

PYROXENES IN THE BLUESCHIST FACIES OF CALIFORNIA*

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ABSTRACT. Blueschist metamorphism of Franciscan Formation in California has produced characteristic pyroxenes as related to their host rock. Pure end-member jadeite is restricted to metasomatized leucocratic masses within serpentinite. Jadeitic pyroxene (jd. 70-90) coexists with quartz in metagraywackes, and omphacite or acmitic pyroxene are present in the metabasalts. Metacherts are characterized by acmitic pyroxenes and contain neither jadeite nor omphacite.

Chemical, optical, and X-ray parameters of the pyroxenes from representative rocks demonstrate strong variations related to rock composition. The jadeites have a space-group symmetry of $C2/c$, whereas the presence of weak reflections in these omphacites is incompatible with this symmetry group, and structural refinement shows the true space group to be $P2_1$.

Experimental work indicates that at the pressure-temperature conditions of the blueschist metamorphism, jadeite and compositionally related pyroxenes are favored by high pressure. The contemporaneous metamorphism demands a similar pressure-temperature environment for the pyroxenes from different rock types, and thus in the silica-deficient environment of the serpentinites pure jadeites form, whereas in other rock types where excess silica is present, only jadeitic pyroxene and omphacite are stable.

INTRODUCTION

It is now well established that the blueschist metamorphic facies is characterized generally by relatively high pressures and low temperatures compared with other facies. The physical and chemical characteristics of the pyroxenes forming in such an environment can be expected to be somewhat different from those of pyroxenes crystallizing in environments where temperature is predominant over pressure. Jadeitic pyroxenes and related types in the blueschist facies form within two distinct geologic environments as part of the blueschist periods of metamorphism: (1) Regional metamorphism of graywackes, basalts, and metacherts produces widespread jadeitic pyroxene, omphacite, and acmitic pyroxenes, respectively. (2) Local concentrations of pure jadeite occur as monomineralic pods and veins in metasomatized tectonic inclusions within sheared serpentinites. This formation of pure jadeite within the sheared serpentinites is considered to be contemporaneous with the blueschist metamorphism of the surrounding graywackes and volcanics of the Franciscan Formation (Coleman, 1961), which is of Jurassic and Cretaceous age. The purpose of this paper is to relate the compositional variations and physical properties of the pyroxenes to the rock types. A comprehensive discussion of the geology related to the Franciscan blueschists is given by Bailey, Irwin, and Jones (1964).

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PETROLOGY

The pyroxenes in the blueschists, although generally sodic, do show a broad compositional range characteristic of the rock types within which they crystallize: metagraywackes, metacherts, metabasalts, and serpentinites.

Metagraywackes.—The metagraywackes and shales are the most abundant rock types within the Franciscan blueschist terrains, and hence the associated jadeitic pyroxene is the most common species. The metagraywackes are characterized by a lack of distinct planar structures and in the field have the same appearance as unmetamorphosed graywackes. The characteristic mineral assemblage is quartz–jadeitic pyroxene–lawsonite–white mica with varying amounts of glaucophane, aragonite–calcite, chlorite, and albite. Lower-grade rocks with a bulk composition equivalent to that of the jadeitic pyroxene-bearing metagraywackes contain the assemblage quartz–white mica–chlorite–albite–lawsonite–aragonite. Although the jadeitic pyroxenes contain 70 to 90 mole percent of the jadeite component, the occurrence of albite + quartz in veins and segregations rather than pure end-member jadeite, $\text{NaAlSi}_2\text{O}_6$, indicates that quartz + albite is stable and that the pressure is below the reaction curve albite \rightarrow jadeite + quartz.

Metacherts.—Even though the metacherts produce rather spectacular metamorphic specimens within the blueschists of California, they represent only a small proportion (less than one percent) of the total Franciscan section. The metacherts are characterized by extremely thin beds (0.5 to 10.0 mm) and abrupt changes in bulk composition from one bed to the next. Aegirine and aegirine-augite are the pyroxenes characteristic of these metacherts, and the commonly associated minerals are: quartz, garnet, crossite-riebeckite, stilpnomelane, deerite, and white mica. Too few analyses are available to estimate the probable range in composition of the pyroxenes, although the jadeite component is probably less than 20 mole percent. The discontinuous nature of the chert exposures precludes tracing any relationship between pyroxene compositions and the grade of metamorphism.

Metabasalts.—The results of metamorphism are more significant and more readily recognized in metabasalts than in the other rock types under discussion, because the original pyrogenic minerals of the metabasalts are less stable during metamorphism. The metabasalts have been classified as type II, type III, or type IV (Coleman and Lee, 1963). Type II metabasalts contain omphacite rich in acmite component (greater than 30 mole percent) and associated with glaucophane, lawsonite, pumpellyite, 1M white mica, chlorite, and aragonite. The igneous textures and structures are retained in the type II metabasalts, but the rock has completely recrystallized. The type III metabasalts have the same mineral assemblages as type II metabasalts, but coarser crystals and a well-developed metamorphic fabric characterize the intermediate type. The pyroxene common in these type III metabasalts is omphacite which has a composition

nearly identical to that of omphacites from type IV eclogites. In the type IV metabasalts, the mineral assemblages include garnet, glaucophane, epidote, and white mica. Omphacite is again the pyroxene most commonly present, appearing both in eclogites and also in glaucophane schists, and having a relatively constant composition of about 35 mole percent jadeite and 50 mole percent diopside; the remaining 15 percent varied widely.

Serpentinites.—The occurrence of nearly pure end-member jadeite, $\text{NaAlSi}_2\text{O}_6$, is restricted to the sheared serpentinite bodies within the Franciscan Formation, and these jadeites are not associated with quartz. The largest known deposits of jadeite in the California Coast Ranges are contained in the New Idria serpentinite mass; smaller finds of jadeite have been reported from serpentinite masses located elsewhere (Coleman, 1961). Two distinct environments are recognized for the New Idria jadeite deposits: (1) tectonic inclusions of albite-crossite-pyroxene schist containing jadeite as an essential mineral or in crosscutting veins; acmite is a common accessory mineral in the schist; (2) podlike bodies characterized by a central core of jadeitic pyroxene surrounded by a calc-silicate rim. The veins in the schist contain pure white jadeite associated with albite and analcite, whereas the pods contain dark green, nearly monomineralic jadeitic pyroxene, surrounded by a rim containing pectolite, hydrogarnet, thomsonite, and sphene. The composition of the white jadeite in the veins from tectonic inclusions is 97 mole percent jadeite, but that of the dark-green variety from the schists and pods ranges from nearly pure to 75 mole percent jadeite. In both environments, sufficient metasomatic exchange has taken place with the surrounding serpentinite so that the original host rocks containing the jadeite have unusual chemical compositions, undersaturated with respect to silica and enriched with respect to sodium and aluminum. The presence of pure jadeite here places the pressure above the reaction $\text{Jd} \rightleftharpoons \text{Ne} + \text{Ab}$. Thus the blueschist facies lies between the breakdown curves for pure jadeite and pure albite.

MINERALOGY

The mineralogical discussion is based on study of fourteen analyzed pyroxenes from the California blueschist terrains; data for representative samples are presented in tables 1 through 4. No data are available at present for samples from the metacherts. The jadeites and jadeitic pyroxenes from serpentinites have been described by Coleman (1961). The jadeitic pyroxenes from the metagraywackes were discussed by Coleman (1965), and the omphacites from metabasalts were studied by Coleman and others (1965). Some of the present data are new, however, notably some X-ray diffraction powder data and the unit-cell constants. In the experimental work, care was taken to obtain and use only homogeneous, purified samples.

Chemistry.—The chemical analyses of representative pyroxenes are given in table 1, and the calculations of formulas in table 2. The formulas

TABLE 1

Chemical analyses of pyroxenes from the blueschist facies, California

Oxide	Serpentinites		Metagraywackes	Metabasalts	
	Clear Creek, New Idria district, San Benito County	Jadeitic pyroxene ² R-1853	Angel Island, San Fran- cisco Bay	Ward Creek, Sonoma County	Tiburon Peninsula, Marin County
	Jadeite ¹ R-1854		Jadeitic pyroxene ³ B-48	Acmitic pyroxene ⁴ 15-CZ-60	Omphacite ⁵ 100-RGC-58
SiO ₂	59.06	56.54	59.20	51.8	54.3
Al ₂ O ₃	24.62	18.38	21.94	11.2	10.0
TiO ₂	0.08	0.44	0.50	2.8	0.20
Fe ₂ O ₃	0.41	5.67	1.42	11.3	3.5
V ₂ O ₃	.....	.....	0.09	.....	.....
FeO	0.18	1.05	0.64	2.4	3.2
MnO	0.03	0.10	0.03	0.11	0.02
MgO	0.17	1.44	1.04	3.6	8.2
CaO	0.35	2.69	1.14	5.1	13.3
Na ₂ O	14.95	13.00	13.70	9.6	6.8
K ₂ O	0.01	0.03	0.08	0.38	0.02
H ₂ O ⁺	0.07	0.20	0.	} 1.9	0.12
H ₂ O ⁻	0.03	0.05	0.05		0.06
Other	.....	0.01	0.04	.....	.....
Total	99.96	99.60	99.87	100.2	99.7

¹ Analyst, Eileen H. Oslund, University of Minnesota. Coleman (1961, table 1, column 2).

² Analyst, Eileen H. Oslund, University of Minnesota. Coleman (1961, table 1, column 3).

³ Analysts, R. E. Stevens, A. A. Chodos, S. T. Neil, A. C. Bettiga, and E. Godijn, U.S. Geological Survey. Coleman (1965, table 1, sample 1). Other elements determined: ZrO₂, 0.009; Cr₂O₃, 0.010; NiO, 0.004; BaO, 0.003; BeO, 0.0005; CoO, 0.0003; CuO, 0.002; PbO, 0.002; Sc₂O₃, 0.008; Ag 0.003 percent.

⁴ Analysts, L. B. Beatty, A. C. Bettiga, and W. W. Brannock, U.S. Geological Survey. Coleman and others (1965, table 5, sample 15-CZ-60).

⁵ Analysts, L. B. Beatty, A. C. Bettiga, and W. W. Brannock, U.S. Geological Survey. Coleman and others (1965, table 5, sample 100-RGC-58).

are expressed as (M2)(M1)T₂O₆, where M2 refers to Ca and Na, M1 to Mg, Al, Fe, and Ti, and T to Si and tetrahedrally coordinated Al as required to make a total of two atoms. The pure jadeites have virtually no Al in tetrahedral coordination, a feature of high-pressure minerals that has been commented on by Thompson (1947) and Yoder (1950), among others. The omphacites have somewhat more Al in tetrahedral coordination, and the acmitic pyroxenes appear to have the most, but the maximum amount in any of these pyroxenes does not exceed 5 percent of the total tetrahedral contents. All remaining Al is assumed to be in octahedral coordination and is included with the M1 cations. The sum of the M1 cations varies slightly above the expected value of 1.00 for the pyroxenes.

TABLE 2

Chemical formulas* of pyroxenes from the blueschist facies, California

Element	Serpentinities		Metagraywackes	Metabasalts	
	Clear Creek, New Idria district, San Benito County Jadeitic pyroxene R-1854	Jadeitic pyroxene R-1853	Angel Island, San Fran- cisco Bay Jadeitic pyroxene B-48	Ward Creek, Sonoma County Acmitic pyroxene 15-CZ-60	Tiburon Peninsula, Marin County Omphacite 100-RGC-58
Si	1.99	1.98	2.02	1.91	1.96
Al	0.01	0.02	.....	0.09	0.04
Σ T cations	2.00	2.00	2.02	2.00	2.00
Al	0.97	0.74	0.88	0.40	0.39
Ti	.....	0.01	0.01	0.08	0.01
Fe ³⁺	0.01	0.15	0.04	0.31	0.10
Mg	0.01	0.07	0.05	0.20	0.44
Fe ²⁺	0.03	0.02	0.07	0.10
Σ M1 cations	0.99	1.00	1.00	1.06	1.04
Na	0.98	0.88	0.90	0.69	0.48
Ca	0.01	0.10	0.04	0.20	0.51
K	.....	.....	.....	0.01	.....
Σ M2 cations	0.99	0.98	0.94	0.90	0.99
Pyroxene Component					
Jadeite	98.0%	73.5%	87.5%	37.3%	37.5%
Acmite	1.0	15.0	3.7	33.3	9.5
Di + He + Tsch	1.0	11.5	8.8	29.4	53.0

* Calculations based on six oxygens per formula unit, (M2) (M1) T₂O₆ where M1 refers to the octahedrally coordinated cations, M2, to the larger cations, and T, to the tetrahedrally coordinated cations, which are made up to 2.00 if necessary by adding Al.

from metabasalts, and the sum of the M2 cations is substantially less than 1.00 for two samples. These variations may reflect the difficulties of obtaining a sufficiently large homogeneous sample for bulk chemical analysis.

The chemical variations among these California pyroxenes are shown on the compositional diagram (fig. 1), on which the approximate fields for pyroxenes from serpentinites, metagraywackes, and metabasalts are indicated. There appears to be a definite compositional gap between the jadeitic pyroxenes from serpentinites and metagraywackes, and the omphacites from the metabasalts. Dobretsov (1962) discusses miscibility limits and mean compositions of jadeitic pyroxenes and concludes that

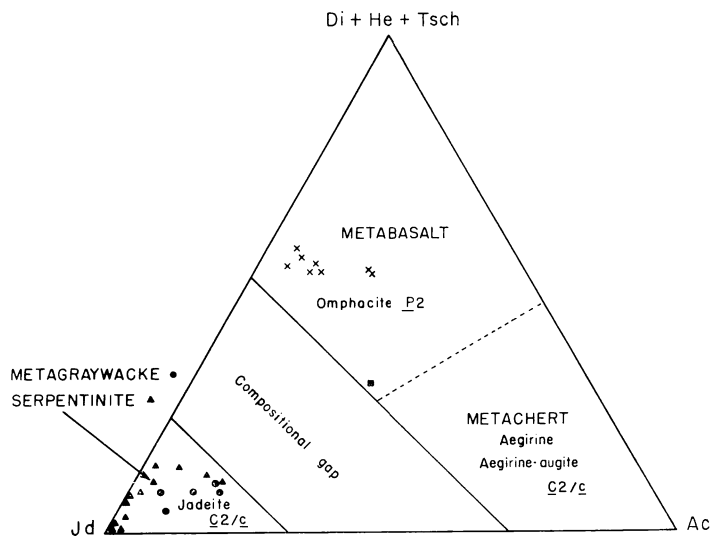


Fig. 1. Triangular diagram showing compositional variation of pyroxenes in terms of the components, jadeite (Jd), acmite (Ac), and diopside (Di) plus hedenbergite (He) plus Tschermakite (Tsch). Analyzed pyroxenes from the blueschist areas of California are represented by triangles for jadeites and jadeitic pyroxenes from serpentinites, dots for jadeitic pyroxenes from metagraywackes, crosses for omphacites from metabasalts, and squares for acmitic pyroxene from metabasalt.

diopside-jadeites (omphacites) are separated by an immiscibility region from jadeites. On his diagram, the compositional gap falls between 60 and 80 mole percent jadeite. The present plot of the California pyroxenes confirms the presence of a natural gap along the diopside-jadeite join, although here it occurs between 45 and 75 mole percent jadeite.

X-ray diffraction studies.—Powder patterns were prepared on a diffractometer for the same pyroxenes described in tables 1 and 2. The observed peaks are indexed and listed in table 3 for the five representative pyroxenes. Unit-cell parameters were obtained from least-squares refinement of the X-ray diffraction powder data (Evans, Appleman, and Handwerker, 1963), and these values are given in table 4. As would be expected, the cell volumes of the acmitic pyroxenes and the omphacites are appreciably larger than those of jadeites and jadeitic pyroxenes.

The crystal structure of jadeite has recently been refined by Prewitt and Burnham (1966); the space-group symmetry is $C2/c$, and the structure is that established for diopside by Warren and Bragg (1928). However, single-crystal, X-ray diffraction photographs of seven California omphacites (Coleman and others, 1965) reveal the presence of weak reflections violating $C2/c$ symmetry (that is, having hkl with $h + k = 2n + 1$, and $h0l$ with $l = 2n + 1$). A crystal structure refinement of one of these omphacites has been carried out in space-group $P2$ (Clark and Papike,

1966) and demonstrates that the crystal has an ordered arrangement of cations, with a formula idealized to $\text{Na}_{0.5}\text{Ca}_{0.5}(\text{Mg},\text{Fe}^{2+})_{0.5}(\text{Al},\text{Fe}^{3+})_{0.5}\text{Si}_2\text{O}_6$. The M2 cation site that is occupied by Na in jadeite splits into four crystallographically distinct sites in *P2* omphacites, and so does the M1 site that is occupied by Al in jadeite. Neither the *P2* symmetry nor the cation ordering can be detected from examination of powder data alone, because the reflections violating *C2/c* symmetry are weak and do not appear on the powder patterns. Structural classifications among clinopyroxenes on the basis of powder data were attempted by Ginzburg and Sidorenko (1964); without single-crystal studies, such classifications are unlikely to be useful, because the initial assumptions are incorrect.

Finally, a word of caution concerning interpretation of data for jadeitic pyroxenes is in order, following preliminary single-crystal examination of a jadeitic pyroxene from a tectonic block at Valley Ford, California. The single-crystal patterns revealed the presence of two phases, tentatively identified as jadeite and an amphibole, coexisting in a crystal that was considered representative and a homogeneous sample. Optical examination showed strong dispersion and a lower birefringence than for pure jadeite, but the presence of two phases was not detected optically. The existence of a natural compositional gap between omphacite and jadeitic pyroxene may indicate a solvus between jadeite and diopside. Thus two-pyroxene rocks can be anticipated within the blueschist facies. Pyroxene samples presented in this paper appear to be one phase as determined by single crystal X-ray and optical determinations, and as yet the authors have not discovered a two-pyroxene rock.

Optical and physical properties.—The optical measurements were made with sodium light, and the index of refraction liquids were checked with the Abbé refractometer. The pyroxene indices of refraction are considered reliable to ± 0.003 , although accurate and reproducible optical determinations on these pyroxenes, particularly the omphacites, were difficult because postmetamorphic deformation of the crystals produced patchy extinction patterns. The increase in indices from jadeite to omphacite (table 4) is probably largely due to the substitution of Fe for Al in the pyroxene structure. The acmitic pyroxene has indices of refraction close to those of omphacite, although its powder pattern resembles that of jadeite.

Erratic variations of the optic axial angles and the extinction angles $Z_{\wedge c}$ (table 4) were found during measurements of these pyroxenes. Comment has already been made on the strong dispersion and lower birefringence of the jadeitic pyroxene from the metagraywackes, and a possible cause suggested. The metagraywacke jadeitic pyroxenes characteristically exhibit such optical anomalies, and early petrologists were thus led to identify the pyroxene incorrectly as clinozoisite.

The specific gravities (table 4) show little variation from jadeite to omphacite, because the mass and volume both increase, and thus the density remains approximately constant.

TABLE 3
X-ray diffraction powder data* for pyroxenes from the blueschist facies, California

Mono- clinic <i>C2/c</i>	Serpentinites				Metagraywackes		Metabasalts			
	Clear Creek, New Idria district, San Benito County				Angel Island, San Francisco Bay		Ward Creek, Sonoma County		Tiburon Peninsula, Marin County	
	Jadeite R-1854		Jadeitic pyroxene R-1853		Jadeitic pyroxene B-48		Acmitic pyroxene 15-CZ-60		Omphacite 100-RGC-58	
hkl	d observed (Å)	Peak height	d observed (Å)	Peak height	d observed (Å)	Peak height	d observed (Å)	Peak height	d observed (Å)	Peak height
110	6.22	15	6.27	10	6.20	30	6.31	55	6.38	15
200	4.50	5								
$\bar{1}11$	4.35	5								
020	4.29	45	4.32	15	4.31	20	4.35	25	4.40	40
021	3.250	5	3.266	5	3.263	5	3.34	10	3.317	10
220	3.104	30	3.124	10	3.117	15	3.163	20	3.179	100
$\bar{2}21$	2.922	75	2.934	70	2.931	95	2.954	35	2.970	100
310	} 2.831	100	} 2.845	100	} 2.841	100	2.880	100	2.893	90
$\bar{3}11$							2.860	70	2.872	35
$\bar{2}02$	2.527	2								
$\bar{1}31$	} 2.490	20	} 2.501	35	} 2.497	30	} 2.515	20	2.541	35
002									2.521	15
221	2.417	25	2.431	25	2.427	30	2.453	20	2.474	50

311	2.206	10	2.214	15	2.214	10	2.259	5	2.258	15
112, 022	2.161	5	2.168	10	2.168	10	2.183	5	2.193	5
330, 331	2.069	30	2.079	15	2.076	20	2.106	20	2.112	60
421	2.046	10			2.055	10	2.086	20	2.082	15
402	1.993	2	2.003	5	2.001	5	} 1.998	15	} 2.014	20
041	1.968	15	1.979	10	1.978	10				
202					1.953	2				
132	1.930	2								
241	1.887	5	1.899	2	1.896	5				
511	1.839	2			1.846	2				
422					1.815	2				
510, 132	1.761	10	1.770	5	1.767	10	1.795	10	1.799	25
150	1.684	10	1.697	5	1.693	10	1.718	15	1.726	40
313, 312	1.651	2	1.658	2	1.657	5				
042, 151	1.624	5							1.659	2
223	1.611	5	1.616	5	1.615	2			1.626	2
531	1.572	20	1.581	10	1.579	15	1.598	15	1.602	30
440	1.552	15	1.559	5	1.558	5	1.583	15	1.588	30
530									1.555	2
600	} 1.499	10	} 1.505	5	} 1.505	5			1.529	10
602										
350	1.488	10							1.525	20

* Diffractometer patterns, $\text{CuK}\alpha$ 1.5418Å or $\text{CuK}\alpha_1$ 1.5404Å; internal standards LiF or CaF_2 used. Indexing based on values calculated from cell constants given in table 4 by comparison with single crystal photographs and calculated powder intensities. Patterns for the jadeitic and aegiritic pyroxenes contained a few peaks not due to pyroxene; some were identified as probably due to sphene and quartz, associated minerals. Variations in peak heights among the samples therefore should not be considered significant.

TABLE 4
Cell constants* and optical data** for pyroxenes from the
blueschist facies, California

Space Groups	Serpentinites		Metagraywackes	Metabasalts	
	Jadeite*** R-1854	Jadeitic pyroxene R-1853	Jadeitic pyroxene B-48	Ward Creek, Sonoma County Acmitic pyroxene 15-CZ-60	Tiburon Peninsula, Marin County Omphacite 100-RGC-58
	<i>C2/c</i>	<i>C2/c</i>	<i>C2/c</i>	<i>C2/c</i>	<i>P2</i>
<i>a</i> (Å)	9.437 ± 6	9.486 ± 8	9.468 ± 6	9.58 ± 2	9.596 ± 6
<i>b</i> (Å)	8.574 ± 6	8.622 ± 6	8.616 ± 6	8.75 ± 2	8.771 ± 6
<i>c</i> (Å)	5.225 ± 6	5.241 ± 4	5.240 ± 4	5.36 ± 5	5.265 ± 6
β	107° 35' ± 5'	107° 35' ± 5'	107° 32' ± 5'	107° 01' ± 10'	106° 56' ± 5'
Cell Volume (Å ³)	403.0	408.6	407.6	425.3	423.9
Specific gravity (observed)	3.33	3.33	3.32	3.30	3.34
α	1.654	1.679	1.670	1.677	1.682
β	1.656	1.681	1.671	1.679	1.689
γ	1.666	1.685	1.678	1.685	1.705
2 <i>V</i> (observed)	70°	64°	60-68°	74°	69°
<i>Z_Ac</i>	35°	38°	40°	49°	48°
Dispersion	none	r > v, strong	r > v, strong	r > v, strong	r > v, weak

* Cell constants obtained from least-squares refinement of powder data, following a computer program by Evans, Appleman, and Handwerker, 1963 (except that the values for omphacite are taken from single-crystal measurements); the given error applies in the last figure, that is, 9.437 ± 6 stands for 9.437 ± 0.006Å.

** Indices of refraction measured at 25°C using Na light; errors estimated as ± 0.003.

*** The cell constants given by Prewitt and Burnham (1966) for jadeite of composition (Na_{0.98}Ca_{0.02})(Al_{0.99}Mg_{0.01})(Si_{1.99}Fe³⁺_{0.01})O₆ from the Santa Rita Peak area of the New Idria district, California, are *a* = 9.418 ± 0.001, *b* = 8.562 ± 0.002, *c* = 5.219 ± 0.001Å, β = 107.58 ± 0.01°, *V* = 401.20 ± 0.15Å³.

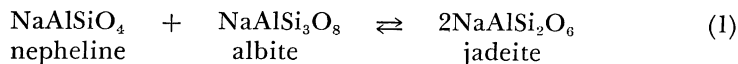
PARAGENESIS

Jadeite, jadeitic pyroxene, omphacite, and aegirine-augite are the characteristic pyroxenes of this high-pressure blueschist metamorphism in California. Even though apparently unique in the widespread occurrence of aragonite, the California blueschist metamorphism does have remarkable similarities to mineral assemblages of blueschist areas elsewhere in the world. The earlier descriptions and discussions of pure jadeite from Burma (Bleek, 1907; Lacroix, 1930), Japan (Iwao, 1953; Seki and Shido, 1959; Chihara, 1960), China (Schuller, 1961), and Guatemala (Foshag, 1957) make it clear that pure jadeite forms within serpen-

tinites associated with blueschists. The occurrence and documentation of the presence of pure jadeite in U.S.S.R. serpentinite bodies similar to those in California, Burma, and Japan have been summarized by Dobretsov (1964). The Borus serpentinites of West Sayan, U.S.S.R., include metasomatized leucocratic inclusions that contain pure jadeite. The serpentinite bodies are surrounded by amphibolite facies associated with minor blueschists (Dobretsov, 1963). In the Pay-Er ultramafic massive, Polar Urals, U.S.S.R., pure jadeite is contained in metasomatized gabbros and albitites within serpentinite, closely associated with blueschists and eclogite-like rocks (Morkovkina, 1960). The Kenterlauss serpentinite massif, Lake Balkash region, U.S.S.R., contains tectonic inclusions of metasomatized leucocratic rocks containing pure jadeite associated with blueschists (Moskaleva, 1962; Dobretsov and Ponomareva, 1965). As might be anticipated, these serpentinite masses containing jadeite are related to narrow elongate belts of high-pressure metamorphism, including blueschists (Dobretsov and others, 1966). There now seems little doubt that pure end-member jadeite is restricted to silica-undersaturated, metasomatized, leucocratic masses contained within serpentinites. The metasomatic alteration and serpentinitization are contemporaneous with the tectonism accompanying blueschist metamorphism. The appropriate bulk compositions within the leucocratic masses reflect exchange of material between serpentinite and inclusions, but the stabilization of jadeite depends fundamentally upon the maintenance of appropriate pressure-temperature conditions.

Jadeitic pyroxene coexisting with quartz within metagraywackes of these narrow blueschist metamorphic belts was first discovered by de Roever (1955) in the eastern Celebes; Bloxam (1956) reported a similar occurrence in California. Later Seki and Shido (1959) and Seki (1960) discovered jadeitic pyroxene in the metagraywackes of the Sanbagawa and Kumikotan metamorphic belts of Japan. The occurrence of glaucophane schist has long been known in the western Alps, but only recently has jadeitic pyroxene (Lorenzoni, 1963; Lefèvre and Michard, 1965) been reported from metagraywackes and metarhyolites and, in particular, in the external border of the Penninic Zone (Bearth, 1966). The jadeitic pyroxene of these metagraywackes is not pure $\text{NaAlSi}_2\text{O}_6$ but contains more than 10 mole percent of other pyroxene components and coexists with quartz together with lawsonite, glaucophane, albite, and white mica. Omphacites (chloromelanites) and acmitic pyroxenes have been reported from blueschists within the high-pressure blueschist belts, and as in California omphacite is usually restricted to rocks of basaltic composition (Bearth, 1959; Chesnokov, 1959; Iwasaki, 1960). Coleman and others (1965) have clarified the relationships between the blueschist eclogites and eclogites of other origins. Omphacites from the blueschist eclogites are richer in jadeite and coexist with garnets containing less pyrope (< 20 mole percent) than is typical of eclogites formed under different pressure-temperature conditions.

Experimental work on pure jadeite has left little doubt that its formation must be favored by high pressures. The stability of jadeite in the silica-deficient environment of the serpentinite occurrences is limited by the equilibrium reaction



The equilibrium curve for this reaction has been determined by the experimental results of Robertson, Birch, and MacDonald (1957) (fig. 2). Even though the calculated curve from the thermochemical data of Kelly and others (1953) does not coincide with the experimental curve, the results from both methods indicate that crystallization of pure jadeite in the silica-undersaturated environment of serpentinites is thermochemically possible at pressure-temperature conditions expected

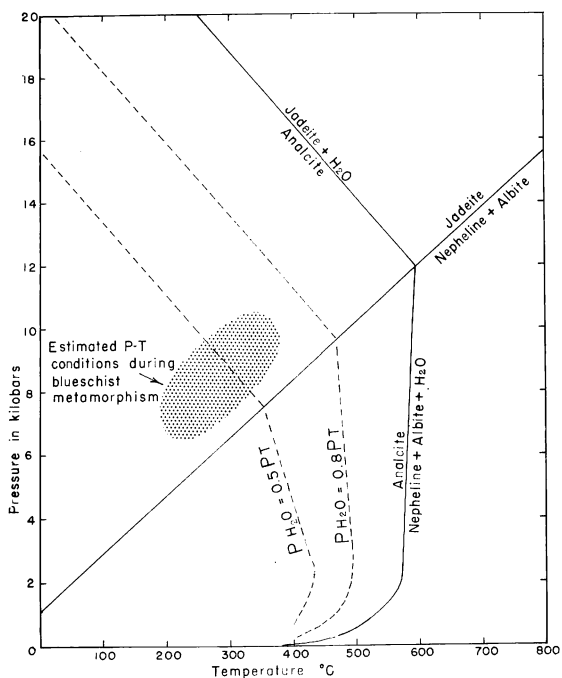
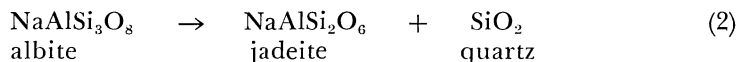


Fig. 2. Pressure-temperature diagram showing equilibrium curves determined experimentally and by thermodynamic calculations. The reactions presented are those that may be characteristic of a silica-deficient environment where jadeite forms within leucocratic masses within serpentinite. The nepheline + albite → jadeite curve is from Robertson, Birch, and MacDonald (1957), the nepheline + albite + H₂O → analcite curve is from Yoder (1964), and the analcite → jadeite + H₂O curve is from Griggs and Kennedy (1956). Dobretsov (1966) has calculated the effect of reducing the partial pressure of water on the two analcite curves, and his calculations at P_{H₂O} = 0.8 PT and P_{H₂O} = 0.5 PT are shown as dashed lines.

within the Earth's crust. When water is present with variable activity during the formation of jadeite within serpentinites, analcite may be present in close association with jadeite (Coleman, 1961; Dobretsov, 1964). If the partial pressure of water is equal to the total pressure, the field of stability for analcite is greatly enlarged (fig. 2). Should the partial pressure of water drop below that of the total pressure, the stability field of jadeite becomes enlarged and that for analcite is restricted (Dobretsov, 1966). The experimental work on the system $\text{NaAlSi}_2\text{O}_6\text{-H}_2\text{O-argon}$ by Greenwood (1961) demonstrates the constriction of the analcite stability field by lowering the partial pressure of water.

For the jadeitic pyroxenes occurring in the metagraywackes, the reaction



most nearly approximates the natural situation. Considering the fact that none of the jadeitic pyroxenes from metagraywackes appear to be pure jadeite in equilibrium with quartz (Coleman, 1965; Bloxam, 1956; Lefèvre and Michard, 1965; Lorenzoni, 1963), the breakdown of pure albite to form jadeite + quartz places the upper limit of the blueschist facies at the equilibrium curve of reaction (2) (fig. 3). Coleman (1965) suggested that substitution of significant amounts of other pyroxene components would lower the pressure necessary to produce a jadeitic pyroxene in equilibrium with quartz (fig. 3). Assuming that formation of the jadeitic pyroxenes in serpentinites and metagraywackes are contemporaneous, it seems unlikely that the pressure-temperature conditions are widely disparate, and therefore the reduction of the pressure required for the equilibration line of reaction (2) by solid solution of pyroxene components lies somewhere between the calcite-aragonite and albite \rightarrow jadeite + quartz equilibrium curves.

Experimental work of Kushiro (1965) on the diopside-albite join shows that 10 to 20 mole percent diopside solid solution in jadeite produces only a slight lowering of the jadeitic pyroxene + quartz stability curve. On the other hand, experimental work by R. C. Newton (University of Chicago, written communication, 1967) has shown that jadeitic pyroxene of the composition $\text{Jd}_{82}\text{Ac}_{14}\text{Di}_4$ in equilibrium with quartz has a stability curve approximately 1 kilobar below that for pure jadeite + quartz.

Pressure-temperature conditions of blueschist metamorphism have been estimated by various methods (Ernst and Seki, 1967; Coleman, 1967), and it is generally agreed that the temperatures probably range from 200° to 300°C and pressure 6 to 9 kilobars. The temperature has been estimated by $\text{O}^{18}/\text{O}^{16}$ fractionation temperature curves for quartz-carbonate pairs from the Cazadero blueschists (Hugh P. Taylor, California Institute of Technology, written communication, 1966). When aragonite is present in equilibrium with the pyroxenes, a minimum pressure can

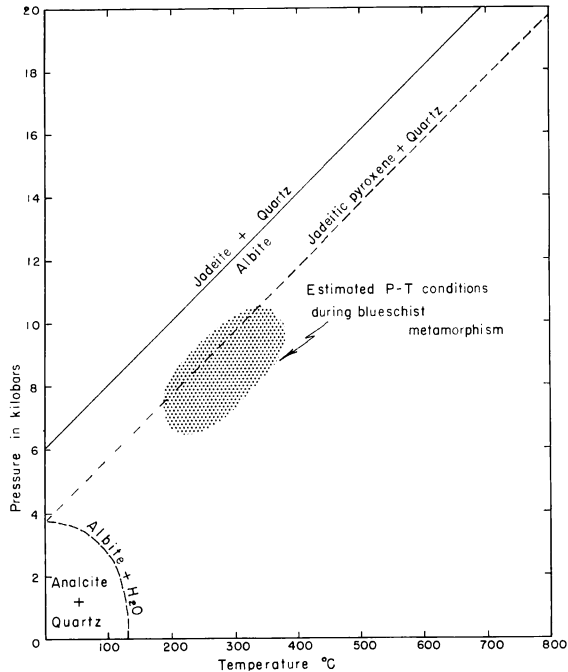


Fig. 3. Pressure-temperature diagram showing equilibrium curves determined experimentally by thermodynamic calculations and petrographic evidence. The reactions presented are those that may be characteristic of a silica-rich environment where jadeitic pyroxene forms within the metagraywackes. The albite \rightarrow jadeite + quartz reaction is from the experimental work of Birch and LeComte (1960), and the dashed line representing jadeitic pyroxene + quartz is inferred from petrographic evidence (Coleman, 1965). For the reaction analcite + quartz \rightarrow albite + H₂O, the experimental work of Hemley as presented at the Geological Society of America meetings (Hemley, 1966) and Campbell and Fyfe (1965) are combined to provide an estimate for the dashed line curve. The lower temperature shown for the reaction analcite + quartz \rightarrow albite + H₂O is from Hemley's unpublished data.

be estimated, and as pure jadeite + quartz does not exist, the maximum pressure is fixed by reaction (2). Segregations and veins containing the assemblage quartz + albite + aragonite are present within metagraywackes having quartz + jadeitic pyroxene + lawsonite + white mica assemblage. In the serpentinites, assuming contemporaneity of metamorphism, the presence of pure jadeite sets a lower limit with its breakdown curve (reaction (1), fig. 2).

The presence of albite in segregations and veins instead of quartz + pure jadeite in the blueschist facies indicates that the pressure-temperature conditions attained during metamorphism are geologically reasonable. Further experimental work on the effect of substitution in jadeitic pyroxenes may provide a more precise estimate of pressure-temperature conditions during metamorphism.

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NOTE ADDED IN PROOF

Since this paper went to press several other papers related to blueschist facies pyroxenes have appeared in print. Although the results reported are in general accord with the conclusions presented here, these references are added for the reader's convenience.

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