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THE PETROLOGY OF THE LOWER CRUST AND UPPER MANTLE BENEATH SOUTHEASTERN CHIHUAHUA, MEXICO: A PROGRESS REPORT

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RESUMEN

En el basalto alcalino de la mina de peridotita La Olivina (localizada ~150 km al SE de Chihuahua, Chih.), se encuentran granulitas y nódulos ultramáficos del manto superior o la corteza inferior bajo la forma de xenolitos. Estos xenolitos ultramáficos pertenecen a tres grupos que se diferencian por su composición de clinopiroxenos: grupo I, alto magnesio (Mg/Mg + Fe = 0.90) y alto Cr_2O_3; grupo II, moderado magnesio (Mg/Mg + Fe = 0.76), alto Al_2O_3 y alto TiO_2; y grupo III, con composición intermedia entre I y II (grupo de transición). Los análisis de minerales primarios muestran que los xenolitos son similares a los de San Carlos, Arizona, E.U., Xalapasco de La Joya, San Luis Potosí, México y Kilburne Hole, New Mexico, E.U. Los xenolitos del manto de La Olivina pertenecen a tres grupos con distinta textura: grupo I, granoblástica (¿metamórfica?); grupo II, granular allotriomórfica (¿ígnea?); y grupo III, granular allotriomórfica (¿ígnea?) con algunas texturas porfiroclásticas (¿metamórfica?).

Los xenolitos de corteza inferior de La Olivina son predominantemente gneises pelíticos y granulitos de piroxeno. Los gneises pelíticos presentan ensambles uniformes de granate + cuarzo + plagioclasa + sanidina + silimanita + rutilo + grafito. La mayoría de las granulitas de piroxeno tienen plagioclasa, aunque algunas presentan escapolita en vez de plagioclasa. Estas muestras del manto inferior son idénticas en ensamble de minerales y muy similares en geoquímica a los xenolitos del Kilburne Hole. Las granulitas y los gneises pelíticos tienen edades modelo de Nd de 1.1 a 1.2 m.a., usando un cociente inicial de condritas, o bien 1.6 m.a. si se usa el modelo de fuente empobrecida. La edad de 1.6 m.a. concuerda muy bien con las edades del Kilbourne Hole, de aquí que se extiendan bajo el norte de México, al menos hasta el área de La Olivina, rocas precámbricas cratónicas, similares en edad, historia metamórfica y composición de protolito a las que están bajo Kilbourne Hole.

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ABSTRACT

Granulite facies metamorphic rocks and ultramafic nodules, of lower crustal and upper mantle origin, respectively, occur as xenoliths in a host alkali basalt at the La Olivina peridot mine, approximately 150 km southeast of Ciudad Chihuahua. The La Olivina ultramafic xenoliths are of three compositional groups that are distinguished by clinopyroxene chemistry: a high magnesian (Mg/Mg+Fe = 0.90), high Cr_2O_3 group (Group I); a moderately-magnesian (Mg/Mg+Fe = 0.76), high Al_2O_3, high TiO_2 group (Group II); and a group compositionally intermediate between these two (Transitional Group). Analyses of primary minerals show that these xenoliths are similar to ones from San Carlos, Arizona (USA), from Xalapasco de La Joya, San Luis Potosí (Mexico), and from Kilbourne Hole, New Mexico (USA). The La Olivina mantle xenoliths are of three textural groups: allotriomorphic granular (igneous?), porphyroclastic (metamorphic?), and granoblastic (metamorphic?). All Group I xenoliths are granoblastic, and most nodules of Group II and the Transitional Group are allotriomorphic granular. Porphyroclastic texture is less common than the other textures in the rocks studied, but it is found in some Transitional Group rocks.

The La Olivina lower crust xenoliths are predominantly pelitic gneisses and pyroxene granulites. The pelitic gneisses are uniform in mineral assemblage with garnet + quartz + plagioclase + sanidine + sillimanite + rutile + graphite. Most of the pyroxene granulites are plagioclase-bearing, but some contain scapolite in place of plagioclase. These lower crustal samples are identical in mineral assemblage and very similar in mineral chemistry to xenoliths described from Kilbourne Hole. The granulites and pelitic gneisses have model Nd ages of 1.1 to 1.2 b.y. using a chondritic initial ratio, or 1.6 b.y. using a depleted source model. The latter age is in excellent agreement with those from Kilbourne Hole. Thus it appears that Precambrian craton, similar in age, metamorphic history, and protolith composition to that which underlies Kilbourne Hole, extends into Mexico at least as far southeast as La Olivina.

INTRODUCTION

Our knowledge of the lithosphere is severely limited by the difficulty in obtaining samples of all except its most shallow levels. In Chihuahua there are few exposures of pre-Mesozoic rocks and only one area where Precambrian rocks crop out (Mauger *et al.*, 1983). Consequently, the southern and eastern extent of the North America craton in Mexico are not well known (Campa and Coney, 1983), and genetic models involving components of the lower crust in Chihuahuan mineral deposits (Cumming *et al.*, 1979) and volcanic rocks (e.g. Moll, 1981) are poorly constrained. Important samples of the unexposed levels of the Chihuahuan lithosphere, that is the lower crust and upper mantle, are found as inclusions (xenoliths) in basalt at the abandoned La Olivina peridot mine near La Perla (Fig. 1). In this paper we describe both ultramafic nodules and feldspathic, granulite facies, metamorphic xenoliths from La Olivina, and compare them to similar inclusions from Kilbourne Hole, New Mexico (USA), approximately 50 km west of El Paso, Texas (Carter, 1970; Padovani and Carter, 1977; Irving, 1980); from San Carlos, Arizona (USA), approximately 150 km east of Phoenix (Frey and Prinz, 1978); and from Xalapasco de La Joya, 33 km northeast of San Luis Potosi, SLP, Mexico (Greene and Butler, 1979; Powell and Gromet, 1980; Aranda-Gómez, 1982; Ruiz *et al.*, 1982).

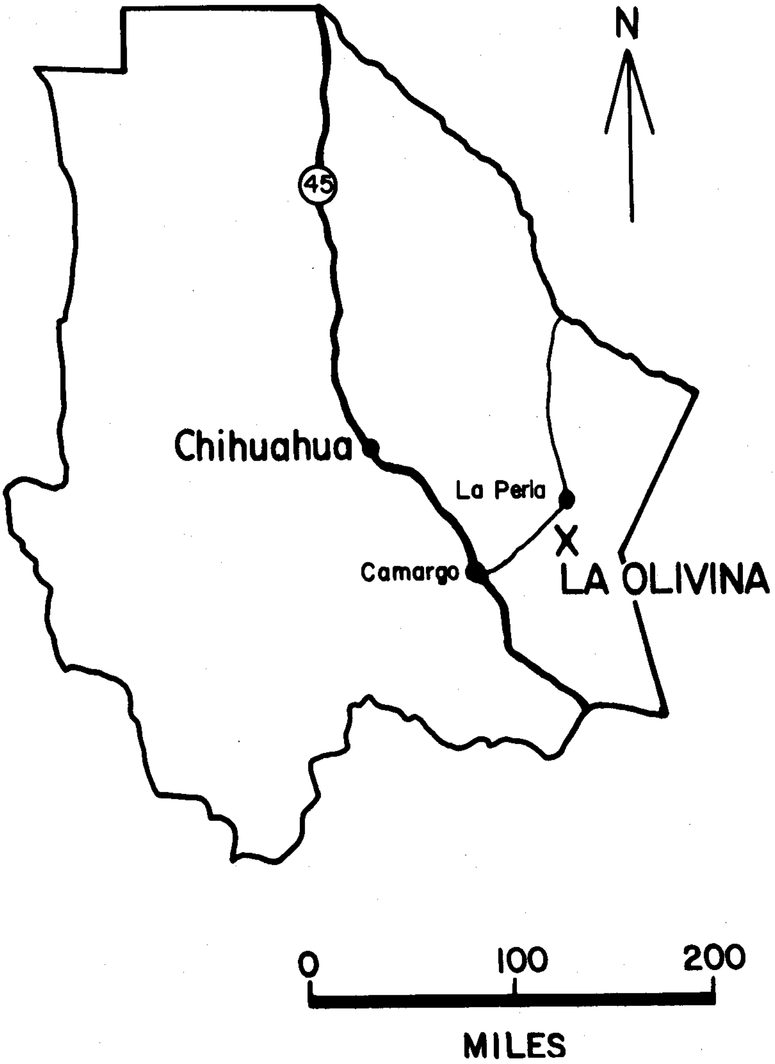

Fig. 1. Location of the La Olivina xenolith locality, State of Chihuahua, Mexico.

The La Olivina xenoliths occur in alkalic basalt cinder erupted from a small cinder cone that lies within an extensive field of basalt flows south of La Perla. A basaltic lava from the field has been dated preliminary by whole rock potassium-argon method at 2 million years. The relationship between the cinder cone and the lava flows is uncertain, but samples from each are very similar petrographically. It seems most likely that the cone is of the same age.

The ultramafic xenoliths consist of abundant peridotites (primarily spinel lherzolites) and rarer pyroxenites (primarily olivine websterites). The lower crustal xenoliths are feldspathic, granulite-facies rocks of varied mineralogy, but with plagioclase - pyroxene granulites and garnet-sillimanite gneisses predominating. Xenoliths of both ultramafic and feldspathic rocks are found up to a maximum size of about 20 cm in diameter. A count of 104 randomly selected xenoliths with a maximum dimension greater than 2.5 cm produced the following relative abundances for the La Olivina xenoliths:

79 % peridotite
12 % pyroxenite
7 % feldspathic metamorphic rocks
2 % upper crustal xenoliths (sedimentary and volcanic rocks that are not considered in this paper).

Thirty-five of the ultramafic and twenty-four of the feldspathic metamorphic rocks have been examined petrographically and minerals from ten ultramafic and seven feldspathic samples have been analyzed by electron microbeam techniques. Neodymium isotopic ratios for three samples and rare earth element data for four samples have also been obtained. Studies on these xenoliths are continuing.

ULTRAMAFIC XENOLITHS

MINERALOGY

Classification. Studies of ultramafic xenoliths from a number of localities have shown that most can be classified into two distinct populations, called the Cr-diopside group and the Al-augite group by Wilshire and Shervais (1975), and Groups I and II by Frey and Prinz (1978). These divisions have proven useful in the study of the La Olivina samples. Group I is composed predominantly of peridotites, such as spinel lherzolites, spinel harzburgites, and spinel dunites, in order of decreasing abundance. Clinopyroxene - rich rocks (e.g. wehrlites) are uncommon in Group I. Pyroxenites of Group I are usually orthopyroxene - rich. Spinel, deep reddish - brown in thin - section, is usually present but only in low abundance. Group I cenoliths can be most easily distinguished by their mineral chemistry. For example, clinopyroxenes from Group I rocks from San Carlos have high Mg-numbers (Mg/(Fe + Mg) = 0.87 - 0.91), relatively high Cr_2O_3 (0.62 - 1.04 wt. %), and relatively low Al_2O_3 (4.9 - 6.0 wt. %) and TiO_2 (0.35 - 0.67 wt. %). Spinel has high Cr/(Cr +

Al+ Fe^{3+}) with values between 0.17 and 0.35. In hand-specimen Group I xenoliths are light to medium green due to the presence of apple - green olivine and emerald - green diopside. They have metamorphic textures that are granoblastic to granoblastic - polygonal (Wilshire and Shervais, 1975). Triple - point (120 degree) grain junctions, kink-bands in olivine, and deformation features in orthopyroxene are common features.

Group II is comprised predominantly of pyroxenites (e.g., spinel olivine clinopyroxenites and spinel olivine websterites). The peridotites that are found are clinopyroxene - rich, and are either spinel wehrlites or spinel lherzolites. The spinel is dark green in thin-section, and is more abundant than in Group I. Clinopyroxenes from Group II xenoliths from San Carlos have lower Mg-numbers (0.77 - 0.82), lower Cr_2O_3 (<0.16 wt. %), higher Al_2O_3 (8.5 – 8.9 wt. %) and higher TiO_2 (0.89 – 1.68 wt. %) abundances than those from Group I. The spinels have relatively low Cr/(Cr+Al+Fe^{3+}) ratios (<0.05). In hand sample these xenoliths are often black or very dark green due to the presence of black augite and dark yellowish - green olivine. Group II textures are neither clearly igneous nor clearly metamorphic (Frey and Prinz, 1978). Most are allotriomorphic granular and contain poikilitic, cumulate-like textures, whereas others appear recrystallized. The xenoliths typically are without fabric and appear undeformed (Wilshire and Shervais, 1975).

Xenoliths and portions of xenoliths that are transitional in mineral chemistry between Groups I and II have been discussed by Wilshire and Shervais (1975), Frey and Prinz (1978), and Irving (1980). The single sample described by Frey and Prinz is a composite xenolith with spinel lherzolite in contact with spinel olivine clinopyroxenite. The minerals from both rock types are chemically similar with intermediate Mg-numbers and Cr_2O_3 concentrations in clinopyroxenes, and intermediate Cr/(Cr+ Al+ Fe^{3+}) ratios in spinel. Al_2O_3 abundances in clinopyroxenes are relatively high, as in Group II. The concentration of TiO_2 in clinopyroxene is even higher than that in Group II samples. The spinel in the sample is brown, although greenish - brown spinel grains occur enclosed within olivine and clinopyroxene. The texture is allotriomorphic - granular with the clinopyroxenite being finer grained than the lherzolite. Irving (1980) described zones a few centimeters wide within Group I lherzolite wall rock at the contact with Group II veins that are transitional in mineral chemistry. He states that subtle chemical changes may extend into the wall rock for a distance of 15 cm or more.

Group I xenoliths are interpreted to represent primary upper mantle lithology, whereas Group II pyroxenites are interpreted to represent veins formed by mineral plating or segregation as basaltic melts moved through the Group I mantle (Wilshire and Shervais, 1975; Frey and Prinz, 1978; Irving, 1980). Wilshire and Shervais (1975) interpreted olivine - rich Group II rocks as being Group I mantle country rock modified by metasomatic reaction with basaltic melts, which deposited the Group II pyroxenite veins. The origin of the transitional xenolith was not addressed by Frey and Prinz, but the work of Wilshire and Shervais (1975) and Irving (1980) demonstrate that zones with transitional mineral chemistry occur in lherzolite wall rock adjacent to Group II veins. These reaction zones are usually peridotite rather than pyroxenite.

The La Olivina xenoliths are classified according to the above scheme. By far the most abundant ultramafic xenoliths are Group I peridotites. Our present xenolith collection indicates that discrete nodules with transitional mineral chemistry, referred to as the Transitional Group xenoliths, are more abundant than typical Group II rocks. With the exception of composite xenolith MN10, which contains the contact between harzburgite and orthopyroxenite, all samples analyzed from La Olivina are discrete xenoliths (single lithology). Other composite xenoliths were collected, but have yet to be extensively studied. The samples dealt with in depth in this paper are described in the Appendix.

La Olivina Group I Xenoliths

GROUP I PERIDOTITES. Most of the La Olivina Group I peridotites are spinel lherzolites (Table 1, Fig. 2). Reddish-brown anhedral spinel crystals, which are interstitial to the major silicate phases and commonly associated with pyroxene, comprise about 1 - 2 % by volume of the xenolith (Table 1). Other phases present include minor amounts of glass located along grain boundaries and trace amounts of phlogopite in at least one sample.

Compositions of the clinopyroxenes, orthopyroxenes, and spinels of the Group I peridotites are presented in Tables 2 and 3. The assemblage is generally Cr-rich and Ti-poor. The Mg numbers (Mg/Mg+ Fe) of both clinopyroxenes, orthopyroxenes, and olivines cluster tightly around 0.90. There is no indication, in our limited data, that either the pyroxenes or olivines have significant compositional variations within individual grains or among different grains within the same rock.

TABLE 1. MODES OF LA OLIVINA ULTRAMAFIC SAMPLES

	Group I					Transitional					Group II
	MN1	MN4	MN10H	MN10X	MN212	MN14	MN16	MN205	MN209	MN219	MN1000
Olivine	70.6	71.7	59.6	---	5.1	---	11.1	10.3	33.8	2.1	<1.0
Orthopyroxene	16.5	13.3	37.1	89.2	89.5	18.8	11.1	3.1	18.5	69.8	7.2
Clinopyroxene	10.9	13.5	2.2	6.5	4.0	72.9	67.7	85.6	46.9	28.1	48.2
Spinel	2.0	1.3	1.1	3.2	0.3	1.0	<1.0	<1.0	0.8	<1.0	4.8
Amphibole	---	---	---	1.1	1.0	7.3	10.1	1.0	---	---	39.8
Phlogopite	<1.0	---	---	---	---	---	---	---	---	---	---
Olivine $\frac{Mg}{Mg + Fe}$	0.90	0.90	0.91	0.91	0.90	---	0.84	0.86	0.83	---	0.85

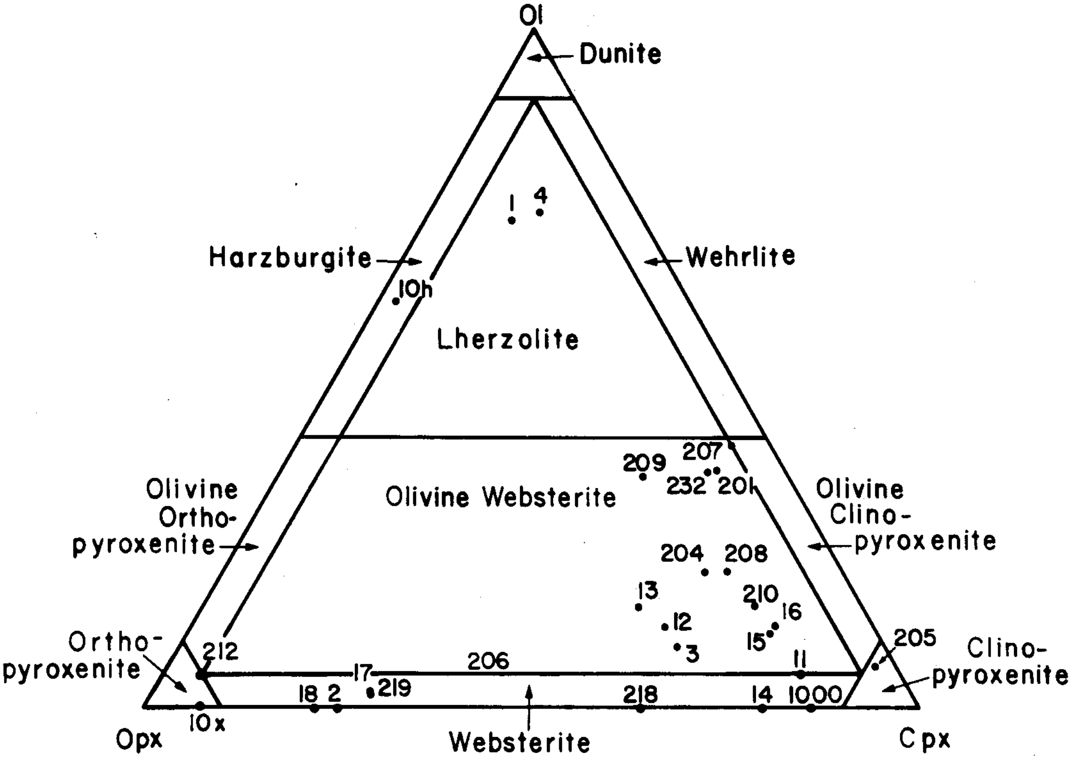

Fig. 2. IUGS ultramafic rock classification diagram (After Strecheisen, 1976) showing modal compositions and sample numbers of the La Olivina samples.

TABLE 2. PYROXENE ANALYSES

	LA OLIVINA											SAN CARLOS[1]					Xalapasco de la Joya[2]	
	Group I					Transitional					Group II	Group I			Transitional	Group II		
	MN1	MN4	MN10H	MN10X	MN212	MN14	MN16	MN205	MN209	MN219	MN1000	PA-6	PA-144	PA658	PA2188	PA-43	1-5-3	3-2-2
Clinopyroxene																		
SiO_2	51.41	51.57	52.18	51.76	51.16	49.67	50.19	49.95	49.43	50.71	48.67	50.8	52.6	52,6	50.7	48.4	55,1	52.1
Al_2O_3	6.19	6.33	6.03	6.20	7.19	7.37	7.29	7.23	6.57	6.52	8.92	6.2	4.9	5.5	8,9	8.9	4,86	6.72
TiO_2	0.45	0.31	0.27	0.23	0.27	0.59	0.45	0.62	1.00	0.50	0.90	0.22	0.35	0.55	2,69	1,19	0,24	0.58
FeO	2.77	3.10	3.03	2.80	2.96	5.67	5.01	4.85	5.22	4.57	7.21	2.88	3.0	2,8	4.3	7.2	3,44	2.88
MnO	0.10	0.05	0.00	0.00	0.00	0.05	0.04	0.00	0,00	0.00	0.03	0.05	0.09	0.07	0.13	0,13	---	---
MgO	15.46	15.43	16.07	16.47	15.77	15,97	15.28	15.58	15.46	15.64	13.02	16.2	17.9	16,0	14.4	13.5	16,97	16.88
CaO	20.80	20.50	20,25	20.45	20.02	19.33	19.72	19.95	20.86	19.67	19.14	19,5	19.7	19.9	20.6	19,1	19,0	20.8
Na_2O	1.39	1.33	1.11	0.88	1.37	1,38	1.08	0.50	0.60	1.27	1.46	2,01	1.24	1.40	0.15	1.23	---	---
K_2O	0.0	0.0	0.06	0.03	0.15	0.03	0.12	0.05	0.07	0.09	0.12	---	---	---	---	---	---	---
Cr_2O_3	0.94	0.88	0.81	1.36	1,01	0.27	0.33	0,47	0.52	0.47	0.16	1.29	0,62	1,04	0.10	0,15	---	---
TOTAL	99.51	99.50	99.79	100.18	99.91	100.36	99.50	99,20	99.75	99,42	99.63	99,15	100,40	99.86	101.97	99.80	99.61	98,96
Mg/Mg+ΣFe	0.91	0.90	0.90	0.91	0,90	0.83	0.85	0,85	0,84	0.86	0.76	0,91	0.91	0.91	0,86	0,77	0.90	0,91
Orthopyroxene																		
SiO_2	54.59	54.39	55.75	54.90	55.31	52.56	54.10	52.87	53.47	54.01	52.82	55.8	56.5	55.7	---	51,1	54.6	54.9
Al_2O_3	4.44	4.48	4.32	4.08	5.31	5.40	5.90	5.30	4.28	4.80	5,52	3.3	3.1	4,2	---	5.3	4.49	5.64
TiO_2	0.08	0.00	0.00	0.00	0.05	0.00	0.13	0.00	0.03	0.07	0.21	0.04	0.17	0.14	---	0,21	0.07	0.00
FeO	6.58	6.35	5.92	5.95	5.97	11.16	9.55	8.97	10.55	9.03	13.05	6.2	5.8	7.0	---	15,0	8.11	7.28
MnO	0.13	0.17	0.02	0.00	0.01	0.11	0.13	0.06	0.06	0.13	0.19	0.09	0.14	0.12	---	0.23	---	---
MgO	33.09	32.58	32.92	35.11	32.78	29.49	29.47	31.80	31.73	30.38	26.94	32.5	33.7	32.2	---	26.8	31.40	32.7
CaO	0.77	0.92	0.61	0.64	0.73	0.89	0.96	0.81	0.67	0.89	1.05	0.66	1.19	0.90	---	1.05	0.85	0.73
Na_2O	0.09	0.13	---	---	---	---	---	---	---	---	---	0.10	0.11	0.10	---	<0.01	---	---
Cr_2O_3	0.39	0.34	0.15	0.23	0.34	0.03	0.06	0.07	0.06	0.15	0.04	0.58	0.32	0.57	---	0.08	---	---
TOTAL	100.08	99.35	99.69	100.92	100.50	99.63	100.29	99.87	100.85	99.46	99.81	99.27	101.03	100.93	---	99.77	99.52	101.15
Mg/Mg+ΣFe	0.90	0.90	0.91	0.91	0.91	0.83	0.85	0.86	0.84	0.86	0.79	0.90	0.91	0.89	---	0.76	0.87	0.89

1. From Frey and Prinz (1978).
2. From Greene and Butler (1979).

TABLE 3. SPINEL ANALYSES

	LA OLIVINA							SAN CARLOS[1]				XALAPASCO DE LA JOYA[2]	
	Group I					Transitional	Group II	Group I		Transitional	Group II		
	MN1	MN4	MN10H	MN10X	MN212	MN209	MN1000	PA-6	PA-658	PA-2188	PA-43	1-5-3	3-2-2
SiO_2	0.05	0.05	0.35	0.33	0.12	0.09	0.13	---	---	---	---	0.87	0.0
TiO_2	0.12	0.09	0.00	0.07	0.00	0.41	0.37	0.16	0.25	0.54	0.21	0.27	0.06
Al_2O_3	54.90	54.50	52.58	51.66	56.02	49.51	57.18	41.5	52.5	65.0	59.5	48.1	54.0
Fe_2O_3**	3.63	3.25	5.07	5.91	3.28	8.18	9.33	0.00	0.7	0.00	5.4	4.39	1.86
FeO	9.00	8.93	9.43	7.17	8.02	15.40	17.25	10.0	8.6	11.5	15.8	10.05	8.83
MnO	0.14	0.09	0.19	0.16	0.00	0.08	0.02	0.20	0.18	0.09	0.23	---	---
MgO	20.59	20.39	20.66	21.91	21.37	16.35	15.82	18.5	20.2	20.6	16.6	19.8	20.4
Cr_2O_3	10.98	11.04	13.27	13.56	10.31	10.78	0.00	29.8	16.3	2.7	2.50	14.6	13.1
TOTAL	99.41	98.35	101.55	100.77	99.12	100.80	100.10	100.50*	99.16*	100.89*	100.77*	98.08	98.25
Mg/Mg+ΣFe	0.75	0.75	0.73	0.76	0.78	0.56	0.52	0.77	0.80	0.76	0.65	0.72	0.69
$Cr/Cr+Al+Fe^{3+}$	0.11	0.12	0.14	0.14	0.11	0.12	0.00	0.33	0.17	0.03	0.03	0.16	0.14

**.- Fe_2O_3 calculated for charge balance

* - Total includes V_2O_3, ZnO, & NiO

1. From Frey and Prinz (1978).
2. From Greene and Butler (1979).

GROUP I PYROXENITES. The two Group I pyroxenites analyzed, MN10-X and MN212, are both orthopyroxenites (Fig. 2). They have an average grain size of 3-4 mm, although this mainly represents the size of the orthopyroxenes. The average clinopyroxene grain size is 0.5 mm. Both pyroxenes rarely show exsolution lamellae, and like the olivine grains, only rarely show any signs of strain. Spinel is deep brown and occurs as anhedral grains, often elongate along grain boundaries of the major phases. Glass is present along grain boundaries, although is not abundant. MN10-X and MN 212 show most of the compositional features typical of the Group I xenoliths from both La Olivina and from San Carlos (Tables 2 and 3), but slight deviations do occur. For example, spinel in sample MN212 has a higher Al_2O_3 concentration and has a lower $Cr/(Cr+Al+Fe^{3+})$ ratio than is typical of the San Carlos samples. Clinopyroxene in MN10-X has a much higher Cr_2O_3 abundance than any other Group I sample. Clinopyroxenes in both MN10-X and MN212 are lower in TiO_2 than those of Group I samples from San Carlos, and this seems to be a feature of all La Olivina samples (Table 2).

Sample MN10-X contains virtually no olivine. The olivine seen in thin section is located near the contact with MN10H and is of the same grain size and composition (Mg-number 0.91) as those in MN10H. It is possible that these grains represent disaggregated MN10H olivines that have been incorporated into the MN10X pyroxenite. They may, therefore, not be in equilibrium with MN10X pyroxenes and spinel, and would not be reliable for geothermometry (see below).

La Olivina Group II Xenoliths

Only a few of the samples examined thus far are Group II, and only one, MN1000, has been studied in detail. It is a websterite with an average grain size of 2 - 3 mm. Exsolution lamellae are not present. The sample contains a high percentage (5%) of spinel for a La Olivina sample, and contains the greatest abundance of amphibole of any sample thus far examined (40%). The spinel is green in color. Glass is present and often associated with the spinel and/or amphibole. Comparison with the San Carlos Group II samples shows strong similarities (Tables 2 - 4); dissimilarity occurs only in Mg-number in the olivine. The olivine in MN1000, however, is probably not in equilibrium with the pyroxene. It occurs as graphic-shaped microlites in clear brown glass possibly formed by decompression melting. The Mg-number of olivine from this sample, therefore, probably is not representative of La Olivina Group II olivines.

TABLE 4. AMPHIBOLE ANALYSES

	LA OLIVINA					SAN CARLOS[1]		
	Transitional				Group II	Group I	Group II	
	MN14	MN16	MN205	MN219	MN1000	PA120-G	PA-7	PA-43
SiO_2	40.61	42.38	40.61	42.20	41.92	42.8	40.2	40.5
TiO_2	3.37	2.49	2.64	2.94	3.42	1.2	5.2	4.2
Al_2O_3	14.72	15.44	14.90	14.61	15.20	13.8	14.5	15.3
FeO	7.62	6.83	6.16	6.20	9.66	4.5	8.4	9.9
MnO	0.00	0.03	0.00	0.00	0.02	0.06	0.10	0.13
MgO	16.43	15.42	16.67	16.45	13.76	17.9	15.1	14.2
CaO	10.51	11.07	10.52	11.05	10.42	9.7	11.2	10.9
Na_2O	2.86	2.78	2.56	2.65	3.37	3.7	2.9	3.0
K_2O	1.32	1.62	0.92	1.84	0.86	1.13	1.07	1.09
Cr_2O_3	0.33	0.34	0.51	0.63	0.00	2.0	0.0	0.0
TOTAL	97.77	98.39	95.49	98.58	98.64	96.74	98.67	99.22
$Mg/Mg+\Sigma Fe$	0.79	0.80	0.83	0.83	0.72	0.88	0.76	0.72

1. From Frey and Prinz (1978).

The high amphibole abundance observed in MN1000 is also a feature of three of the six Group II samples reported by Frey and Prinz (1978), with one sample containing 41.7 % amphibole. The amphiboles from ultramafic xenoliths tend to be either kaersutitic or pargasitic (Frey and Prinz, 1978; Best, 1970; Wilshire and Trask, 1971; Wilshire *et al.*, 1980). The distinction between the two is made on TiO_2 content where kaersutite has greater than 4 wt. % TiO_2 and pargasite less than 4 wt. %. On this basis, all La Olivina amphiboles are pargasitic. Amphibole analyzed from MN1000, however, has the highest TiO_2 content (3.4 wt. %) of any La Olivina amphibole yet analyzed. At San Carlos the amphiboles with the highest TiO_2 contents (4.2 to 5.2 wt. %) are also from the Group II samples (Frey and Prinz, 1978).

La Olivina Transitional Group Xenoliths

Most of the La Olivina pyroxenites studied are transitional in mineral compositions between Groups I and II (Tables 2 and 3). These Transitional Group pyroxenites vary widely in olivine content and in the ratio of orthopyroxene to clinopyroxene. For example, MN219 has a high modal content of orthopyroxene, MN209 a high abundance of olivine, and MN205 is rich in clinopyroxene. The abundance of spinel, amphibole and phlogopite in these samples is unrelated to the modal contents of major phases. The minerals in the La Olivina Transitional Group xenoliths are intermediate between those of Groups I and II in FeO, Al_2O_3, and Cr_2O_3 contents and Mg-numbers (Tables 1 and 2). Within the Transitional Group there is also a range in mineral chemistry as demonstrated by pyroxene Al_2O_3, Cr_2O_3, and Mg-numbers. Compositions range from similar to those of Group II samples to compositions trending toward those of Group I samples (Table 2).

Comparison of Mineralogy With Other Localities

The La Olivina ultramafic xenoliths are generally similar in mineral chemistry to those found at San Carlos, Xalapasco de La Joya (Tables 2 and 3), and Kilbourne Hole (Irving, 1980; Carter, 1970). However, some significant differences do exist. They are most easily seen by comparing clinopyroxene chemistry.

Comparison with San Carlos samples reveals differences in Al_2O_3 and TiO_2 contents in clinopyroxenes. San Carlos Group I samples are less aluminus than La Olivina Group I samples (4.9 - 6.0 % compared to 6.0 - 7.2 % Al_2O_3). San Carlos Group II samples range from 8.5 % to 8.9 % Al_2O_3 while the La Olivina Group II sample contains 8.9 %. The Al_2O_3 content of the respective Transitional Group samples, however, are dissimilar. The San Carlos sample contains 8.9 % while the range for La Olivina samples is 6.5 % to 7.4 %. It may be, however, that the lone San Carlos transitional xenolith is not representative.

The TiO_2 contents of Group I clinopyroxenes from San Carlos range from 0.35 % to 0.67 %, whereas those from La Olivina are slightly less titaniferous, 0.35 % to 0.45 %. Group II clinopyroxenes from San Carlos range from 0.89 % to 1.7 % TiO_2 in its clinopyroxene. This match is similar to that seen in Al_2O_3 contents for Group II clinopyroxenes for each location. Also similar to Al_2O_3 behavior is TiO_2 behavior for Transitional Group xenoliths for the two locations. The range for La Olivina samples is 0.45 % to 1.1 %, whereas the San Carlos sample contains 2.69 % TiO_2. Thus the San Carlos transitional sample is higher in both Al_2O_3 and TiO_2 than the range for La Olivina Transitional Group samples.

The Xalapasco samples described by Greene and Butler (1972) are Group I xenoliths based on olivine and clinopyroxene Mg-numbers, and relative Al_2O_3 and TiO_2 contents. Again, however, when the clinopyroxenes are compared to those from Group I samples from La Olivina, differences can be seen in Al_2O_3 and TiO_2 (Table 2). In particular, Al_2O_3 contents are lower (as exemplified by sample 1-5-3) and TiO_2 contents are higher (as exemplified by sample 3-2-2). The differences shown by these two oxides are not as large between La Olivina and Xalapasco, however, as they are between La Olivina and San Carlos.

These comparisons suggest that there are overlapping but distinct ranges for clinopyroxene Al_2O_3 and TiO_2 contents in the different xenolith groups. Ranges of

Al_2O_3 contents are 4.9 % to 7.2 % (Group I), 6.5 % to 8.9 % (Transitional Group), and 8.5 % to 8.9 % (Group II). Ranges of TiO_2 contents are 0.23 % to 0.67 % (Group I), 0.45 % to 1.0 % (Transitional Group - perhaps as high as 2.69 % if the San Carlos sample is not anomalous), and 0.89 % to 1.7 % (Group II).

Full chemical analyses from Kilbourne Hole have not been published. However, data from two studies show a similarity between Kilbourne Hole xenoliths and La Olivina xenoliths. Carter (1970) demonstrated that clinopyroxene Mg-numbers distinguish two populations of xenoliths at Kilbourne Hole, with ranges of 77 to 86 and 89 to 93. The former would encompass both Group II and the Transitional Group from La Olivina, while the latter corresponds to Group I. This suggests the possibility that Group II and the Transitional Group form a continuum of chemical compositions and are not separate groups, although the continuum is separated from Group I. We have drawn a distinction between Group II and the Transitional Group both because of the precedent set by Frey and Prinz (1978) and because MN1000 appears to be distinctly different from the five Transitional Group xenoliths studied both chemically and texturally. As more La Olivina xenoliths are studied, however, these distinctions may be blurred such that the groups can be merged. A merging of these with Group I seems less likely in view of Carter's work as well as that of Frey and Prinz.

Two xenolith populations at Kilbourne Hole can also be distinguished on the basis of the compositions of their spinels (Irving, 1980). Sample KH73-1L, representing the first group, contains brown spinels with a Cr-number ($Cr/Cr+Al+Fe^{3+}$) of 0.23. Sample KH77-20 represents the second group and contains green spinels with Cr-numbers ranging from 0.02 to 0.04. As Table 3 and the xenolith descriptions indicate, these high-Cr and low-Cr populations correspond to La Olivina Groups I and II respectively, although the La Olivina Group I Cr-numbers are not quite as high as that in KH73-1L. It seems noteworthy in this regard that the spinel in the Transitional Group sample (MN209) has a Cr-number in the range of the Group I samples, not transitional between Groups I and II. Its color, however, is green and not brown as Group I spinels are.

RARE EARTH ELEMENT AND Nd ISOTOPIC COMPOSITIONS

Rare earth element (REE) analyses were made of two Transitional Group pyroxenites (Table 5) by the isotope dilution technique (Hanson, 1976). The analyzed La

Olivina pyroxenites are transitional not only in mineralogy between Groups I and II but also in REE concentrations (Fig. 3). The Kilbourne Hole pyroxenite REE patterns shown in Figure 3 are from Group II dikes in composite xenoliths that cut

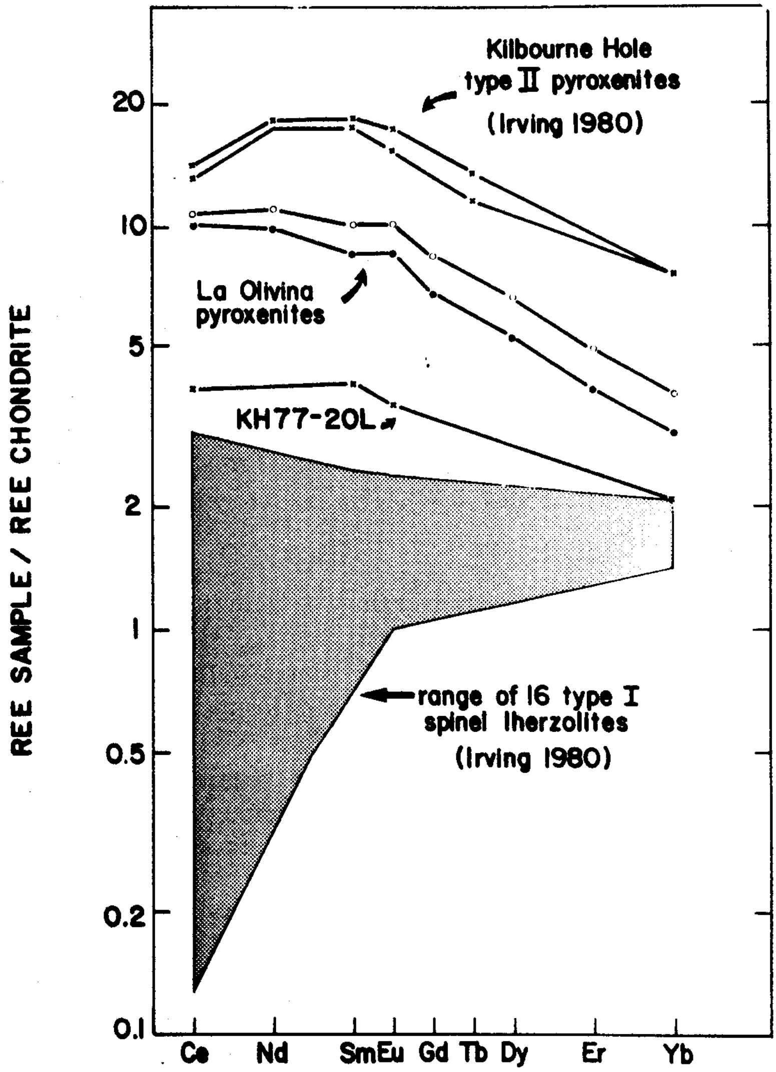

Fig. 3. Chondrite-normalized rare earth element patterns for La Olivina and Kilbourne Hole ultramafic xenoliths. Solid circles represent MN16, open circles represent MN14.

spinel lherzolite (Irving, 1980). Reid and Frey (1971) report REE data on a discrete pyroxenite xenolith (a spinel-olivine clinopyroxenite) that overlaps in compositions with the dikes; thus the available data, although few, suggest that the Kilbourne Hole Group II pyroxenites are rather uniform in REE compositions. Sample KH77-20L, also from Kilbourne Hole (Fig. 3), is a spinel lherzolite wall rock, from a zone adjacent to a Group II pyroxenite vein, that has been modified by reaction (Irving, 1980).

The two analyzed La Olivina pyroxenites are discrete xenoliths, approximately 15 cm in diameter. Their REE patterns are quite similar in shape (Fig. 3), and both have significant positive Eu anomalies. Their REE concentrations are much higher than the Group I spinel lherzolites from Kilbourne Hole, but the concentrations of middle and heavy REE in the La Olivina samples are only about 50 % of those in the Group II pyroxenites from Kilbourne Hole (Fig. 3). The pyroxenite samples from La Olivina differ from most Kilbourne Hole samples, both Group I and II, in that they are not depleted in the light REE. Most Kilbourne Hole Group I spinel lherzolites have chondrite normalized ratios of Ce to Sm ((Ce/Sm)n), between about 0.2 and 0.4 (Irving, 1980; Basaltic Volcanism Study Project 1981), and the Group II pyroxenites have (Ce/Sm)n about 0.75. The La Olivina samples have (Ce/Sm)n greater than 1.0 (Fig. 3).

The whole rock Nd isotopic composition was determined for sample MN14, a Transitional Group websterite. It has present day $\epsilon_{Nd} = +4.8$* (Table 5), which is in the range of volcanic rocks from oceanic islands and convergent plate margins. Jagoutz *et al.* (1980) report isotopic data on one Group I lherzolite from Kilbourne Hole. This sample has $\epsilon_{Nd} = +13$ and $^{87}Sr/^{86}Sr = 0.7025$, which is near the high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$ end of the mid-ocean ridge basalt (MORB) array. Roden *et al.* (1984), in an abstract, report additional analyses of clinopyroxenes from Kilbourne Hole Group I lherzolites. These data define a field that extends from the previously reported high $^{143}Nd/^{144}Nd$ – low $^{87}Sr/^{86}Sr$ point to a point near the values of the bulk earth (about $\epsilon_{Nd} = 0$, $^{87}Sr/^{86}Sr = 0.7045$). This spread in values is interpreted to reflect a mixture of a MORB-like depleted component and a metasomatic component. They also report that basalt rinds on xenoliths and clinopyroxenes from composite Group II inclusions are isotopically more homogeneous, and these plot in the high $^{143}Nd/^{144}Nd$ – low $^{87}Sr/^{86}Sr$ end of the ocean island basalt field (presumably about $\epsilon_{Nd} = +8$ to $+10$).

* – ϵ_{Nd} is defined by DePaolo (1981a) as: $\epsilon_{Nd} = \left(\frac{^{143}Nd/^{144}Nd \text{ ROCK}}{^{143}Nd/^{144}Nd \text{ CHONDRITE}} - 1 \right) \times 10^4$

Table 5

Rare earth element and ^{143}Nd/^{144}Nd analyses of xenoliths

	MN59 Pelitic gneiss	MN19 2 Pyroxene granulite	MN16 Olivine Websterite	MN14 Websterite
Ce (ppm)	145.0	69.3	8.27	8.74
Nd	59.1	39.0	5.85	6.60
Sm	10.5	8.20	1.64	1.94
Eu	1.50	1.78	0.620	0.733
Gd	8.83	7.03	1.76	2.17
Dy	10.0	6.51	1.70	2.14
Er	5.81	3.66	0.830	1.05
Yb	5.43	3.31	0.628	0.796
^{143}Nd/^{144}Nd	0.51192±3	0.51212±2	––	0.51288±4
^{147}Sm/^{144}Nd	0.1075	0.1272	––	0.1778
ϵ_{Nd}	−13.9	−10.0	––	+4.8

^{143}Nd/^{144}Nd values normalized to ^{146}Nd/^{144}Nd = 0.72190, and adjusted to a value of 0.511860 for the La Jolla Nd standard. ϵ_{Nd} calculated for present day with ^{143}Nd/^{144}Nd CHUR = 0.512636 and Sm/Nd CHUR = 0.1967.

TEXTURES OF THE ULTRAMAFIC XENOLITHS

The La Olivina ultramafic xenoliths fall into three textural groups: allotriomorphic granular, porphyroclastic, and granoblastic. The groups are distinguished on the basis of grain size, grain boundary shape, amount of exsolution in pyroxenes, and to a lesser degree the amount of strain recorded by kinkbands and deformation lamellae in the minerals (Appendix).

The most common texture of the pyroxenites is allotriomorphic granular (samples MN14, MN16, MN205, and MN1000). Rocks of this group are usually coarse grained (3-10 mm) with irregularly shaped, non-curvilinear, grain boundaries. They show both lamellar and granular exsolution, and commonly are somewhat poikilitic. Clinopyroxenes from these rocks often have growth twins. Some of the pyroxenites contain vugs that are lined with euhedral amphiboles. These amphiboles clearly must have grown into fluid filled cavities.

The porphyroclastic texture is illustrated by only one sample, MN219, a Transitional Group websterite. This texture is characterized by two distinct grain-size populations, larger porphyroclasts (4 - 7mm) and similar neoblasts (0.1 - 2mm). The porphyroclasts are predominantly orthopyroxene that contain abundant strain lameellae and have anhedral, irregular grain boundaries. The neoblasts, which include orthopyroxene, clinopyroxene, and minor olivine, are strain-free and polygonal, with curvilinear grain boundaries meeting at 120 degree triple-point grain junctions. The porphyroclastic group from La Olivina corresponds roughly, though not precisely, to the "porphyroclastic" texture of Mercier and Nicolas (1975). It differs from that of Mercier and Nicholas by containing no sheared, elongated grains. Moreover, they restricted the term to peridotites, whereas we are applying the term to a pyroxenite.

The granoblastic group is composed of samples MN1, MN4, MN10 (–H and –X), MN209, and MN212. Grain boundaries in this group are curvilinear to straight, and 120 degree triple-point grain junctions are common. The minerals appear undeformed and largely unstrained. The granoblastic lherzolites contain olivine that has a bimodal size distribution, with crystals in the ranges of 1 - 2 mm and 3 - 5 mm. The larger grains usually have widely-spaced kinkbands. Orthopyroxene is typically in the size range 2 - 3 mm. Clinopyroxene is usually smaller (1 - 2 mm), but occasionally reaches sizes up to 7 mm. A few of the larger clinopyroxene grains show well-developed (001) exsolution lamellae. The granoblastic pyroxenites are texturally similar to the lherzolites except that the grain-size is more uniform (about 1.0 - 1.5mm).

Granoblastic samples MN1 (lherzolite) and MN209 (olivine websterite) show a mild foliation due to preferential elongation of grains. The other samples in this group have roughly equant grains.

There is a general correlation between the mineral chemistry groups and the textural groups. All Group I samples are in the granoblastic textural group, and the Group II sample, MN1000, is in the allotriomorphic granular group. Most Transitional Group samples are allotriomorphic, but at least one example of this mineral chemistry group has been found in each of the other two textural groups. For example, MN209, a Transitional Group olivine websterite, has a granoblastic texture, and MN 219, a Transitional Group websterite, exhibits the porphyroclastic texture.

GEOTHERMOMETRY AND GEOBAROMETRY

Thermometric calculations were performed on the xenolith suite by the methods of Gasparik and Newton (1984), Wells (1977), Fabries (1979), Lindsley (1983), and

Mercier (1980). Each of these five methods employs a different strategy for calculation of temperature. The first method employs Mg-Tschermak contents in orthopyroxene in equilibrium with spinel and olivine. The second employs partitioning of Mg and Fe between coexisting pyroxenes. The third utilizes both Cr-Fe^{3+} mole fractions in spinel and Fe^{2+}-Mg ratios in coexisting olivine. The fourth method relates positioning on the pyroxene quadrilateral of two pyroxene that are in equilibrium, one Ca-rich and one Ca-poor, to temperature. The final method is a single-pyroxene thermometer that relies on the temperature dependence of the mole fractions of Ca, Mg, Fe, Mn, Al, Na, and Cr present in the pyroxene. It can be used with either a clinopyroxene or an orthopyroxene. Thus the five methods operate under different assumptions and mutually check one another. The results of the calculations are shown in Table 6.

Table 6

Geothermometry/Barometry results

	Temperature (°C)							Pressure (Kb)	
Source:	1	2	3	4		5		5	
				OPX	CPX	OPX	CPX	OPX	CPX
Sample									
MN 1	968	952	999	1000	1250	1063	1002	20.2	13.2
MN 4	1010	993	972	1050	1225	1066	1002	19.7	14.4
MN10H	1022	1048	970	900	1225	997	1072	19.7	18.7
MN10X*	928	1055	1304	1000	1275	992	1081	15.8	15.4
MN212	1059	1021	1154	900	1300	1070	1064	18.0	15.8
MN 14	–––	1053	–––	950	1275	1065	1169	21.2	24.2
MN 16	–––	1059	–––	950	1250	1130	1112	24.3	20.0
MN205	–––	1095	–––	1000	1250	1062	1107	21.8	17.1
MN209	1055	1022	1047	950	1250	1058	1084	24.2	16.4
MN219	–––	1041	–––	950	1250	1068	1122	23.1	23.0
MN1000*	1352	1008	675	900	1200	1128	1087	24.9	16.5

* – May not be an equilibrium assemblage; see text.

Sources

1 - Gasparik and Newton (1984). Method: Olivine + Spinel + Al-Orthopyroxene.
2 - Wells (1977). Method: Orthopyroxene + Clinopyroxene.
3 - Fabries (1979). Method: Olivine + Spinel.
4 - Lindsley (1983). Method: Single crystal; Orthopyroxene and Clinopyroxene.
5 - Mercier (1980). Method: Single crystal; Orthopyroxene and Clinopyroxene.

The technique used by Lindsley is graphical, whereas for each of the other geothermometers the relationship between equilibrium composition (in the form of lnK) and temperature is explicitly stated in mathematical form. After following Lindsley's projection techniques for placing non-quadrilateral pyroxenes on the pyroxene quadrilateral, the temperature for each pyroxene (Ca-poor and Ca-rich) is read from his temperature-contoured quadrilateral graph. Temperatures were approximated to the nearest 25°C for Table 6, and Lindsley's 10 Kb graph was used. Although in practice each of the two pyroxenes will provide a temperature, Lindsley's technique supposes that each pyroxene pair in equilibrium in a rock will plot on his graph so as to give one unique temperature. As Table 6 indicates, this is not the case with the La Olivina xenoliths. Temperatures vary between the paired pyroxenes by as much as 400°C. By Lindsley's own admission his thermometer does not work well with granulite facies rocks, and encounters problems especially with Al-rich pyroxenes of that facies. It is also suggested that Wo+En+Fs should be greater than 90 for best results. Most of the La Olivina xenoliths have pyroxenes which are below this amount. Nevertheless, the temperatures indicated by the orthopyroxenes are generally in accord with temperatures indicated by the other geothermometers. This suggests that the nonquadrilateral-component projection techniques for clinopyroxenes may be overcorrections with regard to M2 site cations. They are *over*corrections in that the effect of the technique is to move the data point away from the Wo apex toward higher temperature contours.

With the exception of temperatures obtained from two xenoliths, the agreement between the temperatures obtained by the four non-graphical geothermometers for any individual xenolith is quite good. The average for the temperature ranges for these xenoliths is less than 100°C. This is reassuring in view of the differences in approach of each of the thermometers. In general, the temperature range is from 950°C to 1150°C. Group I xenoliths have a slightly lower range (about 950°C to 1100°C) than the Transitional Group xenoliths (about 1050°C to 1150°C).

The two xenoliths that do not fit this pattern are MN10X and MN1000. In each case there is reason to suspect that the olivines in these rocks are not in equilibrium, as has been mentioned earlier. In each case it is the thermometers that involve olivine equilibria that give the most deviant results. For MN10X, the temperature range is 928°C to 1304°C, a range of 376°C. The highest and lowest temperatures obtained are both from olivine-equilibria thermometers (those of Gasparik and Newton, and Fabries). Temperatures obtained for this rock by the pyroxene thermometers are more in line with the temperatures of the other xenoliths (992°C to 1081°C) and are within 89° of each other. For MN1000, the temperature range is 675°C to 1352°C, a range of 677°C. Again, the highest and lowest temperatures are from olivine-equilibria thermometers. The pyroxene thermometers give a temperature range of 1008° to 1128°, a greater range than the average range for other La Olivina xenoliths but still within reason. In the case of each of these two xenoliths the deviant temperatures obtained by the olivine-equilibria thermometers should be regarded as further evidence that the olivines in these rocks are not in equilibrium with the other minerals.

The equilibria used in the above geothermometers are useful as such because they are quite sensitive to temperature. However, they are insensitive to pressure over the interval of interest in studying ultramafic xenoliths (Evans, 1977). The only constraint on pressure, then, becomes the aluminus phase - plagioclase, spinel, or garnet - and the pressures of transition between them (Obata, 1976; Dankwerth and Newton, 1978). This provides only for an unsatisfying pressure range of 5 Kb to about 20 Kb for the temperature range of 800°C to 1200°C. Mercier (1980) calibrated a single-pyroxene geobarometer that, while based on theoretical considerations, relies on empirical observations on Cr-Al solubility in the pyroxenes. The results of calculations for La Olivina xenoliths using the Mercier method are presented in Table 6.

In general, pressures obtained from orthopyroxenes are higher than those obtained from coexisting clinopyroxenes. The range for orthopyroxenes is 15.8 Kb to 25.6 Kb, while the range for clinopyroxenes is 13.2 Kb to 24.2 Kb. The Group II and the Transitional Group xenoliths generally give higher pressure estimates than the Group I xenoliths. The upper limit for the stability field of spinel in the temperature range of 800°C - 1200°C is generally regarded to be in the range of 15 Kb to 18 Kb (Basaltic Volcanism Study Project, 1981). This would place the majority of the La Olivina xenoliths in the garnet stability field. However, O'Neil (1981) has shown experimentally with reversed data that high-Cr spinels ($X_{Cr}^{Sp} > 0.21$) have an extended stability range of up to 40 Kb at 1100°C. High-Cr spinel will form at the expense of garnet at 33 Kb and 1100°C. All La Olivina spinels analysed, with the exception of that in MN1000, have X_{Cr}^{Sp} greater than 0.21 (Table 3). It is therefore possible that the pressures obtained from the Mercier method for La Olivina xenoliths are not unreasonably high. The majority of La Olivina xenoliths may have formed in the 16 Kb to 24 Kb range. This corresponds to 53 to 77 kilometers depth by the pressure-depth conversion method given by Ave'Lallemant *et al.* (1980).

DISCUSSION OF THE MANTLE BENEATH LA OLIVINA

By far the most abundant type of ultramafic xenolith at La Olivina is granoblastic lherzolite of Group I. The presence of curvilinear to straight grain boundaries, triple-point grain junctions, and the rarity of exsolution lamellae, indicate that the granoblastic texture is due to metamorphic processes such as recrystallization and annealing. In composite xenoliths from La Olivina the Group I lherzolites are cut by pyroxenite veins. These composite xenoliths have not yet been studied in detail, but the veins are dark colored and presumably either Group II or Transitional pyroxenites. The abundance of the lherzolites, their texture, and cross-cutting relations all indicate that this is the principle type of wall rock in the mantle beneath La Olivina. Similar conclusions have been reached for the mantle beneath the southwestern United States by Wilshire and Shervais (1975), Frey and Prinz (1978), and Irving (1980).

The most common texture of the pyroxenites is allotriomorphic. The presence of poikilitic grains, exsolution lamellae and growth twins in pyroxenes, and irregularly shaped grain boundaries, all suggest that this texture is the result of igneous processes. Presumably these rocks have precipitated from basaltic melts as suggested by previous workers. Because the Transitional Group pyroxenites have mineral chemistry intermediate between Group I and II rocks, it is possible that they are the result of reaction between basaltic melts and wall rock. This seems unlikely to us because the textures of most are igneous-like rather than metamorphic-like and because the chemically modified wall rock is usually peridotite rather than pyroxenite (Wilshire and Shervais, 1975; Irving, 1980). However, Transitional Group olivine websterite MN209 (Fig. 2), which has granoblastic texture, may be either a sample of metasomatically modified wall rock or a recrystallized vein.

The porphyroclastic texture (MN 219) with neoblasts, which in some respects resemble granoblastic grains, and with porphyroclasts, which resemble allotriomorphic granular grains, is perhaps a product of metamorphic processes acting upon a rock of igneous origin. It cannot be determined from the small number of xenoliths thus far examined whether there is a continual transition in textures between any of the textural groups. Sample MN16 displays more granular exsolution than the other allotriomorphic granular samples, and it appears perhaps intermediate to the porphyroclastic texture. There is a distinct difference, however, between the textures of the granoblastic samples and the textures of the other rocks. The former appear to have been fully recrystallized whereas the latter show only mild recrystallization, if any.

Some information on the nature of the basaltic melts that precipitated the allotriomorphic Transitional Group pyroxenites can be gleaned from our very limited data on the xenoliths. The Transitional Group pyroxenites have higher Mg numbers than the Group II rocks, thus they probably crystallized from more mafic magmas than the latter. If the melts from which La Olivina and Kilbourne Hole pyroxenites crystallized had similar mineral/melt partition coefficients, then the La Olivina melts had lower concentrations of REE, probably by a factor of two, than the Kilbourne Hole melts. This is indicated by the lower REE concentrations of the La Olivina pyroxenites (Fig. 3). The La Olivina melts were not only enriched in the light REE relative to the heavy REE, but they were more strongly fractionated, that is had a higher ratio of Ce to Yb, than the melts that produced the Kilbourne Hole Group II pyroxenites. The source that produced the La Olivina melts was also probably enriched in the light REE. This source of enrichment in the light REE must have been a relatively recent event, because the ^{143}Nd/^{144}Nd composition of MN14 (Table 5) indicates that the melt was derived from a source that had a long history of light REE depletion.

CRUSTAL XENOLITHS

Pyroxene - Plagioclase granulites

The pyroxene - plagioclase granulites are medium-grained (1 - 3 mm) and garnet-free. Most are intermediate in composition with between 20 and 40 % mafic minerals, but more mafic and more felsic varieties are present. The constituent plagioclase and pyroxenes occur as equigranular crystals that may be segregated into different layers, thus imparting a gneissic appearance to some of the rocks.

The dozen samples examined petrographically contain plagioclase, clinopyroxene, ilmenite and glass, and most also have orthopyroxene (Table 7). K-feldspar, apatite, scapolite, mica, sphene, and a greenish spinel are present in a few samples. In thin-section most of the xenoliths have a granoblastic texture. The clinopyroxenes are commonly pleochroic, mostly in shades of green, whereas the orthopyroxenes are pleochroic from brown to green. Rarely does either pyroxene contain exsolution lamellae. All of the xenoliths contain glass and show at least some degree of melting along grain boundaries.

Plagioclase feldspars from four rocks have compositions within the range An46 - An50 (Table 7). About half of the crystals have rims that are slightly higher in Ca,

Table 7

Modal Analysis and mineral compositions of pyroxene granulites from La Olivina, Mexico

	MN21	MN45	MN35	MN91-B	MN54	MN29
plagioclase	75.2	69.5	60.7	43.8	4.1	––
clinopyroxene	13.5	4.5	19.2	25.6	82.6	47.4
orthopyroxene	2.5	6.3	8.6	10.4	––	––
ilmenite	2.6	5.6	7.3	10.4	2.2	7.3
apatite	1.3	––	––	––	7.0	––
scapolite	––	––	––	––	––	21.3
glass (± crystals)	4.9	14.1	4.2	9.8	4.1	24.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
Plagioclase						
An	50	––	46	46	35	––
Or	4	––	5	4	9	––
Ab	46	––	49	50	56	––
Clinopyroxene						
Wo	44	––	45	46	48	49
En	36	––	37	39	37	37
FS	20	––	18	15	15	14

on the order of 1-2 % An, than the cores. One xenolith (MN54), which is composed predominantly of clinopyroxene, contains plagioclase that is significantly more K- and Na-rich than most of the samples (Table 7). This particular xenolith displays pronounced evidence of reaction, with fritting and resorption along grain boundaries. Additionally, a second of the six samples (MN29) contains scapolite instead of plagioclase. Partial analyses indicate that it is probably a mizzonitic variety.

Pyroxene granulite, MN19, which was analyzed for REE and $^{143}Nd/^{144}Nd$, has a granuloblastic texture with an average grain size of about 0.5 mm, but a few clinopyroxene grains are as large as 2.0 mm. It contains approximately 60 % plagioclase (An53 Or5 Ab42), 20 % clinopyroxene (Wo43 En36 Fs21), 15 % orthopyroxene (Wo3 En54 Fs43), 1 % biotite, 2 % sanidine, and a few percent glass. Other than the presence of minor biotite, this sample appears typical of the pyroxene granulite group.

PELITIC GNEISSES

The 12 xenoliths of pelitic gneiss examined petrographically all contain the mineral assemblage garnet + quartz + plagioclase + sanidine + sillimanite + rutile + graphite. Garnet typically constitutes 10 to 30 % of the rock, and in many samples it averages 4-6 mm in diameter. In most xenoliths the garnet is coated with a thin film of glass produced by decompression melting. This glass contains sprays of quenched (?) pyroxene and octahedra of green to pink spinel. Sillimanite crystals, which are several millimeters long, are present in amounts of 10-20 %, and may show a slight blue color in hand specimen. The sanidine and quartz together form more than 50 % of the average xenolith, and they are usually about 2-4 mm in diameter. The sanidine in about half the samples shows fine lamellae of perthitic exsolution. The plagioclase, rutile and graphite are present only in accessory amounts.

MN59, which was analyzed for REE and ^{143}Nd/^{144}Nd, appears petrographically representative of the pelitic gneisses. The plagioclase and sanidine from this sample have compositions of about An39 Ab53 Or8 and An3 Ab15 Or82, respectively. The garnets are fairly homogeneous almandine and have average compositions of about SiO_2 = 38.7 %, Al_2O_3 = 22.1 %, FeO = 27.6 %, MnO = 0.8 %, MgO = 9.1 %, CaO = 1.7 %. The feldspar and garnet compositions lie in the range of analyses reported for Kilbourne Hole pelitic gneisses (Padovani and Carter, 1976), thus indicating that the pelitic portions of the lower crust beneath La Olivina and Kilbourne Hole are similar in mineralogy and were metamorphosed under nearly identical conditions.

RARE EARTH ELEMENT COMPOSITIONS, ^{143}Nd/^{144}Nd, AND GEOCHRONOLOGY OF THE CRUSTAL XENOLITHS

The REE patterns of pyroxene granulite MN19 and pelitic gneiss MN59 are shown in Figure 4. The shape of the REE pattern of the pelitic gneiss is very similar to that of the average North American shale (Haskin *et al.*, 1968), but the concentrations of the REE are higher in the gneiss by a factor of about two.

The granulite and pelitic gneisses have ϵ_{Nd} = −10.0 and −13.9, respectively (Table 5), which are in the range expected for ancient crustal rocks (*e.g.*, De Paolo, 1981b). Model Nd ages can be calculated for the rocks by assuming an initial ^{143}Nd/^{144}Nd. The granulite and pelitic gneiss have model ages of 1.1 b.y. and 1.2 b.y., re-

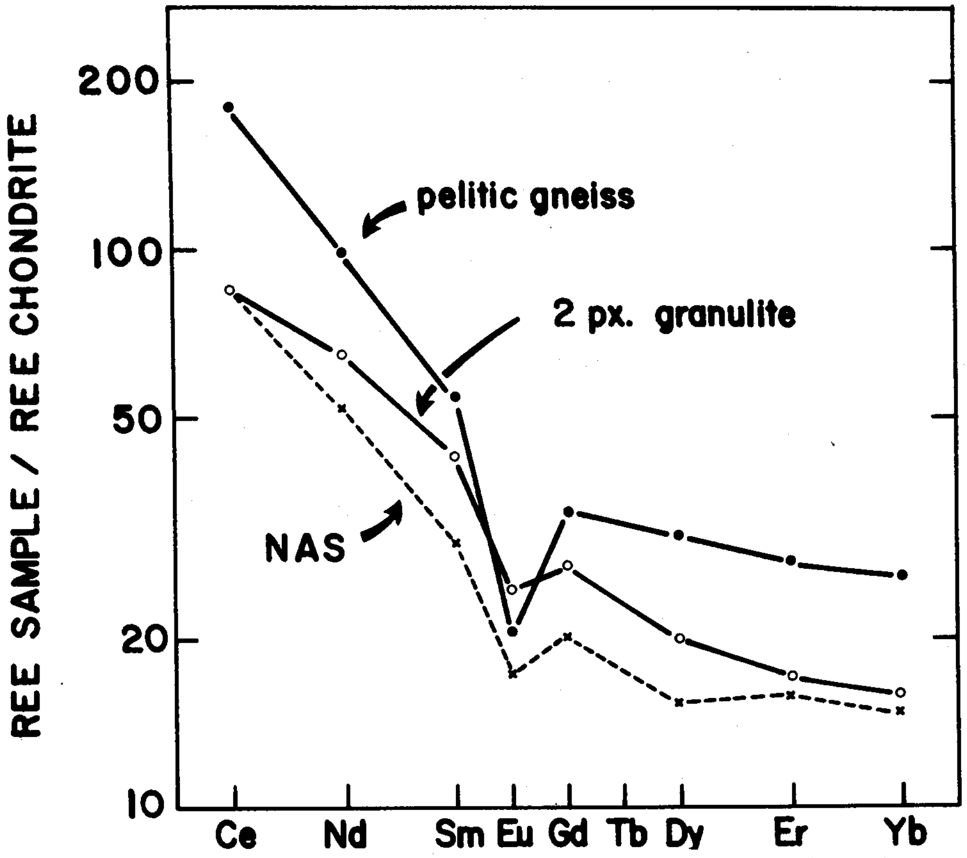

Fig. 4. Chondrite-normalized rare earth element patterns for La Olivina crustal xenoliths and the average North American shale (NAS) of Haskin *et al.* (1968).

spectibly, using a chondritic initial ratio. On the other hand, using a depleted source model (DePaolo, 1981b) the ages are 1.62 and 1.60 b.y., respectively. The latter ages are in excellent agreement with those of crustal xenoliths from Kilbourne Hole reported by Reid *et al.* (1982). Pelitic gneiss xenoliths from Kilbourne Hole have a Rb/Sr isochron age of 1.56 b.y. and a Pb isochron of 1.62 b.y.

DISCUSSION OF THE LOWER CRUST BENEATH LA OLIVINA

The crustal xenoliths at La Olivina and Kilbourne Hole are remarkably similar in metamorphic grade, protolith composition, and model age; thus, North American craton clearly extends into central Chihuahua. Although the La Olivina area lies north of the inferred position of the Mojave-Sonora megashear (Anderson and Schmidt, 1983), it is not certain that the La Olivina granulite xenoliths came from ***unmoved*** autochthonous craton. Two major suture zones are inferred to underlie southeastern Chihuahua. The older is Grenville age (Muehlberger, 1980; Condie, 1982), whereas the younger is late Paleozoic and associated with the Ouachita - Marathon orogeny. La Olivina is approximately 150 km southeast (*i.e.*, outboard) of the 1 b.y. Grenville age, amphibolite facies rocks exposed near Aldama (Mauger *et al.*, 1983). It is not known if granulite terrain underlies (depositionally or structurally) amphibolite grade rocks, none of which have been found at La Olivina, or if the La Olivina area is underlain by craton that has been displaced southeastward by left-lateral movement on an as yet unrecognized fault to the north.

APPENDIX

MN1. LHERZOLITE. Mineralogy: 70.6 % olivine (0.2 - 3.0 mm; 2.0 mm avg.); 16.5 % enstatite (0.5 - 3.0 mm; 1.5 mm avg.); 10.9 % diopside (0.2 - 1.5 mm; 1.0 mm avg.); 2.0 % spinel (< 1.0 mm; 0.75 mm avg.); < 1.0% phlogopite (< 1.0 mm). The texture is granoblastic polygonal, with curvilinear to straight grain boundaries and 120 degree triple-point grain junctions common. Minerals are inequigranular but not bimodal. A very mild foliation is observed in thin section due to preferential elongation during growth of a substantial number of grains. All minerals are non-poikilitic and contain no exsolution nor strain lamellae. Olivines are occasionally kink-banded. Brown spinel exists as elongate interstitial grains and occasionally as anhedral equant grains. Diopside is bright emerald green in hand sample and remains very pale green in thin section. Olivine is bright green in hand sample. Glass is not present.

MN4. LHERZOLITE. Mineralogy: 71.7 % olivine (0.2 - 6.0 mm; 2.0 mm avg.); 16.5 % enstatite (0.5 - 3.0 mm; 1.5 mm avg.); 10.9 % diopside (0.2 - 3.0 mm; 1.5 mm avg.); 1.3 % spinel (0.2 - 1.5 mm; 0.5 mm avg.). The texture is granoblastic polygonal, with curvilinear to straight grain boundaries and 120 degree triple-point grain junctions common. Minerals are inequigranular but not bimodal. No foliation is present. All minerals are non-poikilitic and contain no exsolution nor strain lamellae. Olivines are commonly kink-banded. Spinel exists as elongate interstitial grains and occasionally as anhedral equant grains. It is deep greenish-brown in thin section. Diopside is bright emerald green in hand sample and remains pale green in thin section. Olivine is bright green in hand sample. Glass is not present.

MN10-X. ORTHOPYROXENITE. The two MN10 samples comprise a composite xenolith in which pyroxenite veins the host peridotite. Sample number MN10-X represents the pyroxenite vein while sample number MN10-H represents the harzburgite host. The vein-host rock contact is sharp and planar. MN10-X Mineralogy: 88% enstatite (0.5 - 8.0 mm, 3.0 mm avg.), 6 % diopside (0.2 - 1.0 mm, 0.5 mm avg.), < 1.0 % olivine (1.5 mm avg.), 3 % spinel (< 1.0 mm avg.). The diopside is emerald green in hand specimen and remains pale emerald in thin section. Enstatite occasionally shows lamellar exsolution of the emerald green diopside. No exsolution is present in diopside. Grains show minor strain features, with strain lamellae developed in the enstatite (olivine shows kink-banding in MN10-H). Grain boundaries are straight to curvilinear with 120 degree triple-junctions ubiquitous, giving the rock a polygonal mosaic texture. The hornblende forms interstitially along grain boundaries. Spinel is deep brown and is found forming elongate grains along grain boundaries. Glassy veins are uncommon.

MN10-H. HARZBURGITE. This sample number represents the peridotite portion of sample MN10 (MN10-X represents the pyroxenite portion). Mineralogy: 58 % olivine (0.5 - 3.0 mm, 1.5 mm avg.), 33 % enstatite (0.5 - 3.0 mm, 2.0 mm avg.), 2 % diopside (0.4 - 1.0 mm, 0.7 mm avg.). The diopside is brilliant emerald green in hand specimen and remains pale emerald in thin section. No exsolution is present in the sample. Olivine shows well-developed kink-banding, although no strain features are present in the other minerals. Grain boundaries are straight to curvilinear with 120 degree triple-point grain junctions ubiquitous, giving the rock a polygonal mosaic texture. The diopside in MN10-H contains "dusty" particles and is not nearly as fresh appearing as the diopside in MN10-X. Spinel is deep brown and forms elongate grains along grain boundaries. Glassy veins are common.

MN14. WEBSTERITE. Mineralogy: 72.9 % clinopyroxene (0.1 - 3.0 mm; 0.7 mm avg.); 18 % orthopyroxene (<0.1 - 1.5 mm; 0.7 mm avg.); 7.3 % pargasitic hornblende (0.1 - 2.0 mm; 1.0 mm avg.); 1.0 % spinel (<1.0 mm). All grains are anhedral, except for a few hornblende crystals that are subhedral. Clinopyroxene occasionally exhibits growth twinning. It also commonly shows both granular and lamellar exsolution. Zones of optically continuous grains can be seen in thin section, but this is not extensive. Orthopyroxenes show little or no exsolution: only lamellar exsolution is present. Hornblende poikilitically includes both pyroxenes and is intergrown with clinopyroxene in a few cases. Spinel is green in thin section, is equant and anhedral. Bubble trains cross through several pyroxene grains, occasionally in conjugate pairs, implying the annealing of fractures. The bubbles are fluid inclusions and two phases can be seen in some of them. The texture of the rock can best be described as allotriomorphic granular although many grain boundaries are curvilinear to straight and 120 degree triple-point junctions are rather common. The minerals are equigranular and finer grained than most other allotriomorphic samples. Glass in veins is present, though not abundant.

MN16. OLIVINE WEBSTERITE. Mineralogy: 67 % clinopyroxene (<0.1 -2.0 mm, 0.5 mm avg.), 11 % orthopyroxene (<0.1 - 7.0 mm, 3.0 mm avg.), 11 % olivine (0.5 - 3.0 mm, 2.0 mm avg.), 10 % pargasitic hornblende (<0.1 - 2.0 mm, 0.5 mm avg.), <1 % spinel (<0.2 mm). The olivine and orthopyroxene grains show kink-banding, with the latter showing minor strain lamellae as well. The clinopyroxenes show both lamellar and extensive granular orthopyroxene exsolution. Large patches of clinopyroxene in the same optical orientation are separated by granular patches of orthopyroxene and other clinopyroxene neoblasts, suggesting an advanced stage of granular exsolution. The neoblasts, which are strain-free, have curvilinear grain boundaries and 120 degree triple-point grain junctions. Growth twinning is present in a few of the larger (non-neoblast) grains. Other than the hornblende, which can be subhedral to nearly euhedral, all grains are anhedral. Grain relationships between the larger strained grains suggest an adcumulus texture. Spinel is deep olive green to opaque, and occurs interstitially only. Glassy vein are common.

MN205. CLINOPYROXENITE. Mineralogy: 86 % clinopyroxene (<0.1 - 4.0 mm, 3.0 mm avg.), 3 % orthopyroxene (0.5 - 3.0 mm, 2.0 mm avg)., 10 % olivine (0.5 - 3.0 mm, 2.0 mm avg.), <1 % hornblende (<1.0 mm), ≪1 % spinel (<0.3 mm). The texture is heteradcumulus with orthopyroxene forming interstitially. Both pyroxenes occasionally poikilitically enclose other pyroxenes, olivine, and spinel. Clinopyroxene shows extensive exsolution, both lamellar and granular. Strain lamellae are common in both pyroxenes. Olivines are usually kink-banded. Growth twins are occasionally seen in clinopyroxene. All grains are anhedral with most pyroxene grains showing some embayment. Olivine has straight to curvilinear grain boundaries. Hornblende exists as disseminated very small flakes, often associated with spinel. The spinel is very dark green and found along grain boundaries, especiallv olivine, or poikilitically enclosed within hornblende. Glassy veins are common.

MN209. OLIVINE WEBSTERITE. Mineralogy: 45 % clinopyroxene (1.0 - 4.0 mm, 2.0 mm avg.), 18 % orthopyroxene (0.5 - 3.0 mm, 1.0 mm avg.), 33 % olivine

(1.0 - 3.0 mm, 1.5 mm avg.), <1 % spinel (≪0.1 mm), 2 % opaques (<0.1 mm). Strain lamellae are very occasionally present in the orthopyroxene, otherwise the minerals are strain-free. No exsolution is present. Grain boundaries are straight to curvilinear with triple-point junctions common. All crystals are anhedral. The grains are slightly elongate with the longer axes of many grains subparallel, giving the rock a mild foliation. All opaques occur interstitially. Spinel is brownish-green and occurs only as oriented flakes within clinopyroxene grains; this relationship suggests that the spinel was exsolved from the pyroxene. Glassy veins, although present, are uncommon.

MN212. ORTHOPYROXENITE. Mineralogy: 88 % enstatite (0.5 - 6.0 mm, 4.0 mm avg.), 4 % diopside (0.1 - 1.0 mm, 0.5 mm avg.), 5 % olivine (0.1 - 2.0 mm, 1.0 mm avg.), <1 % pargasitic hornblende (<0.5 mm). <1 % spinel (<0.1 mm). The diopside is a brilliant emerald green in hand specimen and remains a pale green in thin section. The enstatite contains fine exsolution lamellae of the green diopside; occasionally strain lamellae are present. No kink-banding is present, however, even in the olivine. The diopside is strain-free and shows no exsolution. All grains are anhedral, with curvilinear to straight grain boundaries. The texture is mosaic with ubiquitous 120 degree triple-point grain junction. Both hornblende and spinel occur only interstitially, the latter commonly at triple-point junctions. The spinel is deep chocolate brown. Glassy veins are present.

MN219. WEBSTERITE. Mineralogy: 69 % orthopyroxene (<0.5 - 7.0 mm. 0.3 mm and 3.0 mm avgs.), 28 % clinopyroxene (<0.1 - 3.0 mm, 0.3 mm and 1.5 mm avgs.), 2 % olivine (2.0 mm avg.), <1 % pargasitic hornblende (<0.5 mm), <1 % opaques (≪ 0.1 mm). The pyroxenes are represented by two distinct grain-size populations. The larger grains show extensive lamellar and granular exsolution, strain lamellae, kink-bands (in the orthopyroxenes), anhedral irregular grain boundaries, and embayment. Growth twinning was not observed. The smaller grains are without strain features or exsolution, and have curvilinear grain boundaries. They show a mosaic texture and commonly meet in 120 degree grain junctions. These smaller grains "vein" the rock isolating individual large grains. Olivine has some kink-bands. The hornblende is anhedral and interstitial. All opaques are interstitial and seem associated with the larger grains in the rock. Glassy veins are present but uncommon.

MN1000. WEBSTERITE. Mineralogy: 47 % clinopyroxene (0.5 - 10.0 mm, 3.0 mm avg.), 9 % orthopyroxene (0.1 - 6.0 mm, 1.5 mm avg.), <1 % olivine (<1.0

mm), 40 % pargasitic hornblende (<7.0 mm), 4 % spinel (<1.0 mm). The pyroxenes show no strain features, anhedral irregular grain boundaries, no exsolution features, and a general adcumulus texture. Growth twinning is occasionally present in the clinopyroxene. The amphibole is pervasive, occurring both as interstitial anhedral to subhedral (in cavities) grains and as patches within grains along cleavage planes and fractures. The spinel is anhedral, predominantly interstitial, and associated with the hornblende in which it is occasionally enclosed. It is dark green to opaque. Dark grey "dusty"-appearing glass occurs in veins along grain boundaries and junctions, and commonly contains microlites of olivine.

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