COMPOSITION OF ECLOGITE, GARNET RIDGE, ARIZONA

	1	2	3	4	5	6	7	8	9
Clinopyroxene	48.2	88.3	92.9	78	46	51	54	59	62
Garnet	43.2	9.8	5.0	20	36	29	35	33	33
Rutile	3.9	1.5	0.7	2	4	3	4	3	5
Lawsonite and altered lawsonite	4.1	0.1	0.5	0	14	17	2	5	tr
Mica	0.0	0.0	0.0	tr	0	0	4	0	0
Apatite	0.5	0.0	0.0	0	0	0	0	0	0
Pyrite, hematite, and goethite	0.1	0.3	0.9	tr	0	0	1	tr	0

Percentage by volume.
1, 2, 3. GR-P1-11, GR-P1-6, GR-P1-25, respectively.
4. G. R. 1. (O'Hara and Mercy, 1966, p. 342).
5, 6, 7, 8, 9. GR-P2-3, GR-P2-1, GR-P2-17, GR-P2-5, GR-P2-4, respectively.

roxenite appropriately. The pyroxenite-like rocks actually constitute a high proportion of the eclogite nodules. Measurements of the density of 13 nodules range from 3.27 to 3.57 and average 3.43. Most inclusions are essentially massive, but some show distinct alignment of the pyroxene prisms.

Microscopically, most of the inclusions have medium- to fine-grained granular texture. They consist of approximately equidimensional to slightly elongate anhedral grains of pyroxene interlocking with equant, subhedral to anhedral crystals of garnet (Fig. 1). Commonly the garnet occurs as clusters of coalescent crystals. In a few places, aggregates of fine equant pyroxene grains form cores or incomplete intermediate zones within crystals of garnet.

Pyroxene, which ranges in amount from 46 to 93 percent in the measured thin sections (Table 1), is pale green in sections of standard thickness. In some inclusions it shows strong dispersion. Zoning is evident in some grains but it is not common. Alteration to amphibole or other retrograde minerals, common in eclogites occurring elsewhere, is wholly absent. Chemical analyses of samples of pyroxene from three eclogite inclusions (Table 2) show that it is essentially diopsidic jadeite with an appreciable proportion of acmite (Table 3). The jadeite content ranges approximately from 58 to 73 percent. Analyses of one pyroxene from Garnet Ridge and one from Green Knobs, New Mexico, published by O'Hara and Mercy (1966, pp. 341–342) and included in Tables 2 and 3, show a jadeite content of approximately 50 percent. The optical properties of the analyzed pyroxenes from Garnet Ridge are given in Table 4 and the range in properties of omphacite listed by Deer, Howie, and Zussman (1963) is included for comparison.

Garnet, which ranges from 5 to 43 percent by volume (Table 1), is light pink in sections of standard thickness. In several of the nodules examined, the garnet crystals are zoned, showing a gradation from pink cores to almost colorless rims. Small inclusions are abundant

TABLE 2. CLINOPYROXENE IN ECLOGITE, ARIZONA AND NEW MEXICO

	1	2	3	4	5
Chemical Analyses					
SiO_2	55.75	57.40	57.47	56.22	56.38
TiO_2	1.62	0.18	0.31	0.87	0.22
Al_2O_3	14.66	18.06	17.14	13.07	13.74
Cr_2O_3	0.03	0.02	—	0.022	0.001
V_2O_5	0.11	0.04	—	—	—
Fe_2O_3	3.28	5.10	3.35	3.92	4.66
FeO	1.95	0.69	0.90	1.46	1.24
MnO	0.02	0.05	0.06	0.046	0.11
NiO	0.02	0.00	0.00	0.018	0.022
MgO	4.99	2.48	3.92	6.56	6.70
CaO	7.63	2.89	5.40	9.13	7.73
SrO	0.00	0.00	—	—	—
BaO	0.02	0.01	—	—	—
Na_2O	9.70	12.80	11.23	8.80	9.01
K_2O	0.01	0.01	0.01	<0.01	0.06
Li_2O	0.02	0.03	0.03	—	—
P_2O_5	0.00	0.00	—	<0.003	—
CO_2	0.00	0.00	—	—	—
S	—	0.00	—	—	—
F	—	—	0.00	—	—
H_2O^+	0.19	0.24	0.18	—	—
H_2O^-	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.12	99.87
Number of Ions on the Basis of Six Oxygens					
Si	1.962 } 2.00	1.994 } 2.00	1.995 } 2.00	1.976 } 2.00	1.981 } 2.00
Al	0.038	0.006	0.005	0.024	0.019
Al	0.570	0.733	0.696	0.518	0.550
Ti	0.043	0.005	0.008	0.023	0.006
Cr^{+3}	0.001	0.000	—	0.001	0.000
V^{+5}	0.003	0.001	—	—	—
Fe^{+3}	0.087 } 1.02	0.133 } 1.02	0.088 } 1.02	0.104 } 1.04	0.123 } 1.07
Fe^{+2}	0.057	0.020	0.026	0.043	0.036
Mn	0.001	0.002	0.002	0.001	0.003
Ni	0.001	0.000	—	0.001	0.001
Mg	0.261	0.129	0.203	0.344	0.351
Ca	0.287	0.108	0.201	0.344	0.291
Sr	0.000	0.000	—	—	—
Ba	0.000	0.000	—	—	—
Na	0.661 } 0.95	0.862 } 0.97	0.755 } 0.96	0.600 } 0.94	0.614 } 0.91
K	0.000	0.000	0.000	0.000	—
Li	0.003	0.004	0.004	—	—

1. GR-P1-11, Garnet Ridge, Arizona; after correction for the presence of garnet, rutile, lawsonite and iron oxides totalling 1.1%; C. O. Ingamells, analyst.
2. GR-P1-6, Garnet Ridge, Arizona; after correction for the presence of garnet, rutile, and lawsonite totalling 0.8%; C. O. Ingamells, analyst.
3. GR-P1-25, Garnet Ridge, Arizona; after correction for the presence of garnet, rutile, lawsonite, and iron oxides totalling 1.1%; C. O. Ingamells, analyst.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

TABLE 3. CLINOPYROXENE IN ECLOGITE, ARIZONA AND NEW MEXICO

Molecular Proportions of End-Members

	1	2	3	4	5
Jadeite	57.7	73.3	67.1	49.6	49.1
Acmite	8.7	13.3	8.8	10.4	12.3
Diopside	24.0	10.6	20.8	33.2	32.8
Hedenbergite	5.8	2.2	2.8	4.4	3.9
Tschermakite	3.8	0.6	0.5	2.4	1.9

1, 2, 3. GR-P1-11, GR-P1-6, GR-P1-25, respectively, Garnet Ridge, Arizona.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

and tend to be concentrated in the cores. Among these, rutile is common and pyroxene, lawsonite, and apatite less so. In a few xenoliths, evidence of slight rotation of some of the garnet crystals is recorded in their curved trains of inclusions. These same xenoliths are foliated; the pyroxene crystals between layers rich in garnet show elongation, preferred orientation, and reduction in grain size. The garnet of the eclogites, like the pyroxene, is free of retrogressive alteration. Chemical analyses of samples of garnet from three inclusions (Table 5) show that it is pyropic almandine containing an appreciable proportion of grossularite (Table 6). They range approximately from 62 to 70 percent $Fe_3Al_2Si_3O_{12}$ and from

TABLE 4. CLINOPYROXENE IN ECLOGITE, GARNET RIDGE, ARIZONA

	1	2	3	4	5
n_α	1.671	1.671	1.669	1.673	1.662–1.691
n_β	1.678	1.677	1.676	1.683	1.670–1.700
n_γ	1.690	1.689	1.688	1.695	1.688–1.718
$n_\gamma - n_\alpha$	0.019	0.018	0.019	0.022	0.018–0.027
$2V_z$ (calculated)	75°	71°	75°	85°	
$2V_z$ (measured)	79°, 82°	79°, 83°	72°, 76°, 76°, 76°–77°[a], 82°		58°–83°
$Z \wedge c$	47°	50°, 55°	40°, 41°–48°[a], 45°		36°–48°

[a] Zoned crystal.

1, 2, 3. GR-P1-11, GR-P1-6, GR-P1-25, respectively, Garnet Ridge, Arizona; n determinations are ±.002.

4. G.R. 1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).

5. Omphacite; range in optical properties; (Deer, Howie, and Zussman, 1963, vol. 2, p. 154).

TABLE 5. GARNET IN ECLOGITE, ARIZONA AND NEW MEXICO

Chemical Analyses

	1	2	3	4	5
SiO_2	37.53	38.91	38.51	38.10	39.31
TiO_2	1.38	0.00	0.00	0.09	0.35
Al_2O_3	20.65	21.34	21.12	21.89	22.03
Cr_2O_3	0.00	0.00	—	0.017	0.001
V_2O_5	0.02	0.00	—	—	—
Fe_2O_3	0.00	0.30	0.00	1.47	1.07
FeO	30.54	27.91	29.94	26.62	24.00
MnO	1.05	1.04	0.83	0.82	0.74
NiO	0.00	0.00	0.00	0.003	0.002
MgO	2.95	5.79	5.26	5.69	9.52
CaO	5.51	4.29	3.89	5.66	3.35
SrO	0.00	0.00	—	—	—
BaO	0.02	0.00	—	—	—
Na_2O	0.19	0.28	0.27	0.06	0.08
K_2O	0.02	0.03	0.02	0.04	0.03
P_2O_5	0.11	0.03	0.02	<0.003	—
CO_2	0.00	0.00	—	—	—
S	0.00	0.00	—	—	—
H_2O+	0.03	0.08	0.14	—	—
H_2O-	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.45	100.48

Number of Ions on the Basis of 24 Oxygens

	1		2		3		4		5	
Si	5.982	6.00	6.080	6.08	6.063	6.06	5.930	6.00	5.980	6.00
Al	0.018		0.000		0.000		0.070		0.020	
Al	3.861	4.04	3.929	3.96	3.928	3.93	3.946	4.13	3.930	4.09
Ti	0.166		0.000		0.000		0.010		0.040	
V^{+5}	0.002		0.000		—		—		—	
Fe^{+3}	0.000		0.034		0.000		0.172		0.122	
Fe^{+2}	4.069	5.92	3.645	5.94	3.940	6.03	3.464	5.84	3.054	5.86
Mn	0.142		0.137		0.111		0.108		0.096	
Ni	0.000		0.000		0.000		0.000		0.000	
Mg	0.700		1.349		1.234		1.320		2.158	
Ca	0.941		0.719		0.656		0.944		0.546	
Ba	0.001		0.000		—		—		—	
Na	0.060		0.086		0.081		—		—	
K	0.004		0.006		0.004		—		—	

1. GR-P1-11, Garnet Ridge, Arizona, after correction for the presence of pyroxene, rutile, lawsonite, and iron oxides totalling 1.0%; C. O. Ingamells, analyst.
2. GR-P1-6, Garnet Ridge, Arizona; after correction for the presence of pyroxene, rutile, and iron oxides totalling 1.7%; C. O. Ingamells, analyst.
3. GR-P1-25, Garnet Ridge, Arizona; after correction for the presence of pyroxene, rutile, and iron oxides totalling 2.0%; C. O. Ingamells, analyst.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

TABLE 6. GARNET IN ECLOGITE, ARIZONA AND NEW MEXICO

Molecular Proportions of End-Members					
	1	2	3	4	5
Almandine	69.5	62.3	66.3	59.4	52.2
Spessartite	2.4	2.3	1.9	1.8	1.6
Pyrope	12.0	23.1	20.8	22.6	36.9
Grossularite	11.8	11.4	11.0	11.5	5.2
Andradite	4.3	0.9	0.0	4.7	4.1

1, 2, 3. GR-P1-11, GR-P1-6, GR-P1-25, respectively, Garnet Ridge, Arizona.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

12 to 23 percent $Mg_3Al_2Si_3O_{12}$. Analyses of one sample from Garnet Ridge and one from Green Knobs published by O'Hara and Mercy (1966, pp. 341–342) and listed in Tables 5 and 6, show compositions somewhat similar to these. The refractive indices and lengths of the cell edges of the three analyzed garnets are given in Table 7. The refractive indices of the garnets in these eclogites are distinctly greater than those of the garnet that occurs as separate grains within the same kimberlite pipes. As shown by O'Hara and Mercy (1966, pp. 343–346), the latter are pyrope (av. $n=1.747$) and clearly, therefore, have not been derived by disintegration of the eclogite.

Zoned garnet crystals which become lighter in color from core to rim were investigated with the electron microprobe. These analyses show that from core to rim, Mg increases markedly, Ca decreases, Mn decreases, Fe decreases slightly, and Ti remains about constant in amount. In a study of zoning in eclogite garnets, Evans (1965, p. 54) also found that the cores contained more Ca and Mn and less Mg than the rims.

Rutile is present as fine grains, primarily of golden yellow color, in all sections examined and generally constitutes three to four percent of the rock. It occurs mainly as inclusions in garnet, pyroxene, and lawsonite, but to a lesser extent, as discrete grains occurring along boundaries among the other minerals. Commonly it forms euhedral and subhedral crystals of short prismatic habit. No alteration to sphene is evident, even where it is surrounded entirely by lawsonite showing complete alteration to fibrous zoisite.

In addition to inclusions of golden yellow rutile, inclusions of light purple-gray rutile occur in the garnet and occasionally in the pyroxene. They are much less abundant and are

TABLE 7. GARNET IN ECLOGITE, ARIZONA AND NEW MEXICO

	1	2	3	4	5
n	1.797	1.794	1.794	1.790	1.778
a	11.556 Å	11.551 Å	11.551 Å	—	—

1, 2, 3. GR-P1-11, GR-P1-6, GR-P1-25, respectively, Garnet Ridge, Arizona; n determinations are $\pm .002$; a based on 420 peak, CuKα, halite internal standard.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 343).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

generally smaller than the golden yellow variety. They match the golden yellow rutile in their extremely high refractive indices and birefringence, prismatic habit, occasional geniculate twinning, and uniaxial positive character. Partial analysis by electron microprobe has failed to show a chemical difference between the golden yellow and purple-gray varieties of rutile. Both contain essentially the same proportions of titanium, niobium (a few percent), and iron (trace amounts) and are lacking in tantalum, chromium, vanadium, tin, and manganese.

Lawsonite and altered lawsonite are present in most of the eclogite inclusions. They generally constitute from one to five percent, but in a few xenoliths, they form as much as 20 percent. The lawsonite occurs not as inclusions, but as anhedral grains dispersed throughout the granular aggregate of pyroxene and garnet crystals (Fig. 1). Most of the lawsonite grains are slightly smaller than those of garnet and pyroxene.

The lawsonite has the following optical properties:

$$n_\alpha = 1.665 \pm 0.002$$
$$n_\beta = 1.674 \pm 0.001$$
$$n_\gamma = 1.684 \pm 0.002$$
$$2V_\gamma \text{ (calculated)} = 87°$$
$$2V_\gamma \text{ (measured)} = 86°$$

These values match closely the properties of lawsonite from other localities (Deer, Howie, and Zussman, 1962, Vol. 1, p. 221).

In most inclusions, the lawsonite grains show partial alteration to an extremely fine-grained fibrous aggregate, and, in some inclusions, the lawsonite has been altered completely. This contrasts markedly with the essentially unaltered character of the garnet, pyroxene, and rutile. The alteration is much too fine-grained for positive identification optically. However, X-ray examination shows that the fibrous mineral is zoisite—a mineral recorded as a primary constituent of some eclogite found elsewhere (Deer, Howie, and Zussman, 1962, Vol. 1, p. 191; Spry, 1963, pp. 591–592) and which was in fact first described from an occurrence in eclogite (Dana, 1892, p. 514). Although the isochemical breakdown of lawsonite should yield some kyanite (or sillimanite) and quartz or pyrophyllite in addition to zoisite, none was identified in the X-ray diffractograms. Lawsonite, which is stable at relatively high pressures and low temperatures, probably was altered to zoisite upon ascending with the kimberlite to an environment of lower pressure (Newton and Kennedy, 1963, pp. 2972, 2976). The alteration has proceeded inward from grain boundaries and fractures and commonly has left isolated, optically-continuous patches of lawsonite in the fine-grained fibrous matrix. In many cases, the zoisite fibers form radiating aggregates and commonly they radiate outward from a rutile inclusion.

Recently, McBirney *et al.* (1967, pp. 914–915) have described eclogite from Guatemala that contains a small amount of lawsonite along with abundant omphacite and almandine-rich garnet.

White mica occurs in a small proportion of the eclogite inclusions. Although a few small xenoliths may contain as much as five percent, most of the mica-bearing inclusions contain less than one percent. The textural relationships of the mica (Fig. 2) show that it is primary. It occurs in contact with unaltered garnet, pyroxene, and rutile and has approximately the same range in size as the garnet and pyroxene. In places, it is molded on euhedral crystals of garnet. The mica is colorless in thin section and uniaxial, and has $n_\beta = 1.585 \pm 0.002$.

A chemical analysis of white mica separated from one eclogite inclusion (Table 8)

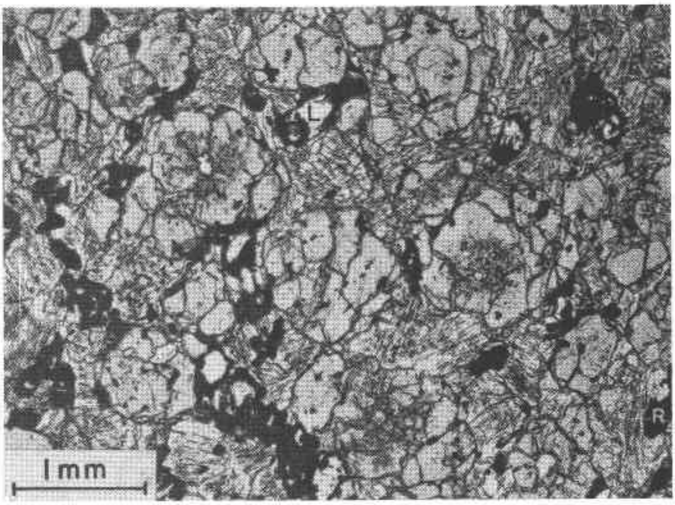

FIG. 2. Eclogite composed of garnet, pyroxene, lawsonite and its alteration products, and rutile. Some garnet crystals show a concentration of inclusions in their cores. White areas with irregular rims and patches of black-appearing material are lawsonite (L) partly altered to an extremely fine-grained aggregate consisting mainly of fibrous zoisite. Completely black-appearing grains are rutile (R).

shows some similarity to the analyses of phengites reported by Ernst (1963, p. 1360). These phengites, which have been found to occur rather commonly in glaucophane schists, are solid solutions between muscovite and celadonite; they are high in SiO_2, low in Al_2O_3, and contain several percent MgO, FeO, and Fe_2O_3. In comparison with the phengite analyses listed by Ernst, the mica in this inclusion from Garnet Ridge is exceptionally rich in CaO and Na_2O. The structural formula of the mica calculated on the basis of 11 oxygens, is given in Table 8. An approximate fit with the mica formula may be achieved by assigning Ca to the octahedral layer.

An analysis of white mica separated from a second eclogite inclusion, made by D. M. Morton with X-ray fluorescence, follows: SiO_2—58.3%; Al_2O_3—18.6%; total Fe, expressed as Fe_2O_3—1.9%; CaO—1.2%; MgO—9.5%; K_2O—10.0%; and Na_2O—<0.2%. The analysis shows that the mica in this eclogite nodule also bears some similarity to the phengites since it is high in SiO_2, low in Al_2O_3, and contains several percent MgO and iron oxides. In differs from the mica in the first xenolith in containing less CaO and much less Na_2O. A partial analysis of the second mica sample by electron microprobe also shows high K_2O, low CaO, and very low Na_2O.

White mica is a constituent of some eclogites which occur at other localities (*e.g.*, Hahn-Weinheimer and Luecke, 1963, pp. 767–768; Spry, 1963, pp. 591–592; Coleman *et al.*, 1965, pp. 491–492, p. 500; McBirney *et al.*, 1967, pp. 914–917).

Pyrite, which is a minor constituent of most xenoliths, is partly altered to hematite and/or goethite. It forms subhedral to rounded equant grains ranging principally from 0.1 to 0.5 mm in diameter. It occurs mainly along grain boundaries between other minerals and much less commonly, as inclusions in clinopyroxene. Recently, Czamanske and Desborough (1967) reported the occurrence of pyrite along with other sulphide minerals in

TABLE 8. MICA IN ECLOGITE, GARNET RIDGE, ARIZONA

Chemical Analysis		Structural Formula[a]			
SiO_2	55.65	Si	3.676	4.000	
Al_2O_3	17.28	Al	0.324		
TiO_2	0.33				
ZrO_2	0.00				
Cr_2O_3	0.04	Al	1.021	1.831	2.048
V_2O_5	0.025	Ti	0.016		
Fe_2O_3	2.01	Cr^{+3}	0.002		
FeO	1.29	V^{+5}	0.001		
CuO	0.00	Fe^{+3}	0.100		
BeO	0.00	Fe^{+2}	0.071		
MnO	0.03	Mn	0.002		
MgO	6.25	Mg	0.615		
CaO	3.07	Li	0.003		
SrO	0.005				
BaO	0.14				
Li_2O	0.01	Ca	0.217	1.286	
Na_2O	4.31				
K_2O	6.10	Ba	0.004		1.069
Rb_2O	0.02	Na	0.551		
H_2O+	3.07	K	0.514		
H_2O-	0.33				
F	0.01				
Cl	0.05				
	100.02				
O=F, Cl	.02				
Total	100.00				

C. O. Ingamells, analyst. Al_2O_3 may include other undetermined oxides of the ammonia group. ZrO_2, Cr_2O_3, V_2O_5, CuO, BeO, SrO, and BaO determined spectrochemically by N. H. Suhr. FeO, H_2O+, and H_2O- determined on -115 mesh sample; shortage of material made a separate determination of H_2O and FeO on unground sample impossible; possible that much of the water reported as H_2O- should in fact be reported as H_2O+. Cl determined approximately by X-ray fluorescence.

[a] Structural formula calculated on the anhydrous basis of 11 oxygens (i.e. the chemical formula of muscovite is expressed as $KAl_2Si_3AlO_{11} \cdot H_2O$). Ca (ionic radius 0.99Å) may occupy octahedral sites.

eclogite nodules from South African kimberlite. They suggest that the sulphide minerals represent an immiscible sulphide liquid which solidified as a single phase and unmixed during cooling.

DISCUSSION

Coleman, Lee, Beatty, and Brannock (1965, p. 485) divide eclogites into three groups, based on their geologic occurrence: Group A, in-

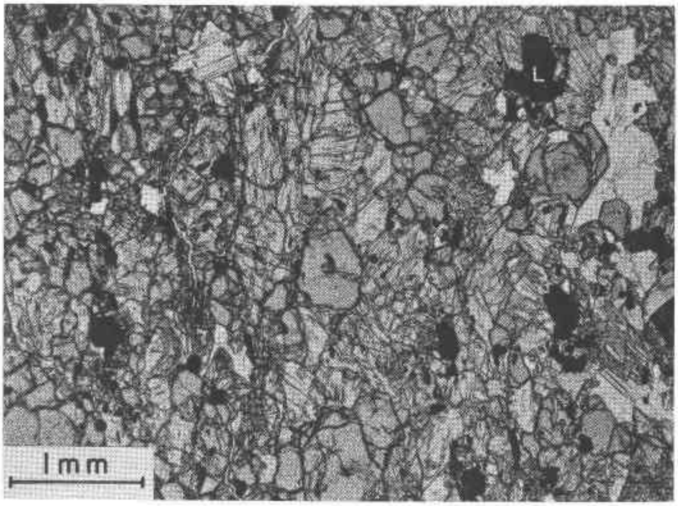

FIG. 3. Eclogite consisting of garnet, pyroxene, white mica, altered lawsonite (L, large black-appearing areas), and rutile (small black-appearing grains). White mica is in contact with unaltered garnet and pyroxene and in places, is molded on euhedral garnet crystals.

clusions in kimberlites, basalts, or layers in ultramafic rocks; Group B, bands or lenses in migmatite gneissic terrains; Group C, bands, lenses, or isolated blocks within alpine-type metamorphic rocks, including glaucophane schists. They note that the garnets of each group are distinctive with respect to pyrope content. Those of Group A generally contain more than 55 molecular percent pyrope; Group B, 30–55 percent; and Group C, from glaucophane schists, less than 30 percent (Coleman *et al.*, p. 499; Fig. 9). They note also that the jadeite content of the coexisting pyroxenes increases progressively from Group A to Group C and that, concomitantly, the diopside content decreases. The pyroxene compositions range continuously from approximately 1 to 37 molecular percent jadeite, with those of Groups A and B showing a broad overlap and those of Group C showing greater consistency (Coleman *et al.*, 1965, pp. 493, 496–497; Fig. 8).

The compositions of four coexisting pyroxenes and garnets in eclogite inclusions from Garnet Ridge are plotted in Figures 4, 5, and 6 along with the compositions of these minerals in Group A, B, and C eclogites as shown by Coleman *et al.* It is clear that the pyroxene in Garnet Ridge eclogite differs markedly from those of other eclogites for it is richer in jadeite than those of Group C and much richer than those of Groups A and B (Fig. 4). The pyrope content of the garnet is within the range characteristic of Group C eclogite and is less than the ranges of Groups A and B (Fig. 5).

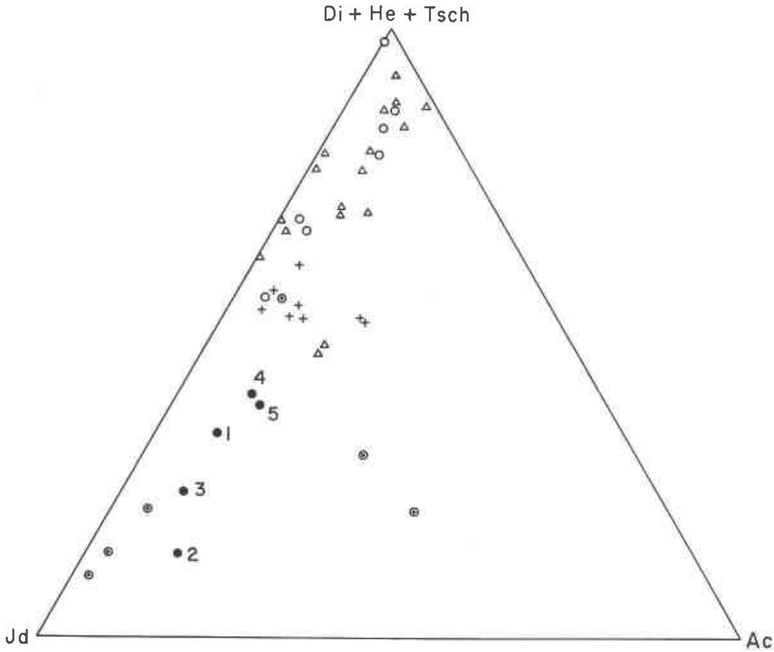

FIG. 4. Molecular proportions of end-members in pyroxenes from eclogites and glaucophane schist facies rocks. Open circles: Group A eclogites; triangles: Group B eclogites; crosses: Group C eclogites; dots: glaucophane schist facies rocks. After Coleman *et al.* (1965, p. 496).

1, 2, 3. GR-Pl-11, GR-Pl-6, GR-Pl-25, respectively, Garnet Ridge, Arizona.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

The Garnet Ridge eclogite occurs as inclusions in kimberlitic pipes and, therefore, would be placed in Group A on the basis of geologic occurrence. However, its garnet and pyroxene depart widely in composition from those of Group A.

The garnets in the eclogites from Garnet Ridge match those of Group C eclogites and the pyroxenes resemble chemically pryoxenes found in rocks of the glaucophane schist facies (Fig. 4). Moreover, most Garnet Ridge eclogite inclusions contain lawsonite—a mineral characteristic of glaucophane schist terrains. These facts first suggest that the inclusions at Garnet Ridge may have been derived from eclogite lenses occurring in a glaucophane schist facies basement pierced by the kimberlite pipes. However, no glaucophane-bearing inclusions have been found, to lend support to this suggestion. Moreover, the Garnet Ridge eclogites do differ from those characteristic of glaucophane schist terrains in the absence of retrograde minerals derived from pyroxene, garnet, and rutile.

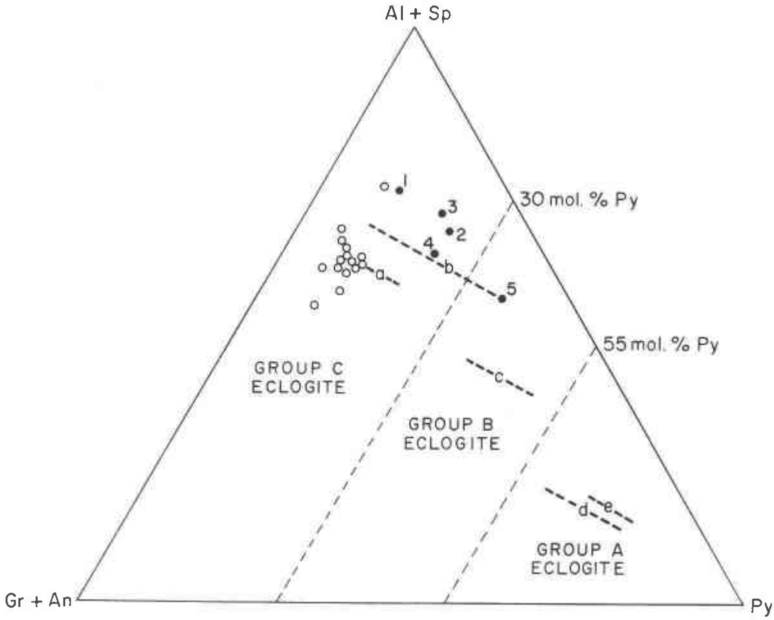

Fig. 5. Molecular proportions of end-members in garnets from eclogites and related rocks. Open circles: eclogites within glaucophane schists (Group C eclogites). Dotted lines: range in composition of garnets from the following rocks: a—amphibolites; b—charnockites and granulites; c—eclogites occurring in gneissic or migmatite metamorphic terrains; d—eclogites associated with kimberlite pipes; e—eclogites within ultramafic rocks such as dunite and peridotite. After Coleman *et al.* (1965, p. 499).

1, 2, 3. GR-Pl-11, GR-Pl-6, GR-Pl-25, respectively, Garnet Ridge, Arizona.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G.K.6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

Regardless of the disparity in composition between the minerals of Garnet Ridge and Group B eclogites, the association of sparse eclogite nodules and abundant xenoliths of granite gneiss and granite at Garnet Ridge may suggest that they are derived from eclogite lenses occurring in a migmatitic granite gneiss basement. However, the facts (1) that no xenoliths of granite gneiss contain eclogite in spite of their abundance and frequent large size, and (2) that similar granite gneiss and granite xenoliths are found in abundance without eclogite nodules in minette diatremes nearby do not favor this idea. The relations suggest, instead, that the eclogite occurs *in situ* separately from the granite gneiss and granite and leads to speculation that it may have been derived from a deeper part of the crust or even from the upper mantle where penetrated by ascending kimberlite.

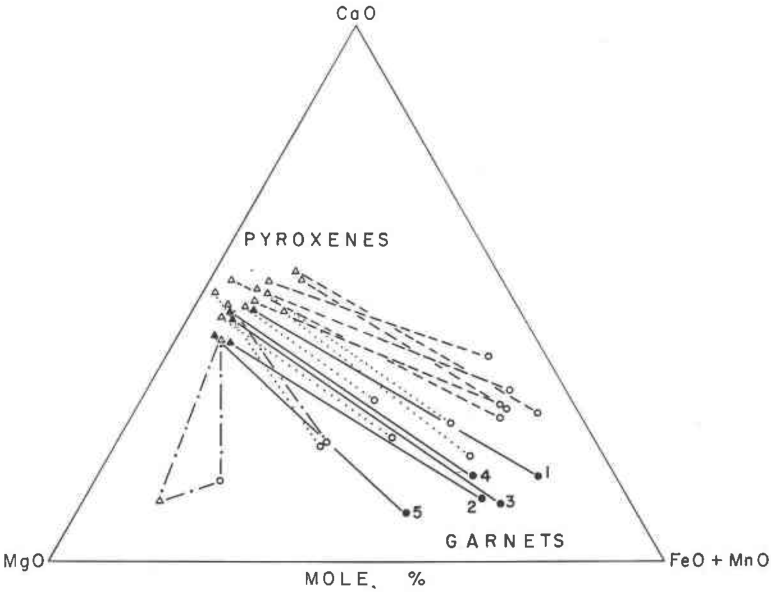

FIG. 6. C F M diagram for coexisting pairs of pyroxenes (triangles) and garnets (circles) in eclogites. Dashed-dotted tie lines: Group A eclogites; dotted tie lines: Group B eclogites; dashed tie lines: Group C eclogites. After Coleman *et al.* (1965, p. 504).

1, 2, 3. GR-Pl-11, GR-Pl-6, GR-Pl-25, respectively, Garnet Ridge, Arizona.
4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).
5. G. K. 6, Green Knobs, New Mexico; (O'Hara and Mercy, 1966, p. 341).

Several writers have examined the hypothesis that, at least beneath the continents, the Mohorovičíc discontinuity, which marks the boundary between the crust and mantle may result from the phase changes attending the transformation of basalt or gabbro to eclogite. The most recent experimental data (Ringwood and Green, 1966; Green and Ringwood, 1967; Cohen, Ito, and Kennedy, 1967; Green, 1967) cast doubt on the validity of this hypothesis, which was postulated initially upon consideration of preliminary, experimentally-determined phase equilibria, seismic velocity data, density requirements, and the chemical equivalence of basalt or gabbro and eclogite. A comparison of the analyses of Garnet Ridge eclogite and of normal tholeiitic and alkali basalt listed in Table 9 shows that this eclogite is not chemically equivalent to basalt. It is richer in soda and differs markedly in its content of some other oxides as well.

The Garnet Ridge eclogites, particularly those rich in pyroxene, which comprise a high proportion of the nodules, contain more alkali than is found in most other analyzed eclogites (Fig. 7). Whereas most of the eclogite analyses plotted in Figure 7 lie near the olivine basalt—tholeiitic

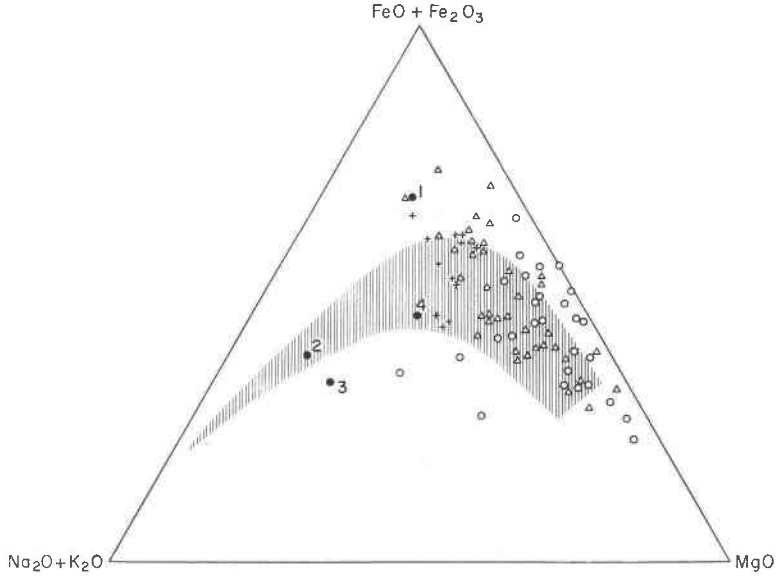

FIG. 7. Alk, F, M in weight percent in eclogites. Open circles: Group A eclogites; triangles: Group B eclogites; crosses: Group C eclogites; stippled area: alkali, tholeiitic, and nepheline basalt trend from Hawaiian Islands. After Coleman *et al.* (1965), p. 503. 1, 2, 3. GR-P1-11, GR-P1-6, GR-P1-25, respectively, Garnet Ridge, Arizona. 4. G.R.1, Garnet Ridge, Arizona; (O'Hara and Mercy, 1966, p. 342).

basalt compositional trend, the pyroxene-rich ones from Garnet Ridge lie near the extension to nepheline basalt.

As shown by the analyses in Table 9, the Garnet Ridge eclogite corresponds more closely in soda content and general chemical tenor to the monchiquite from the Hopi Buttes in northeastern Arizona (Fig. 1) than to basalt. In general, the soda-rich rocks—monchiquite and limburgite—are rare, yet in the Hopi Buttes area, a few tens of miles away from Garnet Ridge, they occur in abundance. Is it possible that there is some genetic significance to the association in northeastern Arizona of abundant monchiquite and limburgite with the apparently unique soda-rich eclogite which has been transported from depth in the kimberlite pipes? Yoder and Tilley (1962, p. 518) state that eclogite melts in a "eutectic-like" fashion and report that "Above 19 kbar pressure the two major minerals of eclogite, garnet and clinopyroxene, begin melting together and coexist with liquid over most of the narrow melting range of about 85°C." (p. 505). Recently, Cohen, Ito, and Kennedy (1967) have determined the eclogite solidus and liquidus over a pressure range from approximately 20 to 40 kbar. They find that the solidus and liquidus are parallel, within experimental error, to those determined by Yoder and Tilley, al-

TABLE 9. ECLOGITE, MONCHIQUITE, AND BASALT

Chemical Analyses

	1	2	3	4	5	6	7	8
SiO_2	43.5	53.8	54.9	50.19	39.00	39.50	50.83	45.78
TiO_2	6.0	2.1	1.2	2.08	3.60	4.75	2.03	2.63
Al_2O_3	17.4	18.1	17.1	15.38	11.72	11.84	14.07	14.64
Cr_2O_3	0.0	0.0	0.0	0.02	—	—	—	—
V_2O_5	0.1	0.0	0.0	—	—	—	—	—
Fe_2O_3	1.5	4.9	4.5	3.84	4.11	4.80	2.88	3.16
FeO	15.6	3.9	2.7	7.15	8.19	8.64	9.06	8.73
MnO	0.5	0.2	0.1	0.23	0.16	0.22	0.18	0.20
NiO	0.0	0.0	0.0	0.01	—	—	—	—
MgO	3.6	2.8	3.9	6.32	12.24	8.43	6.34	9.39
CaO	6.8	3.0	5.2	8.18	11.80	11.25	10.42	10.74
Na_2O	4.3	11.0	10.2	6.24	3.04	3.90	2.23	2.63
K_2O	0.0	0.0	0.0	0.13	0.43	0.89	0.82	0.95
P_2O_5	0.2	0.0	0.0	0.00	1.03	1.96	0.23	0.39
CO_2	0.0	0.0	0.0	—	0.00	0.00	—	—
H_2O^+	0.5	0.2	0.2	0.62	3.30	2.80	0.91	0.76
H_2O^-	0.0	0.0	0.0	0.00	1.30	0.80	0.00	0.00
Total	100.0	100.0	100.0	100.39	99.92	99.78	100.00	100.00

Norms

	1	2	3	4	5	6	7	8
Q	—	—	—	—	—	—	3.71	—
or	—	—	—	0.78	2.61	5.34	4.84	5.62
ab	33.0	59.2	57.7	42.63	13.47	20.50	18.88	22.23
an	28.4	0.3	0.8	13.52	17.27	12.27	25.95	25.34
ne	1.7	18.2	15.6	5.40	6.82	6.96	—	—
wo	1.9	6.0	10.4	11.23	14.75	13.03	10.13	10.62
en	—	—	—	—	—	—	15.78	3.28
fs	—	—	—	—	—	—	11.24	1.32
fo	6.3	4.9	6.9	10.98	21.65	14.87	—	14.08
fa	14.1	—	—	5.36	4.68	3.46	—	6.28
mt	2.3	7.2	5.5	5.53	6.04	7.04	4.17	4.58
cm	—	—	—	0.02	—	—	—	—
hm	—	—	0.6	—	—	—	—	—
il	11.4	4.0	2.3	3.93	6.93	9.12	3.85	4.99
ap	0.4	—	—	—	2.45	4.67	0.54	0.91
H_2O^+	0.5	0.2	0.2	0.62	3.35	2.83	0.91	0.76
Total	100.0	100.0	100.0	100.00	100.02	100.09	100.00	100.01

Normative Feldspar

	1	2	3	4	5	6	7	8
Or	—	—	—	1.3	7.7	13.5	9.6	10.3
Ab	55.3	99.6	98.7	76.0	41.8	55.3	38.9	43.2
An	44.7	0.4	1.3	22.7	50.5	31.2	51.5	46.5

Normative Olivine

	1	2	3	4	5	6	7	8
Fo	39.0	100.0	100.0	74.8	87.0	86.1	—	76.5
Fa	61.0	—	—	25.2	13.0	13.9	—	23.5

1, 2, 3. Eclogite. GR-P1-11, GR-P1-6, GR-P1-25, respectively, Garnet Ridge, Arizona. Calculated from modal analyses, converted to percentage by weight, listed in Table 1 and chemical compositions of constituent minerals listed in Tables 2 and 5.

4. Eclogite. G.R. 1, Garnet Ridge, Arizona (O'Hara and Mercy, 1966, p. 342).

5. Monchiquite, Hopi Buttes, Arizona (Williams, 1936, p. 127, 166).

6. Monchiquite, Hopi Buttes, Arizona (Williams, 1936, p. 127, 166).

7. Average of 137 normal tholeiitic basalts (Nockolds, 1954, p. 1021).

8. Average of 96 normal alkali basalts (Nockolds, 1954, p. 1021).

though their melting interval is slightly smaller and their liquidus is approximately 55° higher than Yoder and Tilley's (Cohen, Ito, and Kennedy, 1967, pp. 513–514). The monchiquite and limburgite cannot be simply the product derived by fusion of the eclogite at depth for they contain much more magnesia and less silica than the eclogite. Since they contain abundant phenocrysts of olivine, however, some accumulation of olivine in a soda-rich magma derived by melting of eclogite might account for the present chemical composition of the monchiquite and limburgite. The minette and trachybasalt of this region, which contain approximately 5–6 percent K_2O and 50–55 percent SiO_2 (Williams, 1936, p. 166), may originate in turn from monchiquite-limburgite magma through assimilation of granitic rock. The principal evidence supporting this suggestion, first made by Williams (1936, pp. 168–170), is the great abundance of partly vitrified granitic xenoliths found in the minette intrusions.

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