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ECLOGITES AND JADEITE
FROM THE MOTAGUA FAULT ZONE, GUATEMALA

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INTRODUCTION

Jadeite occurs as inclusions in serpentinite in the Motagua fault zone. A boulder of remarkable size and purity was found near Manzanal, Guatemala, and chemical, optical, and X-ray studies have been made of a separated sample of the jadeite. Elsewhere in the Motagua fault zone, omphacite-garnet eclogites and glaucophane-lawsonite-omphacite-garnet rocks have been found in similar environments. Only at the Manzanal locality, however, have sodic pyroxenes been found in rocks which are nearly monomineralic.

Although ultramafic rocks form a large part of the Central Guatemalan Cordillera and in many places are associated with metamorphic rocks of the same or higher grade as those in the Motagua Valley, it is only in the major fault zone that occurrences of jadeite, eclogite, and glaucophane-lawsonite rocks have been found.

JADEITE

Occurrence. Although jade is common among the archeological artifacts of the Mayan and Aztec cultures of Middle America, its source was only recently discovered and reported by Leslie and Foshag (1955), who found detrital cobbles in the alluvial terraces of the Motagua River near the small town of Manzanal, Department of El Progreso. McBirney (1963) found detrital jadeite in the gravels of the same river about 70 kilometers upstream, but occurrences in bedrock have not yet been reported. The specimen we have analyzed was found in a road cut through alluvial terrace deposits along the Atlantic highway approximately 100 meters east of the entrance to the town of Manzanal.

In view of the size of the boulder (approximately 100 kilograms) and the abundance of similar material in the immediate vicinity, the bedrock source of the jade must be nearby. Tributary drainage courses leading into the north side of the valley were followed upstream, but although numerous fragments were observed in the stream beds, the rock could not be found in place during the short period when the area was examined. We concluded from the distribution of detrital fragments that the jade came from a zone of strong shearing where metamorphic rocks, including hornblende amphibolite, garnet-biotite gneiss and actinolite schist of the Chuacús Series, have been faulted against serpentines.

Rocks immediately associated with jadeite include the following mineral assemblages. Components in parentheses are present in amounts less than one percent.

(1) Albite—actinolite—(quartz)—(sphene)
(2) Albite—white mica—(quartz)
(3) Dolomite—chalcedony—quartz
(4) Albite—quartz—blue-green amphibole—(apatite)—(sphene)—(zoisite)
(5) Quartz—albite—white mica—(clinozoisite)—(rutile)

Optical properties. Although the rock is apple green in hand specimens, under the microscope it is seen to consist of a nearly colorless intergrowth of about 80 percent jadeite and 20 percent albite with accessory white mica, analcite, and rare rutile, zoisite, and quartz. In the specimens we examined petrographically, jadeite varied from 5 to 85 percent, albite from 5 to 95 percent, and muscovite from a trace to 10 percent. Quartz is less than 5 percent in all specimens containing jadeite. The texture of the

Fig. 1. Typical texture of jadeite from Manzanal, Guatemala. Jadeite grains, many of which are small fragments with uniform crystallographic orientation, are surrounded by clear, untwinned albite. Some jadeite grains have very thin rims of analcite. Diameter represented by drawing about three millimeters.

specimen from which the jadeite was separated for analysis is shown in Figure 1. Individual grains of jadeite, many of which contain small inclusions of albite and mica, tend to be anhedral and nearly equidimensional with an average maximum dimension of about 1.5 mm. Many small grains of jadeite are in optical continuity and appear to be relics of larger crystals partially replaced by the enclosing albite. Rims of analcite a few microns thick are seen on some but not all of the jadeite. Albite, which encloses the jadeite ophitically, is clear and only rarely twinned.

Optical properties of the principal minerals are given in Table 1. Both the axial angle and inclination of Z to c in the jadeite are larger than previously reported values. It is possible that extinction angles may be affected by strain, for some grains are distorted and show variations of the angle Z to c of as much as 2 or 3 degrees in different parts of the same grain, but large extinction angles are also seen in grains which show no visible distortion or strain effects. The $2V_z$ calculated from the refractive

TABLE 1. OPTICAL PROPERTIES OF JADEITE, ALBITE AND WHITE MICA

Jadeite	Albite	White Mica
$2V_z = 74°$	$\alpha = 1.526$	$2V_x = 39°$
$Z \wedge c = 55°$	$\beta = 1.532$	$\beta = 1.597$
$\alpha = 1.653$	$\gamma = 1.538$	
$\beta = 1.658$		
$\gamma = 1.666$		

Density = 3.358 (measured)
(All refractive indices accurate to $\pm.002$.)

indices agrees with the measured value within the limits of error of the measurements.

A sample of jadeite was separated for analysis by crushing the rock to -150, $+300$ mesh and removing other components by means of a Frantz isodynamic separator and methylene iodide. The chemical analysis is

TABLE 2. CHEMICAL ANALYSES OF GUATEMALAN JADEITE

	1	2	3	4	5	5a	5b		
SiO_2	59.40	58.21	58.12	58.26	59.18	58.97	Si	1.996	} 2.000
TiO_2	0.00	0.04	0.31	0.04	0.00	0.00	Al^{IV}	0.004	
Al_2O_3	25.25	23.72	20.32	22.23	23.73	23.77	Al^{VI}	0.942	
Fe_2O_3	0.00	0.91	2.49	0.71	0.31	0.32	Ti	0.000	
FeO	0.00	0.24	0.77	0.21	0.11	0.11	Fe^{3+}	0.008	
MnO	0.00	0.04	0.07	0.03	0.02	0.02	Fe^{2+}	0.003	} 1.999
MgO	0.00	1.20	2.16	2.18	0.95	0.97	Mn	0.001	
CaO	0.00	1.79	3.13	3.72	0.95	1.43	Mg	0.049	
Na_2O	15.34	13.07	12.43	11.91	14.36	14.42	Ca	0.051	
K_2O	0.00	0.18	0.10	0.40	0.00	0.00	Na	0.945	
H_2O^+	0.00				0.04	—			
		0.46	0.16	0.44					
H_2O^-	0.00				0.06	—			
Total	100.00	99.86	100.07	100.13	100.17	100.01			

1. Theoretical composition of pure jadeite
2. Jadeite from Manzanal, Guatemala, W. F. Foshag analyst (Foshag, 1955)
3. Jadeite from pea-green colored celt, Guatemala, J. Fahey analyst (Foshag, 1955)
4. Jadeite from 'jade worker's tomb', Kaminaljuyu, Guatemala, J. Fahey analyst, (Foshag, 1955)
5. Jadeite from Manzanal, Guatemala, K. Aoki analyst (new analysis)
5a. Analysis no. 5 recalculated by subtracting 2 weight percent albite (An_5)
5b. Atomic proportions calculated from 5a. on the basis of six oxygen atoms

given in Table 2, No. 5, together with other analyses of Guatemalan jadeite.

In a grain mount examined optically the sample was estimated to be more than 99.5 percent pure. This estimate was checked by semiquantitative X-ray means and found to be too low. The only extraneous reflection in the X-ray powder pattern of the sample (see below) corresponded to the strongest albite reflection, and it could be exaggerated relative to jadeite reflections by mounting in a loose water slurry to facilitate preferred orientation. Aliquots of the purified jadeite were mixed with known amounts of purified albite, ground and mounted in essentially identical manner as loose water slurries. The ratio of the albite peak

height to that of a neighboring jadeite peak was assumed to vary linearly with mineral proportions in the range of mixtures involved, and from the resulting measurements the albite impurity was estimated as 2 to 3 percent.

The chemical analysis may be recast according to the structural formula of pyroxene in a manner similar to the method used by Hess (1949, p. 624–626) but modified to fit a sodic rather than calcic pyroxene. Almost the whole analysis can be recast into the ideal formulas for jadeite and diopside with only traces of hedenbergite and acmite. Ca is matched exactly by Mg and Fe^{2+} to form diopside and hedenbergite. (In view of the apparent excess of Al_2O_3 in the analysis, Mn in the pyroxene as reported, if actually present in the analysis, might reasonably be recast into $MnAl(AlSi)O_6$.) There remains, however, a slight excess of SiO_2 and Al_2O_3. If the excess SiO_2 is combined with an equimolar amount of jadeite to form albite, the resulting albite is found to amount to 2 percent by weight of the sample, in good qualitative agreement with the semiquantitative X-ray estimation of the albite impurity.

The original analysis has been recalculated by subtracting 2 percent albite (An_5) (Table 2, No. 5a). The chemical formula calculated from the atomic proportions (Table 2, No. 5b) on the basis of O = 6.000 is $Jd^{94.2}$ $Ac^{0.8}Di^{4.6}Hd^{0.4}$.

Most published jadeite analyses reflect small amounts of impurities, principally albite, which were not separated from the sample or allowed for in the calculated composition. No previously reported analysis has shown such a high proportion of the jadeite molecule as that given above.

X-ray properties. From a portion of the jadeite which was purified for chemical analysis an X-ray powder pattern was obtained with a Norelco high-angle diffractometer using $CuK\alpha$ radiation.[1] An internal standard was not used, but the 2θ values were corrected according to a calibration of the machine using a silicon standard. This calibration indicated a consistent zero point error, but no systematic error as a function of 2θ. The peaks recorded were the strongest ones using a slide prepared from a loose water slurry of jadeite powder, in which opportunity for attaining preferred orientation was optimal. It was then found that relative intensities could be progressively altered by using, in turn, a slide prepared from a stiff paste made from the powder and water, and then a slide made

[1] X-ray diffraction data for jadeite and omphacite are recorded in two tables deposited as Document 9424 with the American Documentation Institute, Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington, D. C. 20242. Copies may be secured by citing the Document number and remitting in advance $1.25 for photoprints or $1.25 for microfilm.

by sprinkling dry powder on a smear of petroleum jelly. This sequence presumably is progressive toward a more random orientation. The relative intensities were estimated from peak heights, hence are only rough approximations. They differ significantly from those reported by Coleman (1961, p. 218) and by Seki, *et al* (1960, p. 673). Slides with preferred orientation gave relative intensities more nearly in accord with those of Coleman and Seki, *et al.*

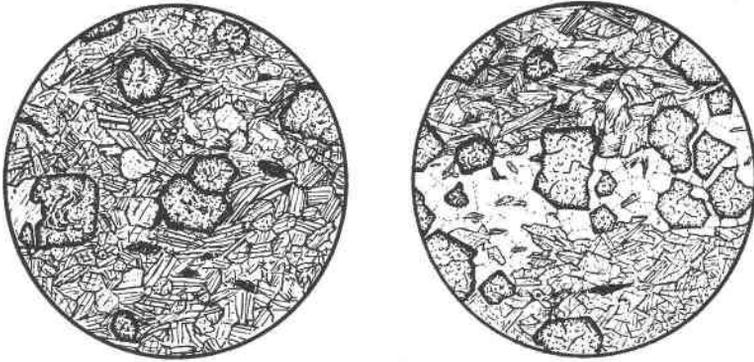The powder data were indexed and refined by the U. S. Geological

Fɪɢ. 2. Typical textures of eclogites from the Rio El Tambor, Guatamela. Example on left is composed primarily of garnet and omphacite with subordinate muscovite, lawsonite, sphene, and rutile. Euhedral garnet porphyroblasts contain abundant inclusions of omphacite and mica arranged in helical patterns. Some omphacite grains, such as those near the top of the drawing, are elongated and form flow lines around garnet porphyroblasts, but most are equidimensional. Example at right consists of bands of omphacite (below) and glaucophane (above), commonly separated by a zone of clear, unstrained quartz. Garnets are scattered throughout the rock with little relation to the bands of other minerals. Actinolite is intimately intergrown with the glaucophane of the upper band. Omphacite is finer-grained and less abundant in the amphibole-rich bands.

Survey using a computer program developed by H. T. Evans, Jr., D. Appleman and D. Handwerker (U. S. Geol. Surv. Bull., in press), for the use of which we are indebted to D. Appleman. The program yielded the following unit cell parameters and standard errors:

$$a = 9.439 \pm 0.001 \text{ Å}$$
$$b = 8.5846 \pm 0.0004 \text{ Å}$$
$$c = 5.226 \pm 0.002 \text{ Å}$$
$$\beta = 107°27.5' \pm 0.9'$$
$$V = 404.0 \text{ Å}^3$$

The indexing agrees more closely with that of Seki, *et al*, than with that of Coleman, among higher angle reflections reported.

The plagioclase accompanying the jadeite has a $\Delta 2\theta$ $(131 - 1\bar{3}1) = 1.09°$, indicating a low temperature albite (Smith and Yoder, 1956), in agreement with the optical data and with the results of other investigators who, to the knowledge of the writers, invariably report the albite accompanying jadeite to be a low temperature variety.

The density calculated from the cell volume and chemical analysis is 3.340. The measured density is 3.358.

ECLOGITES

Cobbles of eclogite were discovered in the bed of the Rio El Tambor about three kilometers above the village of El Rosario and about ten kilometers south of the jadeite locality at Manzanal. Such rocks have not previously been reported from Central America. We were not able to find the rocks in place, but deduce from their distribution that they are derived from the sheared margins of a serpentine belt within the El Tambor formation, which is described in greater detail elsewhere (McBirney and Bass, in press).

Mineral composition. The garnet-pyroxene eclogite specimens are medium to coarse grained, with deep red garnet porphyroblasts in a bright-green weakly foliated groundmass consisting mainly of omphacite with lesser amounts of muscovite, sphene, rutile, lawsonite, accessory chlorite and possibly cordierite. The modal composition of the analysed specimen based on the average of ten thin sections, is given in Table 3. The maximum density determined from chips of the same specimen is 3.59.

Garnet porphyroblasts are euhedral and reach dimensions as great as half a centimeter in diameter. They contain abundant inclusions of all the minerals present in the groundmass. These are concentrated in the center, where they are arranged in helical patterns. The rims of the garnet porphyroblasts are relatively free of inclusions. Brown chlorite occurs as rare inclusions within the garnet but was not noted in the groundmass.

The groundmass is composed primarily of green omphacite. Much of the pyroxene has a pronounced elongation parallel to (001) and is arranged in foliated clusters sweeping around the garnet porphyroblasts. Elsewhere, however, the omphacite is finer-grained and equidimensional. Muscovite is randomly distributed. It is undistorted and appears to have crystallized at a late stage between earlier pyroxene and garnet grains. Lawsonite plates up to 0.5 mm across occur together with muscovite and anhedral sphene. Rutile is found in the core of a few sphene crystals, but more commonly is irregularly scattered throughout the slide in streaky patches of small granular aggregates.

TABLE 3. COMPOSITION AND PROPERTIES OF ECLOGITE (G-724) AND ITS
CONSTITUENT PYROXENE AND GARNET

	Eclogite	Omphacite	Garnet
	Chemical composition (wt. %)		
SiO_2	49.32	55.80	37.28
TiO_2	1.60	0.33	0.36
Al_2O_3	14.52	11.05	20.79
Fe_2O_3	3.50	2.24	1.50
FeO	7.00	2.36	27.44
MnO	0.18	0.04	0.71
MgO	6.57	8.68	2.59
CaO	11.25	13.50	8.69
Na_2O	3.94	6.40	—
K_2O	0.81	0.00	—
H_2O+	0.12	—	—
H_2O-	0.93	—	0.21
P_2O_5	0.06	—	—
Cr_2O_3	0.02	—	—
Total	99.82	100.40	99.57

Mode		Formula norm		Atomic proportions of omphacite		
Omphacite	60.2	Ap	0.10	Si	1.972	5.971
Garnet	23.9	Il	2.24	Al^{IV}	0.028	0.029
Muscovite	11.3	OR	4.80	Al^{VI}	0.431	3.888
Rutile	1.2	Ab	27.98	Ti	0.009	0.043
Sphene	2.4	An	19.73	Fe^{3+}	0.059	0.181
Lawsonite	0.2	Mt	3.69	Fe^{2+}	0.070	3.662
Opaque		Cm	0.02	Mn	0.001	0.096
Chlorite		Di	28.86	Mg	0.460	0.581
Cordierite?	0.8	Ol	7.90	Ca	0.511	1.491
Apatite		Ne	4.71	Na	0.438	—
	100.0		100.00	WXY	1.979	
		Density	3.59		3.28	4.01

Formula proportions

Omphacite		Garnet	
Ac	6.0	Sp	1.4
Jd	38.6	Gr	24.3
$CaTiAl_2O_6$	0.9	Py	9.8
$CaAl_2SiO_6$	3.2	Al	63.7
Wo	23.5	An	0.8
En	23.0		
Fs	3.6		

Optical properties

$\alpha=1.668$ $n=1.793$

$\beta=1.676$ $a=11.57$ Å

$\gamma=1.691$

$2V_z=72.5°$

$z \wedge c=43°$

The chemical composition and properties of the rock, omphacite, and garnet are given in Table 3. In bulk composition, the eclogite resembles an alkali olivine basalt. It would be classed in the 'C' group of Coleman *et al*, (1965) on the basis of its occurrence, the composition of the pyroxene and garnet, and the partition of calcium and magnesium between the garnet and pyroxene.

The garnet has a composition which falls within the range reported for several rock types, including eclogites, granulites, amphibolites, and biotite schists (Wright, 1938; Yoder and Tilley, 1962). Its low pyrope content is characteristic of garnets from eclogites within glaucophane schists and is lower than that found in inclusions in kimberlites, basalts, ultramafic rocks, or migmatites.

TABLE 4. OPTICAL PROPERTIES OF AMPHIBOLES

Glaucophane	Actinolite
α_x 1.618 ± .002	1.619 ± .002
β_y 1.633	1.632
γ_z 1.637	1.643
$2V_x$ 38°	77°
$Z \wedge c$ 4°	13°
X colorless	very pale green
Y lavender	green
Z blue	blue-green

The pyroxene is also typical of analysed pyroxenes from eclogites (Coleman *et al*, 1965) and differs from those of granulites in the high ratio of jadeite to tschermakite components (White, 1964). The X-ray powder pattern for the omphacite[1] was indexed and refined by the U. S. Geological Survey with the same program used for the jadeite pattern. The following unit cell parameters and standard errors were obtained:

$$a = 9.56 \pm .01 \text{ Å}$$
$$b = 8.78 \pm .01 \text{ Å}$$
$$c = 5.25 \pm .01 \text{ Å}$$
$$\beta = 106°47' \pm 5'$$
$$\text{volume} = 421.6 \text{ Å}^3$$

Dr. M. Allan Kays has kindly examined the micas from two eclogite specimens; X-ray diffraction patterns indicate that both are diocta-

[1] See footnote, p. 912.

hedral muscovite. The patterns conform to those listed by Smith and Yoder (1956) for the 3T polymorph but additional reflections indicate that $2M_1$ may also be present. This is consistent with the optic angle (36 to 38 degrees) and refractive indices ($\alpha = 1.565$, $\beta = 1.597$, $\gamma = 1.602$, all $\pm .002$). A partial analysis indicated that the sodium content is low ($Na_2O = 0.37\%$, $K_2O = 9.37\%$). No trioctahedral mica was detected in either the petrographic or X-ray examination.

Amphibole-bearing eclogite. Another specimen consists of contrasting blue and green layers about 2 cm in width, which result from variations in proportions of glaucophane and omphacite. Bands of equant omphacite, porphyroblastic garnet ($n = 1.793 \pm .002$), clear unstrained quartz, muscovite, accessory apatite, and pumpellyite in approximately that order of abundance, alternate with bands of glaucophane, actinolite, garnet, muscovite, fine-grained omphacite, scattered clusters of granular sphene, and accessory lawsonite. Glaucophane and actinolite are closely associated in an intergrowth from which we were unable to separate pure specimens for analysis. In some grains actinolite wholly encases glauco- phane, but the reverse has not been seen. The optical properties listed below suggest that the composition of the amphiboles, especially the glaucophane, may vary somewhat from that of similar amphiboles studied by Lee *et al* (1966).

The amphiboles form discrete grains independent of omphacite; there is no petrographic evidence that they are secondary alteration products. Rather, they appear to be equilibrium phases closely associated with pyroxene and other minerals of the rock.

Similar rocks have been described from California, the Swiss and Italian Alps and elsewhere. They are considered by many workers to result from retrograde metamorphism of pyroxene eclogites, even though replacement of the pyroxene by amphiboles is not always evident from textural relations.

Lee and his co-workers made a meticulous study of a two-amphibole glaucophane schist from the Cazadero area of California and concluded that actinolite and glaucophane were primary amphiboles co-existing in equilibrium with garnet, muscovite, rutile, sphene, and apatite. The rock they studied did not, however, contain omphacite or lawsonite as does the Guatemalan specimen. Addition of these minerals to the as- semblage may pose a problem, because of the apparently excessive num- ber of phases. Until more is known about the stability relations of these minerals, it is impossible to rule out the possibility that the amphiboles were formed by retrograde alteration of pyroxene.

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MYRMEKITE IN CHARNOCKITE FROM SOUTHWEST NIGERIA: A DISCUSSION

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In his paper "Myrmekite in Charnockite from South West Nigeria," Dr. F. H. Hubbard (1966) has presented a number of valuable observations on myrmekite. He particularly stresses that myrmekite development is completely restricted to interfaces between alkali feldspar and a neighbouring feldspar which may be either plagioclase or alkali feldspar. The type and extent of development of myrmekite, according to him, is dependent on the type of alkali feldspar, *i.e.*, whether it is "Strained" type or "Normal" type and the nature of the interface between the feldspars. His observations lend support to Schwantke's hypothesis (1909).

I feel, however, that Hubbard generalizes his particular findings and his observations could be explained more conveniently by Shelley's hypothesis (1964).

Hubbard's observation (1966 p. 770) that " . . . in the immediate vicinity of the myrmekite-alkali feldspar contact, there is generally a