MINERALOGICAL MAGAZINE, DECEMBER 1979, VOL. 43, PP. 483-6

Spinel lherzolites from Xalapasco de la Joya, San Luis Potosi, SLP, Mexico

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SUMMARY. Ejecta associated with the Xalapasco de la Joya maar 33 km northeast of San Luis Potosi, SLP, Mexico, contain a diverse assemblage of nodules of postulated lower-crust/upper-mantle origin. Spinel lherzolites constitute the most abundant group of nodules and display chemical evidence that crystallization or equilibration took place at temperatures and pressures consistent with upper mantle genesis. Estimated equilibration temperatures and pressures range from 825 to 1025 °C and 7 to 19 kb.

THE Xalapasco de la Joya maar occurs 2 km west of Federal Highway 57/80 and 33 km northeast of San Luis Potosi, SLP, Mexico. The crater is a truncated cone with elliptical upper and lower surfaces, the upper surface having axes of 1150 and 850 m whereas the relatively flat floor of the crater has axes of 400 and 250 m. Maximum relief is 300 m (Gaskin *et al.*, 1973). The crater is developed in the folded and faulted Cuesta del Cura Formation of Upper Albian to Cenomanian age (Humphrey, 1956) in which the predominant lithology is grey limestone (with allochems of pellits) with nodules of black chert.

An ejecta blanket reaching 100 m thick covers the north, west and east sides of the structure but is absent along the southern margin. The ejecta contains a predominence of comminuted carbonate with minor proportions of ash and scoria. Sedimentary structures such as graded bedding, cross bedding, and bomb sags are common within the ejecta.

A suite of nodules, interpreted as having been derived from the deep crust or upper mantle has been found within the ejecta blanket and around the perimeter of the structure. Three nodule types have been recognized: graphite-bearing garnet granulites composed of varying proportions of alkali feldspar, plagioclase, orthopyroxene, quartz, garnet, graphite, and glass; plagioclase-hypersthene-rich rocks; spinel lherzolites composed of varying proportions of olivine, orthopyroxene, clinopyroxene, and spinel. This note is a preliminary description of the spinel lherzolites.

Petrography. From 400 spinel lherzolites 233 samples larger than 5 cm in diameter were slabbed and point counted using a binocular microscope and a fixed grid prepared from a Hollerith card. An average of 300 grains per slab were counted. Modal analyses of thin sections prepared from randomly selected nodules agree within 2% of those using the entire slab. The average proportions of olivine, clinopyroxene, orthopyroxene, and spinel are 61.9, 12.4, 21.9, and 3.8% respectively; the coefficients of variation being 0.16, 0.45, 0.35, and 0.59 respectively. Thus, olivine has the lowest relative variability of the phases present in the suite. Averages from the Xalapasco de la Joya lherzolites are noticeably lower in olivine and higher in total pyroxene than those from Kilbourne Hole, New Mexico (Carter, 1970). We have not observed the olivine-clinopyroxene-spinel nodules which Carter found at Kilbourne Hole although we have observed a few harzburgite nodules of olivine-orthopyroxene-spinel.

The measured modes were entered into a non-linear mapping analysis programme, described by Howarth (1973), to assess the degree of structure within the suite of 233 samples of lherzolite from the Xalapasco structure. Approximately 82% of the samples belong to an extremely tight cluster with the remainder more or less evenly distributed around the periphery of the central cluster (Greene, 1975). Six samples were chosen for detailed chemical and petrographic analysis. Measured modes (from thin sections) are given in Table I. Two of the samples (1-3-5 and 7-2-5) are from the densely

TABLE I. *Summary of modal and average chemistry*

	1-3-5	1-5-3	2-2-3	2-3-6	3-2-2	7-2-5
MODES						
Olivine	60	29	62	86	16	71
CPX	25	25	16	7	44	11
OPX	11	35	16	7	32	17
Spinel	3	10	4	tr.	9	1
			Olivine			
SiO_2	40.3	40.6	40.3	39.4	40.0	40.2
Al_2O_3	—	—	—	—	—	—
FeO	9.01	11.61	10.01	8.43	9.93	10.00
NiO	0.23	0.40	0.37	0.22	0.40	0.43
MgO	50.7	47.4	49.0	49.7	48.0	48.2
CaO	0.10	0.08	0.07	0.07	0.08	—
Sum	100.34	100.09	99.76	97.82	98.41	98.83
			Orthopyroxene			
SiO_2	56.0	54.6	56.3	56.8	54.9	56.6
Al_2O_3	3.66	4.49	4.35	2.87	5.64	3.18
TiO_2	0.13	0.07	0.10	0.03	—	0.14
FeO	4.25	8.11	6.55	5.74	7.28	6.78
MgO	34.81	31.40	33.3	33.3	32.7	31.9
CaO	0.61	0.85	0.89	1.13	0.73	0.70
Sum	99.46	99.52	101.49	99.82	101.15	99.30
			Clinopyroxene			
SiO_2	56.0	55.1	53.1	53.6	52.1	52.5
Al_2O_3	5.89	4.86	6.12	3.91	6.72	6.14
TiO_2	0.38	0.24	0.43	0.38	0.58	0.47
FeO	2.37	3.44	2.78	3.17	2.88	2.57
MgO	16.33	16.97	16.19	17.77	16.88	16.04
CaO	21.2	19.0	18.6	19.5	20.8	20.7
Sum	102.17	99.61	97.25	98.31	98.96	98.42
			Spinel			
SiO_2	—	0.87	—		—	—
Al_2O_3	53.8	48.1	52.5		54.0	58.5
TiO_2	0.06	0.27	0.06		0.06	0.07
Cr_2O_3	12.31	14.6	16.6		13.1	9.86
FeO	11.02	14.0	10.8		10.5	10.1
MgO	21.1	19.8	19.0		20.4	21.1
Sum	98.33	97.64	98.96		98.09	99.63
Equil *T*	825	1025	990	950	875	910 °C
Equil *P*	8	19	17	18	7	13 kb

populated cluster and the remaining four from the fringe area.

Hand specimens are uniformly fresh, light olive green, medium grained, holocrystalline to hypocrystalline aggregates mostly surrounded by a thin crust of basalt. Glass is less than 1 % of the nodule volume. In thin section the rocks are allotriomorphic granular with interpenetrating grain boundaries of the three silicate phases. Pale orange-brown spinel (less than 1 mm) occurs as rounded to irregularly-shaped grains concentrated between the orthopyroxene and clinopyroxene. Reddish brown turbid glass usually occurs as veinlets and fracture fillings and these veinlets sometimes contain euhedral olivine as opposed to the anhedral habit of the larger olivines which frequently exhibit evidence of strain in the form of kink bands. The orthopyroxene has fine schiller exsolution structure and the clinopyroxene coarse exsolution lamellae. Evidence for partial melting is widespread in the form of a vermicular texture generally surrounding or penetrating unaltered portions of the clinopyroxenes and the incipient development of such a texture in the orthopyroxenes. Healed fractures revealed by the presence of planar bubble trains in the olivines suggest partial recrystallization.

Mineral chemistry. The Rice University ETEC electron microprobe was used to determine the composition of the phases in the six samples. Individual spot analyses are given in Greene (1975). The olivines range from Fo_{87} in sample 1-5-3 to Fo_{91} in 1-3-5 but are unzoned with variation within each sample generally less than 1 %. Stormer (1973) showed that Ca increases in olivine with decrease in load pressure but the grains analyzed are unzoned and uniformly low in Ca.

Orthopyroxenes range from En_{81} in 1-5-3 to En_{92} in 1-3-5; the Wo content ranges from 1 to 3 % (Table I). As schiller structure is generally present we believe that these analyses represent the composition of the host material. The orthopyroxenes were probably saturated with Al_2O_3 for the temperature at which they crystallized as these phases are intimately associated with an Al-bearing spinel. Clinopyroxenes range from 41.2 to 50.0 Wo, from 43.0 to 51.7 En and from 4.0 to 7.7 Fs (Table I). With the exception of 3-2-2 these phases contain no observable exsolution lamellae so that the analyses are thought to be representative of the bulk composition of the grains. In sample 3-2-2 analyses were confined to the host phase.

Spinels are highly Al-rich with little computed Fe^{3+} (based on the ideal spinel formula of $R^2R^3_2O_4$). 100Mg/(Mg + Fe) ratios range from 71.3 to 78.6. Glass is present in all samples examined except for 2-3-6. No glasses were analyzed in areas less than 20 microns wide because of the probability of depletion of some of the major cations in glass adjacent to olivine (Kushiro, 1974). The glass analyses exhibited considerable variation in composition (Table II) and the sum of the elements analyzed for is sometimes less than 90 %. This may reflect volatile variation and, or, errors in analysis.

Petrogenesis. Understanding the petrogenesis of spinel lherzolites is essential to the development of geochemical models for the upper mantle (Carmichael *et al.*, 1974). We have followed the methods suggested by MacGregor (1974) in analyz-

TABLE II. *Glass and rock compositions*

	1	2	3	4	5	6	7	8
SiO_2	56.28	58.13	56.0	57.0	59.5	44.24	45.16	42.86
Al_2O_3	19.99	18.79	20.6	20.8	21.6	3.59	3.54	6.99
TiO_2	1.94	1.88	0.8	1.2	2.3	0.10	0.76	0.71
FeO	2.75	4.22	2.7	3.0	1.8	7.22	8.04	8.97
MgO	2.14	2.62	2.7	3.3	1.5	42.02	37.47	35.07
CaO	4.43	6.25	8.4	6.9	3.4	2.47	3.08	4.57
Na_2O	8.64	6.93	7.1	5.9	4.3			
K_2O	3.82	2.16	1.3	1.1	5.6			
Cr_2O_3						0.42	0.43	0.18

1. Glass. This study: 1-5-3.
2. Glass. This study: 2-2-3.
3. Glass. Frey and Green (1974), no. 2669.
4. Glass. Frey and Green (1974), no. 2700.
5. Glass. Frey and Green (1974), no. 2640.
6. Computed Xalapasco de la Joya upper mantle composition, this study.
7. Pyrolite of Green and Ringwood (1967).
8. Undepleted upper mantle under Kilbourne Hole, New Mexico from Carter (1970).

ing the chemical data obtained from the Xalapasco de la Joya lherzolites. Temperatures of equilibration were estimated from the Davis and Boyd (1966) diopside-enstatite solvus using probe analyses from the cores of coexisting clino and orthopyroxenes. These temperatures must be considered as approximate as the CPX and OPX contain appreciable Al_2O_3 and FeO and thus depart from the ideal $CaMgSi_2O_6$-$MgSiO_3$ join. Equilibration temperature estimates can be used to estimate equilibration pressures by using the Al_2O_3 content of the orthopyroxenes (MacGregor, 1974). Estimates of equilibration temperatures and pressures are given in Table I.

The spinel lherzolites from the Xalapasco de la Joya structure plot (in pressure-temperature space) within a band defined by other suites of spinel lherzolites (MacGregor, 1974) and, from Table I, there is a considerable variation in equilibration pressure which most likely indicates that these nodules are accidental fragments of the upper mantle beneath central Mexico rather than suites of cognate xenoliths associated with the host magma.

Frey and Green's (1974) analysis of the glass in spinel lherzolites from a Victorian basanite is somewhat similar in composition to the Xalapasco red-brown glass (Table II). They concluded that the glass resulted from the partial melting of a more primitive ultramafic source. Arndt (1977) reported the results of a series of experiments in which a spinel lherzolite nodule from British Columbia was heated at 1220 °C and 1440 °C to produce 5 % and 8 % liquid respectively. Photomicrographs of these samples (Arndt, 1977, figs. 22A and 22B) exhibit textural features that are very similar to those in the Xalapasco nodules.

For comparative purposes we have computed an average chemical composition of the upper mantle underneath the Xalapasco structure using the measured modes of the 233 spinel lherzolites and the average chemical compositions of the four phases. This computed composition is compared with the pyrolite of Green and Ringwood (1967) and the computed undepleted upper mantle beneath Kilbourne Hole, New Mexico (Carter, 1970) in Table II. Although such computations are fraught with difficulty and uncertainty it would appear that, to a first approximation, the mantle beneath the Xalapasco structure is more refractory than other postulated upper mantle compositions. Our data are consistent with a refractory residuum of partial melting for the origin of these spinel lherzolites.

Acknowledgements. We thank the Society of Sigma Xi for a grant to G. M. G. and to the Geology Foundation of the University of Houston for support. Dr B. N. Powell, Rice University, kindly made the Rice University microprobe available.

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[*Manuscript accepted for publication 3 April 1979*]