THE AMERICAN MINERALOGIST, VOL. 51, MARCH–APRIL, 1966

ECLOGITE, PERIDOTITE AND PYROPE FROM THE NAVAJO COUNTRY, ARIZONA AND NEW MEXICO

M. J. O'Hara and E. L. P. Mercy, *Grant Institute of Geology, University of Edinburgh.*

Abstract

Chemical data are reported for pyropes, an olivine, the constituent minerals of a lherzolite and two eclogite xenoliths from three diatremes in the Navajo Reservation, together with optical data for garnets from various gneiss xenoliths. The xenocryst garnets are not derived from the xenoliths and many are similar to those reported from diamantiferous kimberlites. The eclogites are extremely sodic types, and are not comparable to previously described materials from any source, while the lherzolite contains a pyroxene assemblage considerably more aluminous than any reported from diamantiferous kimberlites. Chrome contents of pyrope from altered peridotite inclusions in a Czechoslovakian diatreme, which is superficially similar to kimberlites and the Navajo diatremes, are comparable with those of "crustal" garnet-peridotites but are lower than those from garnet-peridotite xenoliths in diamantiferous kimberlite.

Introduction and Previous Work

Numerous volcanic necks of probable Pliocene age pierce the predominantly arenaceous and argillaceous sediments of Upper Palaeozoic, Mesozoic and Tertiary age which outcrop in the Navajo Indian Reservation in Arizona, New Mexico and Utah. The volcanic necks are described as diatremes and have been compared to the diatremes of the Schwabian Alb, the maar-type volcanoes of the Eifel district, and the Permian vents of East Fife (Gregory, 1917; Williams, 1936; Shoemaker *et al.*, 1962). The necks are filled with tuffs and agglomerates, accompanied by relatively minor amounts of intrusive and extrusive basic igneous rock. The activity was mainly explosive. The magma-types represented are alkaline, silica-undersaturated varieties which have been divided into two provinces, one characterized by monchiquite, the other, more potassic, province by minette. Olivine leucitites and rocks described as alnöite are reported from the minette province, which also contains seven diatremes filled by rocks described as "kimberlite (serpentine microbreccia)," by Allen and Balk, 1954 and Shoemaker *et al.*, 1962.

The agglomerates and tuffs of both provinces consist predominantly of cognate igneous fragments (limburgite, monchiquite, minette) and xenolithic or xenocrystal materials derived from the sediments penetrated by the diatremes. The agglomerates of the minette province contain in addition a variety of materials which are inferred to have been derived from greater depth, *i.e.* the Precambrian basement and upper mantle. The xenolithic materials recorded include granite, biotite granite, granodiorite and diorite, all of gneissoid aspect, hornblende schists, muscovite schist, chloritoid schists, limestone, quartzite, slate and chert, all of which may be ascribed to a crustal origin. Other, scarcer, fragments which may originate in an ultramafic zone (upper mantle) include harzburgite, lherzolite, websterite, talc schist and talc-anthophyllite schist. Xenocrystal materials recorded include magnesium olivine (peridot) (Fa_{7-9} at Buell Park according to Allen and Balk, 1954), enstatite, chrome-diopside, pyrope and hornblende. Garnetiferous granites and diorites are ubiquitous in the agglomerates of the minette province. Gregory (1916, 1917), Reagan (1927), Williams (1936), Malde (1954) and Malde and Thaden (1963) refer all the garnet, whether in xenoliths or as xenocrysts, to the pyrope variety, and conclude that the garnet crystals were derived from the garnetiferous and feldspathic rocks cut by the diatremes at depth. No measurements of physical properties are reported for the garnets, but analyses of chrome pyrope crystals by Genth (1862) and Seebach (1906) were made on materials probably collected from these localities. Garnet-peridotite has not been reported from the garnet-rich tuffs and agglomerates, the extent of whose geochemical and petrographic similarity to kimberlite has not been evaluated but Watson (1960) reported lawsonite-bearing eclogite from Garnet Ridge. Williams (1936) compares the garnet-rich diatremes near Comb Ridge with the cryptovolcanic structures of Ohio, Kentucky and Tennessee and a detailed description of outcrops at Garnet Ridge has been given by Malde and Thaden (1963) who recognize intrusive and extrusive serpentine breccias.

Apart from their very common occurrence in true kimberlite diatremes pyrope xenocrysts are also known in the agglomerates associated with one of the volcanic necks in East Fife (Balsillie, 1927) and pyrope crystals and crustal garnet-peridotite xenoliths, together with very rare diamond, are reported from an agglomerate and associated gravels at Hugels Linhorka, Czechoslovakia (Rost, 1962; Kopesky and Sattran, 1962). Pyrope crystals are also recorded from a basaltic agglomerate near Minusinsk, U.S.S.R. (Okhapkin and Chubugina, 1961), from alnöite breccia in the Solomon Islands (Allen and Deans, 1965), from alnöite dikes at Ithaca, New York (Martens, 1924), and pyrope-bearing peridotite and eclogite nodules have been described from agglomerates and tuffs at Salt Lake Crater, Oahu, Hawaii (Yoder and Tilley, 1962). These other occurrences of garnetiferous materials in volcanic necks share with the Navajo volcanoes and with kimberlites the geochemical characteristic of an alkaline silica-undersaturated basic magma type.

The Present Study

Xenoliths and xenocrysts were collected from three diatremes in the minette province of the Navajo Indian Reservation. These were Green Knobs, by Red Lake, north of Fort Defiance, Arizona and Garnet Ridge

TABLE 1. REFRACTIVE INDICES OF GARNET CRYSTALS COLLECTED FROM ANT-HILLS AT GREEN KNOBS

Material	n
Pale violet garnets ~20% of sample	1.736, 1.737, 1.738
Wine-coloured garnets ~70% of sample	1.745, 1.746, 1.746, 1.747
Orange garnets ~10% of sample	1.744, 1.751

south-east of Mexican Hat, Utah, both of which are described as "kimberlite," and Agathla (El Capitan) at the southern entrance to Monument Valley. A specific search was made for garnet and garnetiferous materials with a view to establishing the origin of the garnets and the presence or absence of eclogite-facies materials.

GREEN KNOBS

Garnet and olivine crystals were found in abundance on the surfaces of ant hills, particularly those on the east side of the outcrop. Olivine greatly exceeds garnet in abundance. Three varieties of garnet were recognized in the grains, one pale violet, another and more abundant type being wine colored, and the third orange. Refractive indices of grains (up to 3 mm diameter) chosen at random were determined by the immersion method, and indicate the presence of at least two compositions of garnet, both apparently rich in the pyrope molecule (Table 1).

Partial chemical analyses of an aggregate of the wine colored garnets is given in Table 2, together with that of the pale violet garnets. The darker

TABLE 2. PARTIAL CHEMICAL ANALYSES OF MINERALS FROM GREEN KNOBS

	Aggregate of pale violet garnets $n{\sim}1.737$ Sample No. 667	Aggregate of red garnets, $n{\sim}1.746$ Sample No. 668	Aggregate of green olivines
TiO_2	0.22	0.16	0.02
Al_2O_3	22.55	22.82	n.d.
Cr_2O_3	0.20	1.82	0.004
Fe_2O_3	12.78* (Fe₂O₃ + FeO)	2.55	9.20* (Fe₂O₃ + FeO)
FeO		7.52	
MnO	0.21	0.42	0.099
NiO	n.d.	0.005	0.37
MgO	15.15	18.73	49.88
CaO	7.50	5.62	0.01
Na_2O	n.d.	0.05	0.03
K_2O	n.d.	0.01	0.01

* Total Fe as Fe_2O_3.

garnet, of high refractive index, is richer in Cr_2O_3 and the pyrope molecule, but poorer in CaO than the pale violet garnet.

Olivine crystals of up to 3 mm diameter are common. Refractive indices of four olivine grains and one of the rare grains of orthopyroxene (4 mm diameter) are listed in Table 3, together with their estimated compositions (Tröger, 1956). Chemical data for the olivine are listed in Table 2. The partial analysis of the olivine aggregate indicates a composition close to $Fa_{8.5}$, distinctly richer in fayalite than indicated by the refractive indices of the grains examined individually.

Two lherzolite nodules and one harzburgite nodule were collected. The first lherzolite nodule, specimen no. G.K.5 is a coarse grained (2 to 5 mm) unfoliated granular rock composed of yellow-green olivine ($\beta=1.664$: Fa_7), abundant pale brown schillerized enstatite ($\alpha=1.665$, Of_{7-8}) and scarcer bright green chrome diopside ($\beta=1.678$). A second lherzolite

TABLE 3. OLIVINES AND ORTHOPYROXENE FROM GREEN KNOBS

Material	r. i.	Composition Mol. %
Green olivines	$\beta=1.659$	Fa_4
	$\beta=1.661$	Fa_5
	$\beta=1.663$	Fa_6
Yellow olivine	$\gamma=1.683$	Fa_7
Enstatite	$\beta=1.664$	Of_4

nodule, G.K.3, is superficially similar to the first in all respects except its greater abundance of chrome diopside. No spinel or garnet was observed in either rock. Chemical analyses of the pyroxenes and olivine from sample G.K.3 are shown in Table 4, together with an analysis of chrome diopside from the neighboring Buell Park diatreme (Allen and Balk, 1954). Noteworthy features are the relatively high aegirine and jadeite contents of the clinopyroxene, and its comparative poverty in Cr_2O_3 compared to the chrome diopsides of garnet peridotites from kimberlite (Nixon *et al.* 1963; O'Hara and Mercy, 1963). The two pyroxenes contain much more R_2O_3 than the pyroxenes of garnet periodotites from kimberlite. The olivine has a higher Fe/Mg ratio than the coexisting orthopyroxene, a feature also found in the garnet peridotites from crustal and kimberlite sources but the reverse is true of peridotite nodules in basalts (Ross *et al.* 1954; O'Hara and Mercy, 1963).

The harzburgite nodule, specimen G.K.4, is a coarse grained (2–5 mm) granular, unfoliated rock composed of olivine and common schillerized enstatite. This specimen is more altered than the two lherzolites and the olivines are partly replaced by relatively large crystals of anthophyllite and a magnesium-rich chlorite showing normal first order interference colors.

In addition there are several rounded patches about 5 mm diameter composed entirely of a second chlorite having very low birefringence and

TABLE 4. CHEMICAL ANALYSES OF MINERALS FROM GREEN KNOBS AND BUELL PARK

	Lherzolite nodule G. K. 3			Buell Park
	Olivine	Orthopyroxene	Clinopyroxene	Chrome diopside
SiO_2	41.10	51.77	52.74	54.17
TiO_2	0.02	0.05	0.19	0.02
Al_2O_3	0.32	4.00	4.86	1.43
Cr_2O_3	0.001	0.27	0.66	1.24
Fe_2O_3	2.49	1.68	1.42	1.43
FeO	7.06	4.58	1.08	1.09
MnO	0.14	0.14	0.09	0.06
NiO	0.40	0.12	0.051	n.d.
MgO	48.77	33.52	16.76	17.37
CaO	0.02	1.59	20.47	22.63
Na_2O	0.01	0.18	1.41	n.d.
K_2O	0.02	0.03	0.02	n.d.
H_2O+	n.d.	2.05	n.d.	0.23
Total	100.35	99.98	99.75	99.67
Si	.998	1.840	1.906	1.969
$Al^{[4]}$	.002	.160	.094	.031
$Al^{[6]}$	.007	.008	.113	.030
Ti	—	.001	.005	.001
Cr	—	.008	.019	.036
Fe^{3+}	.046	.045	.039	.039
Fe^{2+}	.143	.136	.033	.033
Mn	.003	.004	.003	.002
Ni	.008	.003	.001	—
Mg	1.766	1.776	.903	.941
Ca	.001	.061	.793	.881
Na	—	.012	.099	—
O	4.000	6.000	6.000	6.000

anomalous polarization colors, indicative of an alumina-rich variety such as penninnite. There is a superficial similarity to altered garnet, and similar features have been reported in peridotite fragments from a basalt breccia pipe in Russia (Okhapkin and Chubugina, 1961).

The mineral compositions and particularly the schillerized appearance of the enstatite in these peridotite fragments more closely resemble the features of peridotite nodules in kimberlite than those of the peridotite nodules in alkali basalts, but the mineral compositions in the nodule G.K.3, have closer affinities with materials from alkali basalts (see discussion).

A fragment of creamy green clinopyroxene rock (G.K.6) was found in the agglomerate at Green Knobs. Separation of this material disclosed the presence of about two percent of pale pink garnet ($n=1.778$) and a trace of rutile. The rock may, therefore, belong to the eclogite facies. Analyses are reported in Table 5. The most remarkable features are the extremely high sodium content of the pyroxene, yielding nearly 60% of

TABLE 5. ANALYSES OF MINERALS FROM GREEN KNOBS AGGLOMERATE

	From "eclogite" G.K. 6			Structure formulae	
	Clinopyroxene	Garnet		Clinopyroxene	Garnet
SiO_2	56.38	39.31	Si	1.981	2.990
TiO_2	0.22	0.35	$Al^{[4]}$	.019	.010
Al_2O_3	13.74	22.03	$Al^{[6]}$	.550	1.965
Cr_2O_3	0.001	0.001	Ti	.006	.020
Fe_2O_3	4.66	1.07	Fe^{3+}	.123	.061
FeO	1.24	24.00	Fe^{2+}	.036	1.527
MnO	0.11	0.74	Mn	.003	.048
NiO	0.022	0.002	Ni	.001	—
MgO	6.70	9.52	Mg	.351	1.079
CaO	7.73	3.35	Ca	.291	.273
Na_2O	9.01	0.08	Na	.614	—
K_2O	0.06	0.03	O	6.000	12.000
Total	99.87	100.48			

the jadeite and aegirine molecules, and the calcium-poor, but iron and manganese-rich character of the garnet. Similar characters are found in an eclogite sample from Garnet Ridge, and cannot be matched among previously described eclogites (see below).

GARNET RIDGE

One large fragment and five small chips of eclogite were recovered from the surface gravels at Garnet Ridge, in which loose garnet crystals are abundant. The six eclogite fragments are superficially similar, but were recovered from a wide area. A description of the large eclogite fragment follows.

G.R.1. This is a subangular fragment of about 700 grams, with a coating of white alteration products similar to that seen on many eclogite fragments from the South African kimberlite pipes. The rock is composed of about 20% pink garnet, $n=1.790$; 78% pale green clinopyroxene, $\alpha=1.673$, $\beta=1.683$, $\gamma=1.695$ and 2% red-brown rutile, plus a trace of hematite white mica and pyrite. The clinopyroxene has large +2V, and very strong dispersion such that most grains will not extinguish between crossed nicols in white light. The pyroxene grains reach a maximum size of 2mm and show a tendency to acicular form;

TABLE 6. ANALYSES OF ECLOGITE AND CONSTITUENT MINERALS FROM GARNET RIDGE

	Rock	Clinopyroxene	Garnet	C.I.P.W. norm of rock			Structure formulae	Pyroxene	Garnet
SiO_2	50.19	56.22	38.10	Or	0.77		Si	1.976	2.965
TiO_2	2.08	0.87	0.09	Ab	36.41		$Al^{[4]}$	.024	.035
Al_2O_3	15.38	13.07	21.89	An	13.57		$Al^{[6]}$	.518	1.973
Cr_2O_3	0.023	0.022	0.017	Ne	8.88		Ti	.023	.005
Fe_2O_3	3.84	3.92	1.47	Di	15.73	Di	Cr	.001	.001
FeO	7.15	1.46	26.62	Hd	6.06	Di	Fe^{3+}	.104	.086
MnO	0.23	0.046	0.82	Fo	5.92	Ol	Fe^{2+}	.043	1.732
NiO	0.014	0.018	0.003	Fa	2.88	Ol	Mn	.001	.054
MgO	6.32	6.56	5.69	Ilm	3.95		Ni	.001	—
CaO	8.18	9.13	5.66	Mt	5.57		Mg	.344	.660
Na_2O	6.24	8.80	0.06	Cm	0.03		Ca	.344	.472
K_2O	0.13	<0.01	0.04				Na	.600	—
P_2O_5	<0.003	<0.003	<0.003				O	6.000	12.000
H_2O+	0.62	n.d.	n.d.						
Total	100.40	100.12	100.45						

they are arranged in a poorly foliated interlocking texture. The garnet crystals are small (1 mm or less) and subhedral. Rutile forms small rounded blebs among the pyroxene.

The clinopyroxene exhibits a vermicular structure (? incipient symplectite) at the grain boundaries when examined at high magnifications (×400). Some of the (?) pyroxene crystals have been totally converted, and rarer pyroxene crystals partly converted to a white opaque mass of fibrous material with low birefringence. Watson (pers. comm.) reports similar fibrous aggregates as alteration products of lawsonite. Some of the garnet occurs as small inclusions in the pyroxene.

Chemical analyses of the rock, clinopyroxene, and garnet are listed in Table 6. The similarity of the garnet and pyroxene compositions to those reported from Green Knobs is most striking.

G.R.2. A small fragment of eclogite from this locality, is petrographically similar to G.R.1, described above, but garnet is less abundant in this specimen than in the previous one, while pyrite, hematite and a little magnetite are present in rather greater quantities. Other chips of eclogite found at this locality share the feature of rather low garnet/pyroxene ratios, which is not a usual feature of eclogite nodules from kimberlite or gneiss terrains.

Other garnetiferous xenoliths found at Garnet Ridge include.

G.R.3. A coarse grained 2–3 mm unfoliated granular rock composed of plagioclase now converted to saussurite, pyroxene, converted to fibrous green hornblende, and clusters of red garnet.
G.R.4. Coarse grained (3 mm) poorly foliated granular rock composed of plagioclase and saussurite, magnetite, clinopyroxene and large (1 cm) red garnets.
G.R.5. Coarse grained (up to 4 mm) well foliated garnet-sillimanite-cordierite-mica schist with common quartz and oligoclase.
G.R.6. Medium grained (1–2 mm) well foliated garnet-plagioclase-amphibolite.

TABLE 7. PROPERTIES OF GARNETS FROM GARNET RIDGE

n	Source	Comments
1.735	Single large (3–10 mm)	red; pink powder
1.736	crystals	pale red; pale pink powder; 3 sets acicular inclusions
1.740	crystals	pale orange; pale orange powder
1.745	crystals	red-violet; red powder
1.746	crystals	dark smoky brown; grey powder; 3 sets acicular inclusions
1.747	crystals	wine red; red powder
1.748	Granular garnet aggregate, 1–2 mm grain size.	pale red grains
1.757	Granular garnet aggregate, 1–2 mm grain size.	pale red grains. Some rutile.
1.759	Granular garnet aggregate, 1–2 mm grain size.	red, with grains of ilmenite
1.762	Single large crystal	wine colored; green powder; ? rich in Cr_2O_3
1.763	Granular aggregate	red
1.766	Granular aggregate	pale red
1.768	Single large crystal	wine colored; red powder.
1.780	In coarse grained (3 mm) garnet-hornblende-plagioclase granulite (G.R. 4)	
1.781	In coarse grained garnet-sillimanite-cordierite gneiss. (G.R. 5)	
1.788	In medium grained (1–2 mm) hornblende schist (G.R. 6)	
1.789	In coarse grained saussuritised and amphibolised pyroxene granulite (G.R. 3)	
1.790	In foliated eclogite fragment. (G.R. 1)	

Large amounts of garnet were recovered from the surface gravels at Garnet Ridge. The refractive indices of a number of garnets, representing loose single crystals, aggregates of crystals, and garnet from eclogite, granulite and amphibolite minerals facies xenoliths are listed in Table 7, and compared with garnets from other sources in Table 8. Chemical analyses of two fractions of the garnet crystals are presented in Table 9, together with earlier analyses of garnets, probably from this source. The chrome-rich pyrope is almost identical with that from Green Knobs.

Agathla (El Capitan)

A restricted range of garnetiferous materials was recovered in a brief search at this locality. All are small (2–4 cms) xenoliths from the agglomerates.

E.C.1. Garnet-hornblende-augite-labradorite granulite.
E.C.2. Garnet-augite-hornblende-saussurite granulite. Garnet $n = 1.767$.

Table 8. Refractive Indices of Garnets from Garnet Ridge Compared with Those from Green Knobs, Agathla (El Capitan) and Other Peridotite and Eclogite Sources

Material	Source	n
Single crystals	Green Knobs	1.736–1.751, av. 1.743
Single crystals	Garnet Ridge	1.735–1.768, av. 1.747
Single crystal	Agathla	1.773
Granular aggregates	Garnet Ridge	1.748–1.766, av. 1.759
Crystals in kimberlite (less sample K.47)	(Nixon *et al.*, 1963)	1.732–1.767, av. 1.746
from garnet-peridotite nodules in kimberlite	(Nixon *et al.*, 1963)	1.743–1.758, av. 1.749
from garnet-peridotite nodules in kimberlite	(O'Hara and Mercy, 1963)	1.737–1.763, av. 1.751
from garnet-peridotite lenses in gneiss	(O'Hara and Mercy, 1963)	1.740–1.753, av. 1.746
Eclogite xenolith	Green Knobs	1.778
Eclogite xenolith	Garnet Ridge	1.790
Garnet-pyroxene xenolith	Agathla	1.772
from eclogites in kimberlite (5)	(Nixon *et al.*, 1963)	1.753–1.796, av. 1.772
from eclogites in kimberlite (9)	(O'Hara and Mercy, unpublished)	1.758–1.770, av. 1.762
other garnetiferous xenoliths	Garnet Ridge	1.780–1.789, av. 1.784
other garnetiferous xenolith	Agathla	1.767

TABLE 9. ANALYSES OF XENOCRYSTAL GARNETS FROM GARNET RIDGE WITH SOME OLDER GARNET ANALYSES, POSSIBLY FROM THIS SOURCE

	Composite of single crystals n 1.73–1.75 Sample No. 665	Composite of granular aggregate garnets n 1.75–1.77 Sample No. 666	Garnet, Santa Fe (Genth, 1862)	Garnets. Colorado River Arizona (Seebach, 1906) $n=1.742$ Duplicate analyses on same material	
SiO_2	42.52	40.78	42.11	43.29	43.45
TiO_2	0.18	0.83	n.d.	n.d.	n.d.
Al_2O_3	21.93	21.79	19.35	20.87	21.12
Cr_2O_3	1.86	0.001	2.62	2.50	2.21
Fe_2O_3	1.13	2.18	14.87[2]	10.21[2]	10.21[2]
FeO	8.90	14.47			
MnO	0.42	0.27	0.36	0.58	0.46
NiO	0.010	0.003	n.d.	n.d.	n.d.
MgO	18.10	9.95	14.01	18.26	18.58
CaO	5.41	9.88	5.23	4.62	4.45
Na_2O	0.04	0.07	n.d.	n.d.	n.d.
K_2O	<0.01	0.02	n.d.	n.d.	n.d.
P_2O_5	0.009	n.d.	n.d.	n.d.	n.d.
Total	100.54	100.24	99.00[1]	100.69	100.48

[1] Includes 0.45% loss on ignition.
[2] Total iron as FeO.

E.C.3. Garnet crystal, $n=1.773$.
E.C.5. Granular rock, coarse (2 mm) grain size with distinct foliation, composed of dark green clinopyroxene $\beta=1.696$, and red garnet ($n=1.772$), plus a small amount of plagioclase and biotite. The clinopyroxene and the garnet are full of minute acicular birefringent inclusions very similar to those reported from some eclogites in kimberlite.

DISCUSSION

The loose single garnet crystals collected at Garnet Ridge are apparently similar to the garnets reported from Green Knobs, which in turn are similar in their properties to garnets reported from kimberlite pipes in Africa (Dawson, 1962; Nixon *et al.*, 1963) and to garnets from garnet-peridotites of the eclogite mineral facies (O'Hara and Mercy, 1963) (Table 8, and compare the analyses in Tables 2 and 9 with those of chrome-rich pyrope garnets from kimberlite diatremes in the literature cited). The aggregates of granular garnet from Garnet Ridge are texturally and chemically dissimilar to any material reported from garnet-peridotites, being exceptionally poor in chromium and rather rich in calcium and iron (Table 9). These apparently form a distinct group of materials (perhaps late garnet accumulates crystallised from a differentiating kimberlite fluid at high pressures). *None of the material from the two types of independent garnet at Garnet Ridge, or from Green Knobs can be confused with the garnets of higher refractive index derived from the garnetiferous xenoliths.* The majority of the garnet found in these diatremes has originated from a source other than the eclogites, or the garnet-pyroxene-plagioclase and garnet-hornblende-plagioclase gneisses, which occur as xenoliths.

Pyrope-rich garnets are known from a number of sources which are neither eclogite facies garnet-peridotites nor kimberlite, such as the pyropes from granulite facies rocks in N.W. Scotland (O'Hara, 1961), from the Knockormal "eclogite" near Ballantrae, Scotland (Bloxam and Allen, 1959), from ariégite layers in spinel-bearing lherzolites in the Pyrenees (Lacroix, 1900, O'Hara and Mercy, unpubl. data) and from a bronzitic pyropite from the Sittampundi complex, Madras (Subramaniam, 1956) which is probably a granulite facies rock (O'Hara, 1960). Pyrope-garnet with Cr_2O_3 content greater than 0.5% by weight has, however, only three proven sources—xenocrysts in kimberlite, garnet peridotite xenoliths in kimberlite and garnet peridotite lenses in orogenic regions, all of which are ultrabasic environments. Garnetiferous peridotite lenses are not known in the orogenic regions of the American continent and consequently the composition of some of the garnets in the Navajo province suggests at least a superficial similarity to true kimberlite diatremes, and may imply an upper mantle source for the xenocryst garnet. Chrome-poor garnet such as that from Garnet Ridge is, however, also found as xenocrysts in kimberlite diatremes (Nixon *et al.*, 1963) and may have precipitated from an ultrabasic fluid at high pressures. The chrome-poor pyropes reported by Nixon *et al.* (1963) are distinctly more magnesian than that from Garnet Ridge which resembles more closely the chrome-poor pyrope reported by Orlova (1961) as an associate of and inclusion in diamonds from the southern Urals.

That this similarity to kimberlite may be only superficial is suggested by a study of the compositions of the pyroxene assemblage of the peridotite nodule from Green Knobs, which is compared with pyroxene assemblages from peridotite nodules in kimberlite, in alkali-olivine basalt, and the pyroxene assemblages stable at 30 kilobars in an ultrabasic environment, deduced from experimental studies (Fig. 1). The Green Knobs peridotite assemblage contains pyroxenes which are considerably richer in the R_2O_3 constituents, show more extensive mutual solubility, and which probably reflect higher temperatures of equilibration than the available analysed materials from kimberlite diatremes. The pyroxene assemblage of the lherzolite nodule G.K.3 closely resembles that of the 'alumina-poor' groups of nodules from basalts, believed to have crystallised at relatively low pressures (O'Hara and Mercy, 1963). Such physical conditions are less-likely to have lain within the stability field of diamond than are those indicated by the phase assemblage of garnet-peridotite inclusions in kimberlite.

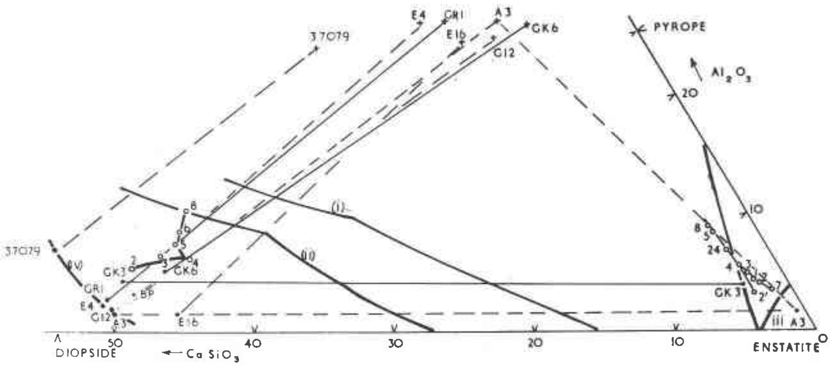

FIG. 1. Weight per cent plot of "equivalent" Al_2O_3(=Al_2O_3+Cr_2O_3+Fe_2O_3 expressed as equivalent weight of Al_2O_3, minus the weight of Al_2O_3 equivalent to Na_2O+K_2O)−$CaSiO_3$(=CaO expressed as equivalent weight of $CaSiO_3$)−$MgSiO_3$(=sum of FeO+MnO+NiO+MgO expressed as the equivalent weight of $MgSiO_3$). The two pyroxenes of lherzolite G.K.3, the chrome diopside from Buell Park (B.P.) and the two garnet-pyroxene assemblages G.K.6 and G.R.1 are plotted and compared with (i) solvus boundary in synthetic pryoxenes in the system CaO-MgO-Al_2O_3-SiO_2 at 1600°C, 30 kilobars (based on data by O'Hara, 1963c; Davis, 1963). (ii) solvus boundary in synthetic and natural pyroxenes at 1450°C, 30 kilobars (based on data by O'Hara, 1963a, b; Davis, 1963), (iii) tentative solvus boundary for orthopyroxene at 50 kilobars, 1450°C, estimated from data by Davis, (1963), Boyd and England, (1964), Macgregor and Ringwood, (1964), (iv) an apparent solvus boundary for clinopyroxenes from true kimberlite sources, (v) the mineral parageneses of some specimens from kimberlite:—the garnet peridotite A.3 (O'Hara and Mercy, 1963); the eclogite 37079 (O'Hara, 1963b); the eclogites E.4, E.16 and G.12 (Nixon *et al.*, 1963) and (vi) the pyroxene parageneses of spinel-bearing peridotite nodules in basalts from a variety of localities, numbered according to Ross *et al.*, (1954) 1–4 and 7, plus a group from one locality, Dreiser Weiher, Eifel, numbered according to Frechen (1963), (with one enstatite recorded as 2′ instead of the original 2).

The compositions of the clinopyroxene and its included garnet from the Green Knobs diatreme are comparable with those of the clinopyroxene and garnet from the eclogite in the Garnet Ridge diatreme. The compositions of the eclogite and of the two clinopyroxenes are exceptionally rich in Na_2O, the pyroxenes having the highest Na_2O contents of any recorded from eclogites, whether from gneiss terrains, kimberlite sources or glaucophane schist facies terrains. The garnets on the other hand contain notably less CaO than those of other eclogites. This peculiarity of composition combined with their occurrence in two widely separated localities of a particular alkaline province suggests that they are in some way connected with the genesis of the explosive magmas which gave rise to the diatremes, but the conditions leading to their crystallisation appear to be different from those pertaining in true kimberlite.

A comparison of the pyroxene and garnet compositions is made in Fig. 1 and the Ca-Mg-Fe projection (Fig. 2) with those of some eclogite nodules in kimberlite. These diagrams bring out the differences between the materials from the Navajo diatremes and those from African diamantiferous kimberlite diatremes. Figure 2 also contains a suggestion of

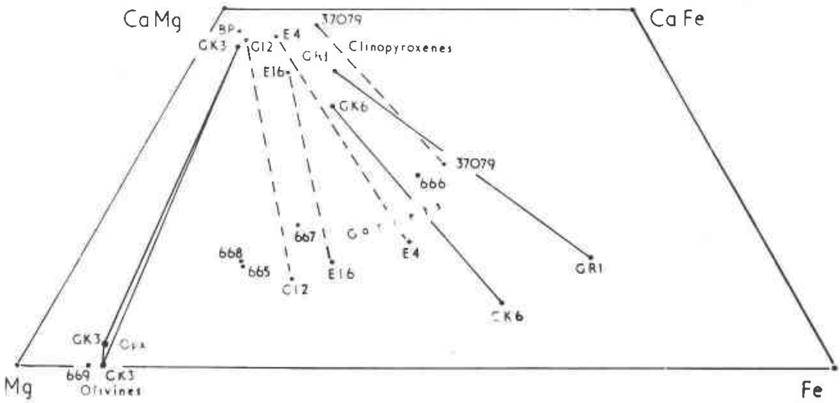

FIG. 2. Ca-Mg-total Fe atomic percentage plot of minerals from the Navajo Province, compared with minerals of eclogites from kimberlite sources. This diagram may be compared with similar plots of related data given by O'Hara (1960) and O'Hara and Mercy (1963, fig. 22). Key as in Fig. 1, with the exception of the four garnet analyses which are numbered as in Tables 2 and 9.

the existence of a trend in the compositions of xenocrystal garnets from the Navajo diatremes. Further work may show whether or not this is significant.

Carboniferous alkali olivine basalt breccia pipes containing three varieties of pyropes, plus chrome diopside, enstatite etc., have been described from the Minusinsk region of Russia (Okhapkin and Chubugina 1961). The assemblage appears to have affinities with that reported in the Navajo country and that at Elie, Scotland.

Pyrope xenocrysts are known from the diatremes at Elie Ness, Fife, Scotland (Balsillie, 1927) in association with a Carboniferous or Permian alkali basalt province, but neither chrome diopside, nor eclogite, nor peridotite xenoliths have yet been obtained from these breccias[1]. Basalt

[1] Altered spinel lherzolite xenoliths have been reported from the Andross vent breccias.

flows in the nearby Ruddons Point vent contain abundant spinel-bearing peridotite nodules. Balsillie (1927) reports two groups of pyrope xenocrysts, with refractive indices respectively greater or less than 1.75, similar to the situation in the Navajo and other diatremes.

Allen and Deans (1965) have described an alnöite breccia from the Solomon Islands in which ferri-ilmenites, chrome-poor pyrope and chrome-bearing diopside xenocrysts are accompanied by more massive alnöite with spinel-bearing peridotite nodules. They stress the similarity between these circumstances and those observed at Salt Lake Crater, Oahu, Hawaii (Yoder and Tilley, 1962), where the pyrope is, however, present in clinopyroxene-orthopyroxene- and olivine-bearing nodules. Allen and Deans (1965) recognise that the Malaita diatreme is related to, but not identical with, true kimberlite, a conclusion which can be extended to the Navajo diatremes. Martens (1924) has reported pyrope, nickel-rich magnesian olivine, enstatite, chromite, chrome-diopside and graphite from alnöite dykes at Ithaca, New York.

Pyropes, chrome diopsides, zircons, ilmenites and a suite of minerals including very rare diamond, characteristic also of kimberlite pipes have been described from gravels in Czechoslovakia, part of which at least are derived from neigboring diatremes associated with the basic alkaline igneous activity of that region (Rost, 1962) and the regional setting of these diatremes with respect to the central European volcanic activity has been discussed by Strnad (1962). Recently Kopesky and Sattran (1962) have demonstrated that in at least one diatreme the source of the garnet-peridotite xenoliths, and hence probably of many of the loose pyrope crystals, is a layer or lens of "crustal" garnet-peridotite within the gneissose basement rocks penetrated at a shallow depth by the diatreme. We have examined specimens of the drill core which penetrated the garnet-peridotite lens, and of the xenoliths and agree that the two materials are very similar except with regard to the extent of alteration of the olivines and orthopyroxenes, extensive serpentinisation affecting the drill core material while most of the olivine has been pseudomorphed by talc in the xenoliths. Texturally, the two specimens exhibit large (up to 10 mm) prophyroclasts of garnet set in a fine grained ($\sim$0.5 mm) matrix of altered olivine and scarcer pyroxene; prominent layering of the garnet is present in one of the xenoliths. Such a texture has only rarely been described from garnet-peridotite inclusions in kimberlite (*e.g.* Williams, 1932, plate 145) but it is highly characteristic of the garnet-peridotite lenses which are found in the metamorphic terrains of Norway and Switzerland (O'Hara and Mercy, 1963). It appears from modern analyses that the Cr_2O_3 content of pyropes derived from peridotite xenoliths in kimberlite (1.9–7.5% according to Nixon *et al.*, 1963; O'Hara and Mercy, 1963), is higher than that of pyropes from garnet peridotite lenses in Norwegian and Swiss gneisses (0.3–1.7% in a sample examined by O'Hara and Mercy, 1963) and 0.7% is recorded in garnet from "crustal" garnet peridotite from Czechoslovakia (Kokta and Nemec, 1936) although higher values of up to 2.6% are reported from garnet in the Bohemian province in the pre-1900 literature (v. John, 1892; Lemberg, 1875). Fiala (1965) reports 6.85% Cr_2O_3 in garnet from a Czech garnet peridotite with only 0.5% pyroxene. Seven others contained 0.85–2.02% Cr_2O_3, from rocks with more substantial amounts of pyroxene. Tröger (1959) in a review of compositions of garnets from various sources has presented figures for the molecular percentage of uvarovite in pyropes. These figures appear to indicate relatively high Cr_2O_3 values in the garnets from serpentines and peridotites from Bohemia, America and for the garnet from Elie. The method of calculation is not, however, clear to us because Lemberg (1875) does not give a figure for the Cr_2O_3 content of two of the garnets from Zoblitz, nor for one of those from Greifendorf, while Heddle (1878) specifically records the absence of Cr_2O_3 in the Elie garnet. The two garnets from Meronitz and Triblitz analysed by v. John (1892) which contained Cr_2O_3 1.98% and 1.80% respectively are not reported as having been derived from serpentinite and may well have been derived from the gravels, in which case they may be xenocrysts of true igneous origin from the nearby diatremes.

A knowledge of the Cr_2O_3 contents of the garnets from the Czechoslovakian occurrence might strengthen the case for regarding them as either typical kimberlite garnet-peridotite nodules or accidental xenoliths of typical but distinct gneiss terrain garnet peridotite lenses. Cr_2O_3 values, determined on hand picked material, are: drill core material 0.62 wt. % Cr_2O_3; nodules 0.56, 1.57 wt. % Cr_2O_3.

These results show the Cr_2O_3 contents of the garnets to be outside the range reported in nodules from true kimberlite, but within the range reported from crustal garnet peridotites. The results confirm our previous assessment of these nodules (O'Hara and Mercy, 1965) which is that they are accidental xenoliths of crustal garnet peridotite caught up in a breccia pipe by a coincidence which is unlikely to be repeated in other provinces and has no significance with regard to the problem of the genesis of garnet-peridotite xenoliths and pyrope xenocrysts in other diatremes, such as those of the Navajo province. It remains to be decided whether any of the garnet-peridotite xenoliths or pyrope xenocrysts in these Czechoslovakian diatremes are derived from another, deeper source, but it seems likely, in view of the other minerals reported from the gravels that some of the chrome-rich pyrope reported in the literature is similar in character and origin to that reported from kimberlites, or to that from Elie, the Solomon Islands, the Ithaca dikes and the Navajo diatremes.

ACKNOWLEDGEMENTS

The materials described were collected by the senior author during a visit to the U.S.A. made possible by the tenure of a research fellowship at the Carnegie Institution, Washington and of a Fulbright travel grant. Our thanks are due to the council of the Navajo tribe for permission to collect the specimens.

REFERENCES

ALLEN, J. B. AND T. DEANS (1965) Ultrabasic eruptives with alnöitic-kimberlitic affinities from Malaita, Solomon Isles. *Mineral. Mag.* (*Tilley vol.*) **34,** 16–34.

ALLEN, J. E. AND R. BALK (1954) Mineral resources of Fort Defiance and Tohatchi quadrangle, Arizona and New Mexico. *New Mexico Bur. Mines Mineral. Res. Bull.* **36.**

BALSILLIE, D. (1927) Contemporaneous volcanic activity in East Fife. *Geol. Mag.* **64,** 481–494.

BLOXAM, T. W. AND J. B. ALLEN (1959) Glaucophane-schist, eclogite, and associated rocks from Knockormal in the Givran-Ballantrae complex, South Ayrshire. *Trans. Roy. Soc. Edinb.* **64,** 1–17.

BOYD, F. R. AND J. L. ENGLAND (1964) The system enstatite-pyrope. *Yearb. Carnegie Inst.* **63,** 157–161.

DAVIS, B. T. C. (1963) The system enstatite-diopside at 30 kilobars pressure. *Yearb. Carnegie Inst.* **62,** 103–107.

DAWSON, J. B. (1962) Basutoland kimberlites. *Bull. Geol. Soc. Am.* **73,** 545–560.

FIALA, J. (1965) Pyrope of some garnet peridotites of the Czech massif. *Krystalinikum* **3,** 55–74.

FRECHEN, J. (1963) Kristallisation, Mineralbestand, Mineralchemismus und Förderfolge der Mafitite vom Dreiser Weiher in der Eifel. *Neues Jb. Miner. Mh.* 1963, 205–225.

GENTH, F. A. (1862) Contributions to mineralogy. *Am. Jour. Sci.* 2nd ser., **33,** 190–206.

GREGORY, H. E. (1916) Garnet deposits on the Navajo Reservation, Arizona and Utah. *Econ. Geol.* **11,** 223–230.

——— (1917) Geology of the Navajo country; a reconnaissance of parts of Arizona, New Mexico and Utah. *U. S. Geol. Surv. Prof. Paper,* **93.**

HEDDLE, M. F. (1878) Chapters on the mineralogy of Scotland. Chapter third—The Garnets. *Trans. Roy. Soc. Edinb.* **28,** 299–319.

JOHN, C., v. (1892) Ueber die chemische Zusammensetzung der Pyrope und einiger anderer Granate. *Jb. k.-k. geol. Reich.* **42,** 53–62.

KOKTA, J. AND F. NEMEČ (1936) Granát ultrabasických hornin od Černnía. *Věda. Přiodni, Praha,* **17,** 176–180.

KOPESKÝ, L. AND V. SATTRAN (1962) On the genesis of pyrope in the Czech Mittelgebirge. *Věstnik Ustredniho Ustavu Geologiskêno.* **37,** 269–283 (In Czech).

LACROIX, A. (1900) Les roches basiques accompagnant les lherzolites et les ophites des Pyrénées. *8th Int. Geol. Congr. Rep. Paris,* 806–838.

LEMERG, J. (1875) Ueber die Serpentine von Zoblitz, Greifendorf und Waldheim. *Zeit. dt. geol. Ges.* **27,** 531–549.

MACGREGOR, I. D. AND A. E. RINGWOOD (1964) The natural system enstatite-pyrope. *Yearb. Carneg. Instn.* **63,** 161–163.

MALDE, H. E. (1954) Serpentine pipes at Garnet Ridge, Arizona. *Science,* **119,** 618.

——— AND R. E. THADEN (1963) Serpentine at Garnet Ridge. *U.S. Geol. Surv. Bull.* **1103,** 54–61.

MARTENS, J. H. C. (1924) Igneous rocks of Ithaca, New York, and vicinity. *Bull. Geol. Soc. Am.* **35,** 305–320.

NIXON, P. H., O. VON KNORRING AND J. M. ROOKE (1963) Kimberlites and associated inclusions of Basutoland: a mineralogical and geochemical study. *Am. Mineral.* **48,** 1090–1132.

O'HARA, M. J. (1960) A garnet-hornblende-pyroxene rock from Glenelg, Inverness-shire. *Geol. Mag.* **97,** 145–156.

——— (1961) Zoned ultrabasic and basic gneiss masses in the early Lewisian metamorphic complex at Scourie, Sutherland. *Jour. Petrol.* **2,** 248–276.

——— (1963a) Melting of garnet-peridotite at 30 kilobars. *Yearb. Carnegie Inst.* **62,** 71–76.

——— (1963b) Melting of bimineralic eclogite at 30 kilobars. *Yearb. Carnegie Inst.* **62,** 76–77.

——— (1963c) The join diopside-pyrope at 30 kilobars. *Yearb. Carneg. Inst.* **62,** 116–118.

——— AND E. L. P. MERCY (1963) Petrology and petrogenesis of some garnetiferous peridotites. *Trans. Roy. Soc. Edinb.* **65,** 251–314.

——— AND E. L. P. MERCY (1965) On diamantiferous diatremes. *Econ. Geol.* **60,** 830–832.

OKHAPKIN, N. A. AND V. L. CHUBUGINA (1961) Pyropes and chrome-diopside in basaltic pipes of the Minusinsk intermontane basin. *Doklady Acad. Sci., U.S.S.R.,* **132,** 629–631 (transl. A.G.U.)

ORLOVA, M. T. (1961) Varieties of garnets, ilmenite and olivine from diamond-bearing regions of the Urals (Russian). *Byul. Vses. Nauchn.-Issled. Geol. Inst.* **3,** 111–127.

REAGAN, A. B. (1927) Garnets in the Navajo country. *Am. Mineral.* **12,** 414–415.

ROSS, C. S., M. D. FOSTER AND A. T. MYERS (1954) Origin of dunites and of olivine-rich inclusions in basaltic rocks. *Am. Mineral.* **39,** 693–737.

ROST, R. (1962) Doplňky k mineralogii pyropových šterků v českém středohoří. *Cas. Miner. Geol.* **7,** 407–417.

SEEBACH, M. (1906) Chemische und mineralogische Studien am Granat. *Inaug. Diss. Ruprecht-Karls-Univ. Heidelberg.*

SHOEMAKER, E. M., C. H. ROACH AND F. M. BYERS, JR. (1962) Diatremes and uranium deposits in the Hopi Buttes, Arizona. In *Geol. Soc. Am.* Buddington Vol. 327–355.

STRNAD, J. (1962) Souvislost části evropského neogenního vulkanismu s kimberlitovým magmatismem. *Cas. Miner. Geol.* **7,** 434–442.

SUBRAMANIAM, A. P. (1956) Mineralogy and petrology of the Sittampundi complex, Salem district, Madras state. *Bull. Geol. Soc. Am.* **67,** 317–390.

TRÖGER, W. E. (1956) *Optische Bestimmung der Minerale.* Stuttgart.

——— (1959) Die Granatgruppe: Beziehungen zwischen Mineralchemismus und Gesteinsart. *Neues. Jb. Mineral., Abh.* **93,** 1–44.

WATSON, K. D. (1960) Eclogite inclusions in serpentine pipes at Garnet Ridge, northeastern Arizona. *Bull. Geol. Soc. Am.* **71,** 2082–2083.

WILLIAMS, A. F. (1932) *The Genesis of the Diamond.* 2 Vols. Benn, London.

WILLIAMS, H. (1936) Pliocene volcanoes of the Navajo-Hopi country. *Bull. Geol. Soc. Am.* **47,** 111–172.

YODER, H. S., JR. AND C. E. TILLEY (1962) Origin of basalt magmas: An experimental study of natural and synthetic rock systems. *Jour. Petrol.* **3,** 342–532.

Manuscript received, July 8, 1965; accepted for publication, November 20, 1965.