Observations on terrestrial ureyite and ureyitic pyroxene

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ABSTRACT

Ureyitic clinopyroxene with up to 87 mol% ureyite component (Ur, NaCrSi₂O₆) and showing reaction textures with chromite is found in jadeitites from Burma; from Mocchie, Susa, Italy; and in Mesoamerican artifacts from Mexico. Complete ureyite miscibility with jadeite and significant solid solution with omphacite are observed. Minor Ur content is found in jadeitic diopside from a chromite-bearing diopside rock from California and in jadeite and omphacite associated with jadeitites from Guatemala. The relatively uncommon amphiboles eckermannite and nyboite and other sodic amphiboles, often with extensive replacement of octahedral Al by Cr, are common constituents of the Burmese samples. The reaction texture between ureyite or Ur-rich clinopyroxene and chromite and the ubiquitous presence of eckermannite in the Burmese samples are phenomena consistent with the high-pressure interaction of a sodic fluid on albitites in contact with chromite-bearing serpentinites. Although phase assemblages vary for other occurrences of ureyitic pyroxene, comparable interactions of fluid with chromite during jadeitization are required.

INTRODUCTION

The major mineralogical references (e.g., Deer et al., 1978; Cameron and Papike, 1981) do not acknowledge the terrestrial occurrence of ureyite, NaCrSi₂O₆; it is only infrequently mentioned as a rare accessory mineral from the iron-rich Mexican meteorites Toluca (Laspeyres, 1897; Couper et al., 1981) and Coahuila (Frondel and Klein, 1965). Moreover, urevite (Ur) is not generally viewed as a significant component in terrestrial pyroxene, and only rare accounts are to be found (e.g., Sobolev et al., 1975; Mevel and Kienast, 1980; Carpenter, 1981). Nevertheless, spectroscopists have known that crystal-field splitting of Cr³⁺ is responsible for the emerald-green color in precious jadeite jade (Rossman, 1980). Among the lapidary "jadeite" jades are rare dark emerald-green rocks that variously go by the names of Maw-sit-sit and Tawmawite, referring to Burmese mine occurrences, and chloromelanite. These rocks are poorly described in the geologic literature and are usually considered mixtures, either in solid solution or as intergrowths, of quadrilateral plus alkali pyroxene. Sometimes they have been labeled as chromian epidote (e.g., Chhibber, 1934). Lacroix (1930) described a Maw-sit-sit from Burma that contained up to 11 mol% Ur in the pyroxene with the assemblage of chromite, albite, nepheline, and an alkali amphibole. More recently, Gubelin (1965) inaccurately described comparable material as chromian albite, and Manson (1979) analyzed and determined a true urevite. Yang (1984) reported up to 86 mol% Ur in association

with jadeite, chromite, and amphibole from the Burmese jades. So there is growing evidence for the occurrence of terrestrial ureyite and ureyitic pyroxene.

Some confusion exists with regard to pyroxene compositions resulting in green jadeites, particularly with the loose use of the term "chloromelanite" for all dark-green jadeitic pyroxenes. Mineralogically, chloromelanite is normally used for a wide range of composition in the middle of the pseudoternary diagram defined by the endmembers jadeite, acmite, and diopside + hedenbergite (Essene and Fyfe, 1967). However, Webster (1983), the authority for gemologists, has considered chloromelanite to be a mixture of jadeite plus "oxides of iron." Clearly there is a nomenclatural problem between the disciplines, but more significantly, these dark emerald-green rocks need analysis.

In this paper we report on the pyroxene compositions and phase assemblages of a suite of dark-green jades from Burma and Italy, several jade artifacts from archaeological sites in Mexico (clarification has been needed on the nature of these jades for some time), and a chromitebearing diopside rock from California. An occurrence of minor Ur solid solution in pyroxene from jadeitites from Guatemala is also described. On the basis of these data, we have tried to develop a model for ureyite paragenesis and to determine the constraints that this model plays on jadeitite genesis. Other questions about comparisons between different jades and sources of jadeitite, both in terms

	Phases present**										
Sample*	ur	jd	omp	cm	ab	wm	amp	anl	chl	Other	Locality
AMNH 32734	Ur ₇₂	Х		х			х		х	Banalsite	Burma: jade mines region
AMNH 35024	Ur ₇₈						X		Х		Burma: jade mines region
AMNH 37970		Ur ₂₄					X				Burma: jade mines region
AMNH 97327		Ur ₃₀		?			X		Х		Burma: jade mines region
AMNH 97328		Ur,	Ur ₃				X			Zoisite	Burma: jade mines region
AMNH 98642	Ur ₈₃	Х	Ur ₃₃	Х			X				Burma: jade mines region
BGS 16853	Ur ₇₈	Х	Ur ₁₆	X							Burma: jade mines region
NMNH R3076-1		Х	Ur ₆				х				Burma: Mogaung region
NMNH R3239	Ur ₇₈	Х		Х			X				Burma: jade mines region
NMNH 94784		Х	Ur ₁		Х		х	х		Talc	Burma: jade mines region
NMNH 104671	Ur ₅₃	Х		X			х				Yunnan, China†
NMNH 104982		Ur ₁₀	Ur ₁₇		Х		Х				Unknown (probably Burma)
NMNH 152707	Ur ₇₇	Х		Х			Х				Burma: jade mines region
NMNH 145011			Ur ₁₀	Х						Diopside, Pyrite	California, U.S.A.: Williams Creek and Buttermilk Creek
NMNH R8802	Ur ₈₇	х		Х			Х		Х	Sphalerite	Mocchie, Susa, Italy
MVJ-42-4			Ur ₃₇	Х	Х				Х		La Palmilla, Motagua Valley, Guatemala
R-15		Ur ₆	Х		Х	х		Х		Na- and Al-bear- ing silicate	Rio La Palmilla, Guatemala
AMNH 30/5556			Ur₂			х				Pyrite	Finca Pompeya, Guatemala: emerald-green pen- dant
AMNH 30/10818		х	Ur.		X	х					Mixteca, Oaxaca, Mexico: emerald-green disk
NMNH 106891	Ur ₇₂	Х	Ur ₁₈	Х		X					Xalitla, Guerrero, Mexico: bead (NMNH Mineral Sci.)
NMNH 391073		Ur ₂	Ur ₇		Х					Au. Cu allov	Chichen Itza, Mexico: ring (NMNH Anthropology)
NMNH 407254		Ura	Urs	Х						.,,	La Venta, Mexico: bead (NMNH Anthropology)
NMNH 419801		Ur ₂	. 5								Guerrero, Mexico: figurine (NMNH Anthropology)

	Table 1	. 1	Material	and	sources
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* AMNH = American Museum of Natural History; BGS = British Geological Survey; NMNH = National Museum of Natural History; R = Ridinger, Jade S.A.; MVJ = authors' field study, 1984.

** Phases are ur, ureyite (Ur₂ = 2 mol% ureyite in pyroxene); jd, jadeite; omp, omphacite; cm, chromite; ab, albite; wm, white mica; amp, alkali amphibole; anl, analcime; chl, chlorite.

† Presumably from the jade mines region in Burma.

of geological and archaeological interpretations, will be handled in papers in preparation.

MATERIALS AND ANALYTICAL METHODS

A seminal Maw-sit-sit specimen was brought to our attention and donated (AMNH 98642) by Joseph Sataloff of Philadelphia, Pennsylvania. Further specimens were obtained from mineral collections at the American Museum of Natural History, Smithsonian Institution (National Museum of Natural History), and the British Geological Survey. Several small Mexican artifacts were borrowed from the Foshag collection overseen by the Anthropology Department at the National Museum. A similar collection of Mesoamerican artifacts was loaned by the Department of Anthropology at the American Museum of Natural History. One specimen with emerald-green color has been analyzed from a field study of Guatemalan jadeitites made by the authors. All specimens are listed in Table 1. Doubly polished thin sections were made from all samples except for those from the anthropological collections. Sections were examined petrographically under the polarizing-light microscope. Artifacts were observed with an incident-light binocular microscope since no modification of the artifacts was permitted.

Chemical compositions were determined with an ARL-SEMQ microprobe using natural and synthetic silicate and oxide standards. Analyses were obtained at 15 kV, 10-nA beam current, and 20 s counting time for peaks and background. The matrix correction technique of Bence and Albee (1968) was employed.

The archaeological specimens presented a problem for probe analysis since the pieces had unusual shapes, the surfaces were not always smooth, and no modifications were allowed. To get around this, the following procedure was used: First a relatively flat to convex surface with promising green color was selected. Then large cracks or flaws were filled with Ambroid glue to avoid uncleanable contamination with evaporated carbon. The surface was lightly dry-buffed using $1-\mu m$ alumina to remove film and contamination from the outermost surfaces. Finally all but the selected area was masked with adhesive tape before coating with evaporated carbon. These specimens were mounted with lowtemperature thermal adhesive to 1-in.-diameter (2.54 cm) blocks so that the selected surface was as near as possible to horizontal. The surface was monitored with reflected-light optics, with backscattered-electron scanning, and with an audio spectrometer signal to determine locations for phase analysis. After probe analysis, the artifact was cleaned by buffing with a Kimwipe soaked in water or acetone.

PETROGRAPHY AND MINERAL COMPOSITIONS

Burmese samples

Dark emerald-green jades from Burma contain pyroxene grains with up to 83 mol% Ur. The jades fall into two groups with some overlap; the first consists of mostly pyroxene-bearing rocks, and the second consists of mostly amphibole-bearing rocks.



Fig. 1. Micrographs of textures in ureyitic jadeitites from the jade mines, Burma. All are in plane-polarized light with a 1-mm scale bar unless otherwise noted. (a) A fractured, corroded chromite (black) with surrounding ureyite (dark gray) in a matrix of less ureyitic omphacite (sample 16853). (b) A chromite with a narrow ureyite rim is intersected by a fracture (horizontal) producing a large zone of ureyite replacement (sample 98642). (c) A large zoned ureyitic omphacite crystal with partially skeletal terminations (black portion is chromite with very thin ureyite rim; cross-polarized light; sample 98642). (d) Subparallel to wheat-sheaf aggregates of acicular ureyitic jadeite (sample 16853).

able z. Representative microprobe analyses of around pyroxer	able 2.	Representative	microprobe	analyses of	f ureyite-bear	ing pyroxene
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	ĥ	2	3	4	5	6	7	8	9	10	11	12	13	14
						W	eight per	cent oxides	s					
SiO ₂	52.3	55.0	53.9	56.1	58.4	56.3	54.5	55.3	53.7	55.0	53.8	51.9	54.4	56.0
TiO,	0.02	0.17	0.08	0.13	0.01	0.43	0.00	0.11	0.02	0.06	0.02	0.08	0.00	_
Al ₂ O ₃	4.01	9.63	6.26	16.3	21.7	9.77	4.19	8.22	4.08	5.80	5.24	5.50	4.08	_
Cr ₂ O ₃	27.6	11.0	24.4	10.9	0.57	1.72	24.5	18.4	26.1	3.71	24.7	3.59	2.33	22.6
FeO	0.91	3.23	1.09	- 1.0	0.76	4.06	1.80	2.24	1.82	4.96	1.03	1.97	1.97	0.4*
MnO	0.04	0.07	0.08	0.06	0.01	0.06	0.02	0.00	0.04	0.00	0.10	0.04	0.02	—
MgO	0.55	4.21	0.44	0.52	1.58	7.14	0.18	0.68	0.38	9.08	0.99	12.1	14.0	5.4
CaO	0.83	5.97	0.57	0.57	2.41	10.0	0.34	0.72	0.48	13.7	1.44	21.2	20.9	3.7
Na ₂ O	13.3	11.2	13.9	14.7	14.0	8.61	13.6	14.8	13.8	6.35	12.9	3.0	2.70	11.6
Total	99.6	100.5	100.8	100.3	99.4	98.1	99.1	100.5	100.5	98.74	100.3	99.4	100.3	99.7
						Ca	tions for	six oxygen	IS					
Si	1.96	1.98	1.98	1.97	2.00	2.04	2.04	2.01	1.99	2.02	1.98	1.91	1.96	2.07
Ti	0.001	0.005	0.002	0.003	0.00	0.012	0.00	0.003	0.001	0.002	0.001	0.002	0.00	—
AI	0.18	0.41	0.27	0.68	0.88	0.42	0.18	0.35	0.18	0.25	0.23	0.24	0.17	_
Cr	0.82	0.31	0.71	0.30	0.015	0.049	0.72	0.53	0.77	0.11	0.72	0.10	0.066	0.66
Fe	0.03	0.10	0.033	0.031	0.022	0.12	0.056	0.068	0.056	0.15	0.032	0.060	0.059	0.01
Mn	0.001	0.002	0.003	0.002	0.00	0.002	0.00	0.00	0.001	0.00	0.003	0.001	0.001	—
Mg	0.03	0.23	0.024	0.027	0.081	0.39	0.010	0.037	0.021	0.50	0.055	0.66	0.75	0.30
Ca	0.03	0.23	0.022	0.022	0.088	0.39	0.013	0.028	0.019	0.54	0.057	0.84	0.81	0.15
Na	0.97	0.78	0.99	0.99	0.93	0.61	0.98	1.04	0.99	0.45	0.93	0.21	0.19	0.83
Total	4.02	4.04	4.03	4.03	4.02	4.02	4.00	4.07	4.03	4.02	4.00	4.03	4.01	4.02

Note: Columns are as follows: (1) Ureyite, 98642, Burma. (2) Ureyitic omphacite, 98642, Burma. (3) Jadeitic ureyite, 32734, Burma. (4) Ureyitic jadeite, 32734, Burma. (5) Jadeite, R3076-1, Burma. (6) Omphacite, R3076-1, Burma. (7) Ureyite, R3239, Burma. (8) Jadeitic ureyite, 104671 (China?). (9) Ureyite, R8802, Italy. (10) Ureyitic omphacite, MVJ-42-4, Guatemala. (11) Jadeitic ureyite, 106891, Olmec bead. (12) Ureyitic diopside, 145011, California. (13) Diopside, 145011, California. (14) Ureyite, Toluca octahedrite (Frondel and Klein, 1965). * Fe determined as Fe₂O₃ for this analysis.

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Pyroxene-rich rock. These rocks are dark green with black specks or blotches. They contain mainly pyroxene with a subordinate amount of chromite ($\leq 10\%$) and light-colored veins of Na- and Mg-bearing amphibole ($\leq 20\%$). Minor veins of glaucophane, serpentine, chlorite, and in one case chlorite with banalsite (see Table 5) are present. The rocks generally have a massive unequilibrated texture with frequent shear zones consisting of variable-sized grains of pyroxene and other phases. Shear zones are bounded by deformed pyroxene showing undulose extinction, but virtually all crystals are slightly deformed, not showing complete extinction in one orientation. Unlike earlier descriptions (e.g., Lacroix, 1930), we did not find nepheline, epidote, or quartz; even albite is rare. Ureyitic pyroxene occurs in several distinct types.

The most Ur-rich pyroxene (reaching 83 mol%) exists in fine radiating coronal aggregates up to 0.5 mm thick surrounding and invading corroded chromites or as concentric bands enclosing chromite (see Fig. 1a). Ureyitic pyroxene appears to replace chromite grains, particularly where veins and shear zones intersect the chromites (Fig. 1b). The highest Cr/(Cr + Al) ratio of these pyroxene grains correlates with the adjacent chromite (see Fig. 2).

Most pyroxene grains have much lower Ur content (from 2 to 30 mol%), and the range of composition for different grains in a single specimen may vary from a nearly binary Jd (jadeite) and Ur solid solution to a quaternary solid solution with the addition of usually less than 20 mol% Di (diopside) and smaller amounts of Ac (acmite) (see Table 2 and Fig. 2). Larger ureyitic pyroxene grains range from euhedral, including skeletal (see Fig. 1c), to anhedral and are 100 μ m to over 5 mm in length. They range from homogeneous to erratically inhomogeneous in composition, though frequently compositional zoning follows growth bands of original euhedral morphology that is usually absent in the final grain. Some large crystals in several samples show corroded interiors or lathlike structure (parallel to c) that appears to be the process of reaction to become amphibole, as suggested by Yang (1984). Smaller crystals are manifested as radiating clusters or "wheat sheafs" or as sheared zones. In many cases, colorless (in thin section) jadeite is juxtaposed as matrix next to green, euhedral, Ur-rich pyroxene grains. Some samples show several generations of pyroxene growth, starting with older large jadeite grains, to intermediate "wheat sheafs" of ureyitic blades, to the ureyite growths around chromite.

Sample 98642 stands out as being the only dark-green one that is substantially calcic, being primarily ureyitic omphacite with lesser jadeite-ureyite; other specimens show occasional zones of omphacitic pyroxene (e.g., 32734, 97328, 18653, and 104982) but fall into the main category of being mostly jadeite-ureyite. Several samples with less-intense green color and no ureyite per se (e.g., R3076-1, 94784), show greater solid solution of Ur in omphacite than in coexisting jadeite.

Most chromites are fractured and corroded and show little or no crystal form, though some appear to have



broken-up parallel to octahedral faces. Grain-size varies from micrometer-sized particles mixed with ureyite to >4-mm, partially fragmented crystals. Chromites may or may not show a reaction with ureyitic pyroxene. When the reaction texture is absent, the associated pyroxene is typical of the coarser grains. Chromite compositions lie very close to the chromite end of the magnesiochromitechromite join, containing almost no Fe³⁺ (inferred from stoichiometry), very little Mg and unusually high Mn and Zn (see Table 3). The Fe/(Fe + Mg) and Cr/(Cr + Al) ratios range from upper limits for "alpine-type ultramafic" and "stratiform" chromites toward pure endmember chromite (e.g., see Irvine, 1967).

Amphibole rock. Sodic amphibole is ubiquitous in Burmese emerald-green jades and is sometimes the major constituent (sample 35024 is primarily amphibole). Lacroix (1930) attributed the name szechenyite (after Krenner) to this amphibole. The most common variety is eckermannite, but compositions range through solid solution to glaucophane, nyboite, richterite, and magnesio-alumino-katophorite (Leake, 1978). The amphibole can be slightly to markedly green in thin section and contains as



	1	2	3	4	5	6	7	8
				Weight per	cent oxides			
SiO ₂	0.63	0.13	0.40	0.53	0.15	0.03	7.30	7.23
TiO ₂	0.02	0.03	0.01	0.004	0.26	0.25	0.008	0.00
Al ₂ O ₃	16.75	9.46	4.83	4.71	11.44	12.01	3.94	3.98
Cr ₂ O ₃	46.1	54.9	59.5	59.3	51.9	50.9	56.0	56.3
V205	0.04	0.02	0.03	0.02	0.05	0.04	0.03	0.02
FeO	24.0	22.6	25.9	26.7	24.6	25.8	23.0	23.0
MnO	4.02	6.24	3.74	3.79	0.20	0.18	4.19	4.32
MgO	3.53	2,78	1.23	1.52	11.46	10.71	1.10	1.11
CaO	0.08	0.07	0.18	0.04	0.22	0.19	0.12	0.11
ZnO	5.05	3.45	2.39	1.53	0.12	0.12	1.12	1.10
Na ₂ O		_	0.35	0.26	_		2.43	2.45
Total	100.15	99.63	98.57	98.36	100.37	100.18	99.2	99.63
			(Cations for	32 oxygens			
Si	0.17	0.04	0.117	0.16	0.04	0.01	2.02	1.99
Ti	0.004	0.007	0.002	0.001	0.052	0.05	0.002	0.00
Al	5.35	3.15	1.67	1.63	3.58	3.78	1.28	1.29
Cr	9.87	12.28	13.82	13.76	10.88	10.72	12.25	12.27
V	0.008	0.004	0.01	0.006	0.011	0.01	0.006	0.003
Fe	5.44	5.35	6.37	6.56	5.45	5.75	5.31	5.30
Mn	0.92	1.50	0.93	0.94	0.04	0.04	0.98	1.01
Mg	1.43	1.17	0.54	0.66	4.53	4.26	0.45	0.46
Ca	0.024	0.02	0.057	0.014	0.06	0.06	0.035	0.033
Zn	1.01	0.72	0.52	0.33	0.02	0.02	0.23	0.22
Na		-	0.20	0.15			1.30	1.31
Total	24.21	24.24	24.23	24.22	24.67	24.69	23.87	23.88

Table 3. Representative microprobe analyses of chromites

Note: Columns are as follows: (1, 2) Chromite in ureyitic Olmec bead, 106891. (3, 4) Chromite in ureyitic omphacite, 98642, Burma. (5, 6) Chromite in diopside rock, 145011, California. (7, 8) Chromite contaminated with ureyite in jadeitite, R8802, Mocchie, Susa, Italy.

Table 4. Representative microprobe analyses of amphibole and chlorite

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	1	2	3	4	5	6	7
			Weight	percent	oxides		
SiO ₂	58.4	48.8	53.8	57.0	56.4	59.6	30.1
TiO ₂	0.25	0.02	0.04	0.19	0.04	0.01	0.00
Al ₂ O ₃	11.2	10.9	6.43	6.00	6.53	9.08	21.0
Cr ₂ O ₃	2.42	6.61	2.04	1.42	0.18	4.63	1.7
FeO	2.65	5.08	4.32	3.51	1.62	1.19	0.87
MnO	0.02	0.02	0.00	0.02	0.62	0.11	0.09
MgO	12.9	13.7	17.5	18.2	19.9	14.6	30.9
CaO	0.34	3.8	5.26	1.30	2.65	0.52	0.13
Na ₂ O	9.91	9.14	8.49	10.8	8.86	8.85	0.02
K₂O		0.24	0.20		1.00		_
Total	98.1	98.3	98.0	98.5	97.9	98.6	95.2
	С	ations fo	r 23 O (ar	nphibole	s) or 28 (O (chlorit	e)
Si	7.84	6.91	7.50	7.78	7.71	7.94	5.76
MAI	0.16	1.09	0.50	0.22	0.29	0.06	2.24
Ti	0.03	0.00	0.004	0.02	0.00	0.00	0.00
"AI	1.61	0.73	0.55	0.75	0.76	1.36	2.50
Cr	0.26	0.74	0.22	0.15	0.02	0.49	0.26
Fe	0.30	0.60	0.50	0.40	0.19	0.13	0.14
Mn	0.00	0.00	0.00	0.00	0.07	0.01	0.01
Mg	2.59	2.89	3.62	3.70	4.06	2.89	8.82
Sum C	4.78	4.96	4.91	5.02	5.10	4.89	
Ca	0.05	0.58	0.79	0.19	0.39	0.08	0.03
Na _B	2.17	1.47	1.31	1.79	1.51	2.03	0.01
Sum B	2.22	2.04	2.09	2.00	2.00	2.11	
Na _A	0.41	1.04	0.99	1.05	0.83	0.25	
K	—	0.04	0.04	0.02	0.17	—	
Total	15.41	16.08	16.03	16.07	16.10	15.25	19.77

Note: Columns are as follows: (1) Chromian glaucophane, 37970, Burma. (2) Chromian nyboite, 32734, Burma. (3) Magnesio-alumino katophorite-eckermannite, 32734, Burma. (4) Eckermannite, 104671, China (?). (5) Eckermannite, R3076-1, Burma. (6) Chromian glaucophane, R8802, Mocchie, Susa, Italy. (7) Chromian clinochlore, R8802, Mocchie, Susa, Italy. much as ~7 wt% Cr_2O_3 , Cr replacing octahedral Al (see Table 4). In hand specimen, these rocks vary in color from dark gray-green where grains are large to a chalky emerald-green where grains are small. Eckermannite may occur as single crystals over 6 mm long surrounded by pyroxene or intergrown in a massive texture enveloping irregular clots or grains (≤ 10 - μ m diameter) of ureyitic pyroxene. Besides the larger crystals, sodic amphibole often occurs as anhedral grains or as a fine fibrous mesh, approaching the texture of nephrite, particularly along sheared zones.

Italian occurrence

Sample R8802 is a small dark-green rock that contains in addition to Ur-rich pyroxene (up to 87 mol% Ur, see Table 2), chromite, glaucophane, chlorite, and accessory sphalerite. The high-Ur pyroxene occurs as lenses (up to 3 mm wide) of micrometer-sized grains that appear to be a replacement of chromite (Fig. 3). Chromites are so corroded that individual grains are too small to obtain accurate analyses (see Table 3). The ureyitic lenses occur in rock that contains less ureyitic jadeite and glaucophane. Pyroxene compositions are low in Ca but occasionally acmitic, up to 26 mol% (see Fig. 2). Large pyroxene grains several millimeters long are dissected and separated into 40–200- μ m fragments. Locally the groundmass pyroxene and amphibole fragments are enveloped with chlorite. Sphalerite occurs as small grains interspersed in the groundmass.

California occurrence

A chromite-bearing rock from Williams Creek, California (145011), consists primarily of diopside that contains small areas with up to 10 mol% Ur. Ureyitic zones are always adjacent to the chromites and grade to almost pure diopside no more than 50 µm away from the chromite. Jd is a minor component in the pyroxene and appears to be correlated with Ur, concentrated up to 20 mol% in the Ur-rich zones (Fig. 2). The most urevitic analysis also shows significant apparent tetrahedral Al, whereas other analyses show little or none (see Table 2). The rock has a brecciated, vein-filled texture, but is nearly monomineralic, consisting of fine-grained pyroxene laths of approximate dimensions $2 \times 20 \mu m$, intervoven in a felted texture. Some grains are much larger, up to 40 \times 800 μ m, and these larger grains are occasionally aligned in vein-filling swaths. The chromites have compositions typical of alpine-type ultramafic chromites, containing less Cr, more Al, and much more Mg than the Burmese chromites described above. Chromite grains are equant, roughly 0.7 mm across, and are severely broken up. There is also a small percentage of euhedral pyrite grains, usually less than 10 µm but up to 200 µm across. Although Ur-bearing pyroxene and chromites are in close contact, the reaction texture seen in Burmese samples is absent.

Mexican and Central American artifacts

Of six small artifacts with obvious emerald-green color and easily measurable Ur content, two contain very ureyitic pyroxene (Ur₄₂ and Ur₇₂ max., see Tables 1 and 2). Since thin sections could not be made from archaeological collection items, these were characterized only by microprobe analysis of a portion of their surfaces. Microprobe analysis and backscattered images indicate that these artifacts are all predominantly jadeitic to omphacitic pyroxene (\geq 90%), with emerald-green spots showing 2 to 42 mol% Ur (Fig. 2), and minor albite and/or white mica (Table 1). The Olmec bead (sample 106891), for which we were able to obtain a thin section, consists of about 80% jadeitic pyroxene, with accessory phengitic muscovite ($\sim 15\%$), chromite, and urevite. Large subhedral interlocking pyroxene grains (about 1 mm long) are pervasively fractured, often along cleavage surfaces, probably the result of the lapidary work done on the bead. Smaller euhedral to subhedral phengite grains (about 0.5 mm across) are interspersed throughout the pyroxene. Anhedral mica sometimes invades pyroxene. Emeraldgreen spots (about 0.2 mm across) with up to 72 mol% Ur enclose smaller corroded chromites and exhibit narrow zones of reaction texture. The chromites have compositions similar to those of the Burmese specimens, being very rich in Cr and Fe²⁺ (see Table 3). Combined pyroxene analyses define two compositional trends, one from Jd to Omp (omphacite) with minor Ur and the other from Ur toward the Omp-Jd field (see Fig. 2). Among analyses in the first trend, Ac content is correlated with Ur for more omphacitic compositions, reaching about Ac₅.



Fig. 3. Micrograph of lens of fine-grained relict chromite, largely replaced by ureyite in sample NMNH R8802, Mocchie, Susa, Italy. Scale bar is 1 mm.

Guatemalan occurrence

In contrast to Burmese jadeitites, the Guatemalan jadeitites examined to date contain no ureyite, but two specimens have been found that have a Ur component varying up to 36 mol% (Fig. 2), which is consistent with their pale to noticeably emerald-green color in hand specimen (details of the jadeitites are discussed elsewhere; Harlow, in prep.). Pyroxene compositions for the two specimens are quite different—one is nearly pure Jd, the other is all Omp. The primarily jadeite rock is reasonably typical of Guatemalan jadeitites (McBirney et al., 1967; Harlow, in prep.) in that is contains variable-sized jadeite grains (up to 6 mm long), some showing subhedral to anhedral outlines with internal growth zoning. Paragonite (Table 5) shows up as a minor ($\sim 10\%$) primary phase rimmed by a very sodic nepheline-like phase, whereas albite, analcime, and omphacite appear as secondary minerals along grain boundaries and fractures and as small inclusions in heavily included, anhedral pyroxene. The urevitic regions are minor and extremely pale green; they appear to be correlated with late-stage calcic (and more acmitic) zones of the pyroxene growth. The omphacitic sample consists of ~95% intergrown lathy pyroxene up to 2 mm long with minor broken or corroded grains of chromite and some intergranular albite and chlorite. Urevitic compositions are particularly associated with chromite (but without any visible reaction zone) and often follow internal euhedral outlines within larger pyroxene crystals. The ureyitic omphacite again shows an enrichment of Ac (up to Ac_{14}) relative to more jadeitic zones (Fig. 2, Table 2). Chromite compositions are similar to those from Burmese samples (Harlow and Barry, in prep.).

DISCUSSION

Pyroxene crystal chemistry

All of the pyroxene with significant Ur content can be described in terms of a solid solution of Ur, Jd, Di, Ac,

	1	2	3	4	5	6
			Weight pe	ercent oxid	les	
SiO ₂	48.8	44.7	54.3	36.0	68.5	70.3
TiO ₂	0.04	0.08	0.00	0.00	0.00	0.00
Al ₂ O ₃	40.6	38.1	21.6	31.44	19.6	18.8
FeO	0.27	0.34	0.43	0.07	0.00	0.03
MgO	0.10	0.41	5.98	0.04	0.00	0.00
CaO	0.15	0.15	0.02	0.07	0.02	0.11
Na ₂ O	6.27	7.80	0.08	9.84	12.6	11.5
K ₂ O	0.58	0.38	10.5	0.00	0.00	0.04
BaO	0.10		0.47	20.2	0.00	0.00
Total	97.0	92.1	93.5	97.8	100.8	100.7
		C	Cations fo	r 22 O (mi	cas)	
		or	8 O (bana	alsite and a	albite)	
Si	6.09	5.93	7.33	1.98	2.98	3.03
Ti	0.003	0.008	0.000	0.001	0.000	0.00
Al	5.97	5.95	3.43	2.04	1.01	0.96
Fe	0.028	0.036	0.05	0.003	0.000	0.001
Mg	0.018	0.082	1.20	0.003	0.000	0.00
Ca	0.020	0.021	0.003	0.004	0.002	0.003
Na	1.52	2.01	0.020	1.05	1.06	0.97
K	0.092	0.063	1.81	0.000	0.000	0.002
Ba	0.005	_	0.025	0.44	0.000	0.000
Total	13.73	14.01	13.95	5.52	5.05	4.97

Table 5. Representative microprobe analyses of micas and feldspar

Note: Columns are as follows: (1) paragonite, 391073 Olmec bead, La Venta. (2) paragonite, R-15, Guatemala. (3) phengitic muscovite, 106891 Olmec bead, Xalitla. (4) banalsite, 32734, Burma. (5) albite, 94784, Burma. (6) albite, 391073 ring, Chichen Itza.

and occasionally Hd (hedenbergite), as determined from cation and charge (sometimes inferred) balances from microprobe analyses. In particular, Ca + Na cations usually sum very close to 1 per 6 oxygens, and a total charge of 4 on M1 + M2 sites is maintained by Cr + Al + Fe -(Ca - Mg) charge-balancing Na, leaving residual Fe²⁺ + Mg to balance Ca. Ti content is generally very small and can be described by a substitution such as Ca + Al =Na + Ti. There is always enough Di component in jadeitic pyroxene to allow this exchange, and this result is similar to the interpretation of Gasparik (1985), although no evidence for a \Box + Ti substitution (\Box is a vacancy) was noticed. While Si cations frequently sum to less than 2 per 6 oxygens, there is no indication that Ti or Al is replacing Si except in the case of a diopside from California (see section below). In some analyses, Si significantly exceeds 2 cations, but in these cases, Ac is usually inferred to be high such that correction for increased oxygen from Fe_2O_3 yields a reduction of total cations and Si. Some authors have reported significant deviations for cation totals in jadeitic pyroxene (e.g., Carpenter, 1979); however, we did not observe significant cation deficiencies, though some very fine grained mixtures of pyroxene and amphibole produced cation totals similar to pyroxene but with high Mg content.

The total compositional range can be seen in Figure 2. The data support complete miscibility between jadeite and ureyite, as shown experimentally by Abs-Wurmbach and Neuhaus (1976), as well as some extension toward omphacitic compositions. The presence of ureyitic omphacite is very interesting, though not totally new (e.g., Sobolev et al., 1975). Experimental studies on the Di-Ur join show only minor to intermediate solid solution of Ur in diopside-a maximum of 24 wt% Ur in diopside at 1 atm and 1150°C (dry), decreasing to 13 wt% at 20 kbar (Ikeda and Yagi, 1972). Under hydrous conditions, the liquidus descends, and only 15 wt% Ur was found at 850°C and 20 kbar (Vredevoogd and Forbes, 1975). Neither set of experiments discovered a Ur-rich omphacitic phase, and only 2 wt% Di was found in ureyite. The natural samples are consistent with little solubility of Ur in diopside (e.g., sample 145011 from California) but show substantial solid solution of Ur into an omphacite-chloromelanite-like pyroxene, at least to 30 mol% Ur at Di₃₅. Two Guatemalan samples and some Mexican artifacts show trends of urevite solution toward omphacite, whereas the Burmese data additionally show a large cluster of compositions in the middle of the Jd-Di-Ur field (dominated by sample 98642; see Fig. 2). The omphacite-jadeite gap, which is obvious in both Burmese and Guatemalan sample data, is tenuous for more ureyitic compositions, particularly for the Mexican artifacts. A number of samples (e.g., R3076-1, 94784, 104982, 30/10818) show greater Ur content in omphacite than in coexisting jadeite, though this correlation also exists for Ac, perhaps being simply a crystallization trend. However, this increased solubility may be related, in a simple-minded way, to the unit-cell volume of urevite being more comparable to omphacite (both ordered and disordered forms) than to jadeite (or diopside). Considering the relationship of ordering to the stability of omphacite, an interesting problem in the site topology for the solid solution with urevite (and acmite) is raised.

Paragenesis

In meteorites, ureyite is presumed to have crystallized from a very sodic silicate melt in equilibrium with metallic iron (Frondel and Klein, 1965). Experimental work on pressure dependence of Jd-Ur solid solution (Abs-Wurmbach and Neuhaus, 1976) is consistent with crystallization of ureyite at very low pressures in the metallic meteorites. Even though ureyite coexists with albite in meteorites, it contains no Jd component.

In terrestrial rocks, the textural association—i.e., corroded chromites surrounded by fine-grained ureyite in most ureyite-bearing samples—suggests a reaction in which chromite is consumed and ureyite produced. All described jadeitites except for the Polar Urals occurrence are hosted in serpentinized ultramafic rock in highly tectonized terranes. The Polar Urals occurrence may be an exception; here jadeitites and albitites are contained in serpentine pyroxenite bands that are part of a system of ultramafics, some of which are unaltered peridotites (Morkovkina, 1960; Dobretsov and Ponomareva, 1965). Chromitites also commonly occur in serpentinites and in Burma are described as adjacent to jadeitites (Chhibber, 1934). Presumably, chromite-bearing ureyitic jadeitites incorporated their chromite from surrounding serpentinite. Therefore serpentine (e.g., chrysotile) and chromite are possible reactants. Similarly, albite, described by Chhibber as a primary constituent of the albitite-jadeitite "dikes" of which the chromiferous jadeitite-amphibolites are part, is a likely reactant. However, it is impossible to write a reaction for a closed system involving only as major species ureyite, jadeite, chromite, eckermannite, albite, and chrysotile.

In igneous and metamorphic rocks, Na and Al are highly correlated or "tied" to one another. If, in our jadeitites, Na is decoupled from Al to make ureyite, the appearance of a nonsodic aluminous phase is demanded. The only reasonable candidate for this aluminous phase is spinel (i.e., in solid solution with the chromites); hence, we can postulate a solid-state exchange reaction in which jadeite and chromite react to form ureyite and hercynite. However, aside from this being unlikely crystal-chemically, the chromites associated with ureyite are among the least aluminous of naturally occurring chromites. Furthermore, there is no evidence for zoning (in particular, zoning with respect to Al) in these chromites.

Allowing for mobility of Na⁺, Fe²⁺, and Mg²⁺, in the presence of "water," i.e., in an open system, it is possible to write four reactions involving ureyite for the Burmese assemblage (considering only the Mg²⁺ endmembers):

$$\begin{split} \text{MgCr}_2\text{O}_4 &+ 4\text{NaAlSi}_3\text{O}_8 &+ 2\text{Na}^+\\ \text{sp} & \text{ab}\\ &= \text{Mg}^{2+} + 4\text{NaAlSi}_2\text{O}_6 + 2\text{NaCrSi}_2\text{O}_6 & (1)\\ & \text{jd} & \text{ur} \\ \end{split}$$

$$\begin{aligned} 5\text{MgCr}_2\text{O}_4 &+ 12\text{Na}_3\text{Mg}_4\text{AlSi}_8\text{O}_{22}(\text{OH})_2 &+ 7\text{Mg}^{2+}\\ \text{sp} & \text{eck} \\ \end{split}$$

$$+ 28H_2O$$

$$= 14Na^{+} + 12NaAlSi_{3}O_{8} + 10NaCrSi_{2}O_{6}$$

ab ur
$$+ 20Mg_{3}Si_{2}O_{5}(OH)_{4}$$

serp (2)

$$2MgCr_{2}O_{4} + 3Na_{3}Mg_{4}AlSi_{8}O_{22}(OH)_{2} + Mg^{2+} + 7H_{2}O$$

sp eck
= 2Na⁺ + 3NaAlSi_{2}O_{6} + 4NaCrSi_{2}O_{6}
jd ur
+ 5Mg_{3}Si_{2}O_{5}(OH)_{4} (3)

$$s_2O_5(OH)_4$$

serp

$$3MgCr_2O_4 + 3Na_3Mg_4AlSi_8O_{22}(OH)_2 + 4NaAlSi_3O_8$$

sp eck ab
+ 7H_2O
= 7NaAlSi_2O_6 + 6NaCrSi_2O_6
jd ur
+ 5Mg_3Si_2O_5(OH)_4. (4)

serp

Similar reactions can be written for the Fe²⁺ endmembers. Though albite is often associated with jadeitites, we do not observe albite in association with ureyite-chromite-bearing assemblages on a thin-section scale. Furthermore, in our samples it is always the case that $[Cr/(Cr + Al)]_{chromite} \ge [Cr/(Cr + Al)]_{jadeite-ureyite}$ where the reaction texture is observed, an observation consistent with the consumption of an aluminous phase such as albite in the production of ureyitic pyroxene. This seems to rule out Reaction 2 in which ureyite and albite occur on the same side. In Reactions 3 and 4, ureyite and the Na-rich phase eckermannite appear on opposite sides, so that eckermannite needs to be accounted for independently of ureyite. The presence of eckermannite independent of ureyite can only be accounted for via

$$8NaAlSi_{3}O_{8} + 5Mg_{3}Si_{2}O_{3}(OH)_{4} + 6Na^{+}$$

ab serp
$$= 3Mg^{2+} + 5NaAlSi_{2}O_{6}$$

jd
$$+ 3Na_{3}Mg_{4}AlSi_{8}O_{22}(OH)_{2} + 7H_{2}O.$$
 (5)
eck

This completes the set of possible reactions given the above assumptions. Adding the appropriate multiples of Reaction 5 to either Reactions 3 or 4 to cancel eckermannite results in Reaction 1 (i.e., there are only three independent reactions). The main point is that, given the observed species and assuming the presence of albite (or other similar Na- and Al-bearing silicates) and chrysotile, an influx of Na⁺ and escape of Mg²⁺ is required to explain the chromite-ureyite reaction. A hydrous fluid might facilitate such a reaction and is consistent with the presence of serpentinite, so long as the pressure is high enough to prevent the formation of analcime.

Geologic implications

Metasomatism. By the above argument, the chromiteureyite reaction and the presence of eckermannite in Burmese samples imply sodic-fluid metasomatism or some similar sodic-fluid-dominated reaction and crystallization process. Metasomatism is also supported by the existence of monomineralic and bimineralic zones of jadeite and jadeite-amphibole. In addition, the restriction of jadeitites to serpentinites or serpentine-bearing bodies suggests a connection between serpentinization and jadeitization. Although this is a much larger question being addressed elsewhere (e.g., Harlow, in prep.; Olds, in prep.), the important implication of ureyite paragenesis is the necessity of a sodic fluid in forming the jadeitites.

P, **T**, and conditions of pyroxene crystallization. The conditions under which jadeitites form are not well constrained: Coleman (1961) estimated conditions of 2 kbar and 250°C for New Idria jadeitites; Dobretsov (1968) estimated conditions with pressures greater than 10 kbar and temperatures near 500°C for jadeitites in the Soviet



Fig. 4. Plots of cation proportions for chromites from three ureyite sources (axes are self explanatory). Large open box and diamond represent general cluster of compositions for Burmese and Italian samples, respectively. Enclosed regions denote the normal range of compositions from alpine-type ultramafic bodies (Irvine, 1967).

Union. Carpenter (1981) suggested a peak P and T of 350–400°C and 6–8 kbar for Guatemalan occurrences based on lawsonite in associated rocks and experimental estimates on the low-pressure breakdown of jadeite to form albite + nepheline. Actually, the lawsonite- and jadeite-bearing inclusions occur in distinctly different serpentinites, separated by the Motagua fault (a misinter-pretation of McBirney et al., 1967), so the former constraint is not appropriate. Obviously, more work needs

to be done on jadeitites in general and the rocks from Guatemala and Burma in particular. Phase diagrams have been worked out for simple closed systems of dry and water-saturated jadeite and albite compositions, but these cannot be easily applied to open fluid-rock systems. (The absence of thermodynamic data for eckermannite and the lack of models for aqueous ionic activities at very high pressures may preclude a rigorous thermodynamic treatment of the above reaction system.) We do know, however, that ureyite can be crystallized from a silicate melt at 1-atm pressure. This observation and limited experimental work (Abs-Wurmbach and Neuhaus, 1976) suggest that ureyite is stable at lower pressures compared to jadeite over a range of reasonable temperatures. Hence the presence of urevite in jadeitites probably places no additional restrictions on required P-T conditions for jadeitite petrogenesis (whatever those may be for the proposed fluid-rock system).

The presence of omphacite adds a needed extra dimension to the pyroxene complexity for determining crystallization and annealing conditions. The jadeite-omphacite gap in Burmese jadeitite pyroxene suggests a crystallization temperature below the crest of the miscibility gap (solvus) in the Jd-Di binary field. Carpenter and Smith (1981) have placed this between 500 and 600°C, at an unspecified pressure probably from 10 to 20 kbar, with an Ac content of between 3 and 12%, comparable to the Burmese values. Crystallization temperatures would be well below this value, appropriately corrected for pressure, considering the measurable size of the gap. Alternatively, in a fluid-dominated environment, a change of crystallization conditions could cause the break in pyroxene compositions. The intimate intergrowth textures of pyroxenes in Burmese jadeitites makes this latter possibility less likely than, for example, in the Guatemalan jadeitites where omphacite is an overgrowth and obviously a later phase than jadeite.

Crystallization stages. That Ur-rich pyroxene occurs in at least two distinct modes in many Burmese samples, i.e., as fine-grained Ur-rich pyroxene aggregates radiating from chromites and as large euhedral crystals with less Ur and more quadrilateral pyroxene components, indicates the occurrence of at least two Ur-forming events or a series of crystallization steps. The ureyite-chromite reaction texture must have been formed latest simply because it is still there and did not have time to recrystallize and homogenize with the rest of the pyroxene. The crystallization of nearly pure jadeite seen in rocks containing both modes of urevite may or may not have occurred simultaneously with a Ur-producing event. If so, ureyite would have formed at conditions within the stability field of jadeite, a possibility consistent with the above discussion on P and T. The association of urevitic compositions to acmitic omphacite in some artifacts and Guatemalan samples suggests that the ureyite formed later than jadeite (jadeite often has omphacite overgrowths), but it is not yet clear why this should be.

Chromite compositions. The chromites associated with all ureyitic samples except 145011 from California fall in a similar and narrow composition range. Although it seems reasonable to assume that these chromites came from adjacent ultramafic rock, their compositions are not within the range of normal podiform chromites from alpine-type ultramafic bodies (Fig. 4; see Irvine, 1967). Either the chromites associated with ureyite are different in origin from typical podiform chromites, or enrichment in the chromite endmember has occurred by some later process (perhaps related to jadeitization or ureyite formation). This subject is being considered more completely in Harlow and Barry (in prep.).

CONCLUSIONS

We have presented further data and documentation on the terrestrial occurrence of ureyite and Ur-rich pyroxenes. The occurrence has been expanded from the jade mines of Burma to Mocchie, Susa, in the western Italian Alps; a source of Mesoamerican jade; and the Motagua Valley of Guatemala (the latter two possibly being related or the same). Ureyite occurs in solid solution with jadeite, as shown by Yang (1984), and with omphacite and to a lesser extent diopside. The reaction textures between ureyite and chromite within jadeitite demonstrate that ureyite is produced at the expense of chromite and requires an outside source of Na⁺, most probably a metasomatic fluid. The juxtaposition of chromite with jadeitite is probably the product of tectonic activity mixing adjacent serpentinite and jadeitite blocks.

ACKNOWLEDGMENTS

Thanks to Bob Coleman and Juhn Liou for reviewing an early version of the manuscript, to Jim Shigley and J. Alexander Speer for critical reviews, to Bruce Bathurst for use of his reaction generating program REACTAPL, to Joseph Sataloff, Mary Lou Rydinger, the British Geological Survey, the Departments of Anthropology and Mineral Sciences at the Smithsonian Institution, and the American Museum of Natural History for generously providing samples and to the Instituto Geográfico Militar of Guatemala for assistance and support during field studies in Guatemala.

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Manuscript received July 29, 1985 Manuscript accepted September 2, 1986