THE AMERICAN MINERALOGIST, VOL. 53, JULY–AUGUST, 1968

ECLOGITE AND ALMANDINE-JADEITE-QUARTZ ROCK FROM THE GUAJIRA PENINSULA, COLOMBIA, SOUTH AMERICA

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ABSTRACT

Large boulders of eclogite in Tertiary conglomerate in the Guajira Peninsula, Colombia, are considered to be derived from a metamorphic sequence (Etpana Formation) of albite-epidote-amphibolite and greenschist facies and containing local serpentinite lenses. Two examples of the eclogitic rocks and their constituent garnet and pyroxene have been chemically analysed. One rock, with a bulk chemical composition approaching that of sodic trachyte, consists of almandine, jadeite ($Jd_{68}Ac_{14}$) and quartz as major phases, and minor primary scapolite, calcite, clinozoisite+paragonite, apatite, rutile and hematite. The association of very jadeite-rich pyroxene with almandine garnet is unique among eclogitic rocks. The second rock has a bulk chemical composition of alkali olivine basalt or hawaiite and contains primary almandine+omphacite ($Jd_{38}Ac_8$)+rutile. The eclogitic rocks are similar to those described from glaucophane schist terranes of California and elsewhere. The mineral parageneses and element partition relationships are used to estimate conditions of crystallization of the eclogitic rocks as $p_{total}=7$–12 kbars, $p_{H_2O} \ll p_{total}$ and $T=200$–$400°C$. The almandine+omphacite+rutile eclogite shows partial alteration to an albite-epidote-amphibolite assemblage.

INTRODUCTION

During mapping in the Guajira Peninsula of Colombia, one of the authors (J. P. L.) discovered large boulders of eclogite in middle Tertiary conglomerate bordering the Cerros de Parashi. The distribution of the conglomerate and demonstration of very local provenance for coarse detritus within it (Lockwood, 1965), indicated that the source for the eclogite boulders lay within the Etpana Formation, a group of phyllites of albite-epidote-amphibolite and greenschist facies of regional metamorphism which also contains local serpentinite lenses.

Recent studies of natural eclogites (Coleman *et al.*, 1965; Banno and Matsui, 1965) and an experimental study of the gabbro to eclogite transformation (Green and Ringwood, 1967) have concluded that the characteristic eclogite mineralogy of pyrope-almandine garnet+omphacite ±quartz forms over a wide range of p, T conditions. In particular, it has

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been inferred (Green and Ringwood, 1967) that eclogites could form stably in dry ($p_{\mathrm{H_2O}} \ll p_{\mathrm{load}}$) basaltic rocks in metamorphic terranes classifiable as within the amphibolite, albite-epidote-amphibolite, greenschist and lawsonite-glaucophane schist facies, assuming that the latter hydrous assemblages formed in country rocks in which $p_{\mathrm{H_2O}} \approx p_{\mathrm{load}}$. The examination of natural eclogites associated with rocks of different metamorphic facies may establish criteria by which eclogites formed under very different p_{load}, T conditions can be recognized. For this purpose we have chemically analyzed the Guajira eclogites and their constituent minerals.

GEOLOGICAL SETTING

The eclogite specimens are from a middle Tertiary conglomerate 6.3 km north of the village of Parashi and near the northwestern margin of the Guajira Peninsula (Fig. 1). In this area the eclogites are abundant constituents of the conglomerate and are associated with boulders of quartzite, calcareous meta-argillite and serpentinite which are identical to rock types of the Etpana Formation outcropping nearby. Also associated are boulders of quartz diorite and dacite porphyry from the Parashi quartz

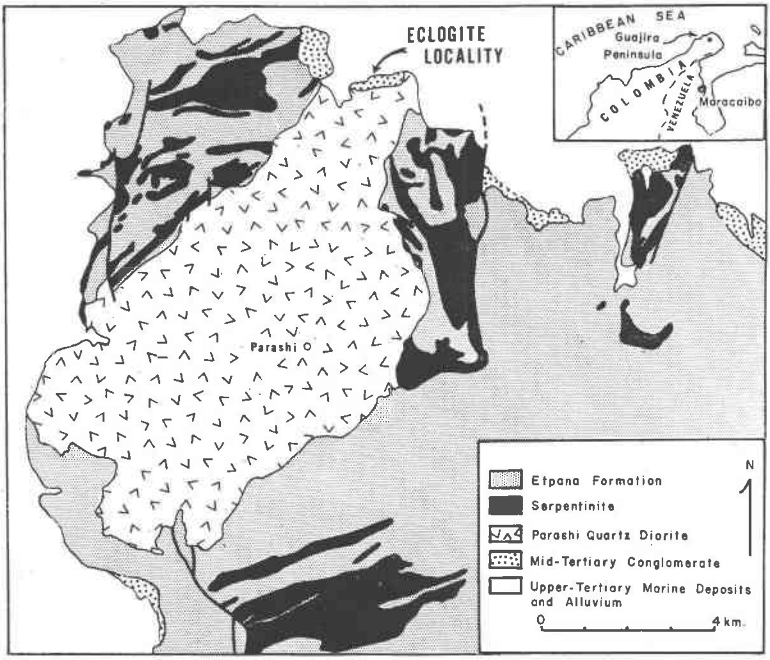

FIG. 1. Geologic sketch map of the Parashi area, Guajira Peninsula, showing the location of eclogite-bearing conglomerate.

diorite, a mid-Eocene (48±4 m.y.) stock which intrudes the Etpana Formation. The conglomerate is very coarse, and some eclogite boulders reach 50 cm in diameter. It is believed that the eclogites are derived from within the Etpana Formation, possibly from a higher level, since eroded away (Lockwood, 1965). Efforts to locate *in situ* sources for the eclogite boulders were unsuccessful.

The Etpana Formation originally consisted of a thick series of finely bedded shales and quartz sandstones with local tuffaceous beds. Its age is believed to be Mesozoic, and possibly Cretaceous, but no fossils have been found. This series has been regionally metamorphosed in Late Cretaceous or earliest Tertiary time to yield phyllites including the following mineral assemblages:

1. quartz-albite-biotite-muscovite-(sericite)-(chlorite)
2. albite-epidote-chlorite-(biotite)-(actinolite)-(calcite)
3. quartz-albite-epidote-biotite-almandine
4. quartz-biotite-muscovite-almandine
5. albite-epidote-biotite-hornblende (blue green)

These assemblages are indicative of a range of metamorphic conditions from the greenschist facies (1, 2) to the albite-epidote-amphibolite facies (5) using the nomenclature of Fyfe and Turner (1966). Regional metamorphism of serpentinites within the Etpana Formation is most obvious within the area of albite-epidote-amphibolite facies and emplacement of these bodies predates the regional metamorphic effects. Glaucophane schist has not been reported in the Guajira Peninsula but it may be relevant that Dengo (1950) described garnet amphibolites containing glaucophane and sodic-pyroxene from near Caracas, Venezuela. Although this area lies about 500 km east of Guajira Peninsula, the Mesozoic reconstruction of the northern Andean and Caribbean orogenic regions by Carey (1958) would place the two eclogite areas about 50 km or less apart.

PETROGRAPHY

The eclogites consist of deep red garnets set in fine-grained, grey-green aggregates mainly of pyroxene. The garnets are euhedral, and in some examples are large. well-formed crystals showing near perfect rhombdodecahedral form. Some eclogites contain coarse crystals (to 3 cm) of a yellow-green epidote-group mineral. There is a strong preferred orientation of pyroxene crystals and a tendency to lenticular or streaky inhomogeneity in abundance of the main phases.

A.N.U. 2832 (JPL J-291A)

This rock consists of about 15 percent of euhedral, very large (to 1.5 cm) garnets set in very fine grained (0.01 to 0.05 mm) pyroxene and quartz. The pyroxene and quartz are inhomogeneously distributed and there are lenticular patches (1–3 mm) in which calcite is locally an important phase. The garnet has a deep red core and paler margin. The outer one-fourth to one-third is virtually free of inclusions but the inner zone has abundant quartz and rutile and minor apatite and pyroxene. Refractive index and the unit cell dimension of the garnet also vary from rim to core (Table 2). Some pyroxene crystals, particularly the larger ones, have concentric or patchy zoning—the nature of this zoning has not been determined.

The rock is remarkably fresh and shows no kelyphitic or grain-boundary alteration of either pyroxene or garnet.

The following minor or accessory minerals are present:

Scapolite is a very widely distributed accessory constituent as very small, anhedral grains associated with the quartz and pyroxene. Textural relations indicate that it is in equilibrium with pyroxene and quartz. Scapolite is more abundant near calcite patches.

Clinozoisite is very rare but forms moderately large (≈ 1 mm) poikiloblastic crystals with euhedral outer margins and common inclusions of quartz and pyroxene. It is intimately intergrown with colorless *paragonite* crystals. The identification of paragonite is based on quantitative electron microprobe analysis: $Na_2O = 5.2 \pm 0.3\%$, $K_2O = 0.2 \pm 0.1\%$, $Fe_2O_3 = 0.2 \pm 0.1\%$. Paragonite only occurs in close proximity or intergrowth with clinozoisite. The intimate and local association of clinozoisite and paragonite is suggestive of replacement of pre-existing *lawsonite* porphyroblasts according to the reaction

$$4\ \underset{\text{lawsonite}}{CaAl_2Si_2O_8 \cdot 2H_2O} + \underset{\text{jadeite}}{NaAlSi_2O_6} \rightleftharpoons \underset{\text{clinozoisite}}{2Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{paragonite}}{NaAl_3Si_3O_{10}(OH)_2}$$

$$+ \underset{\text{quartz}}{SiO_2} \quad + \underset{\text{water vapor}}{6H_2O}$$

Watson (1960) has reported eclogites containing lawsonite from the serpentinized breccia diatremes of Arizona, and Newton and Kennedy (1963) noted incipient marginal alteration of this lawsonite to zoisite.

Calcite was identified by X-ray powder diffraction and aragonite was not observed.

Rutile is a common minor constituent occurring randomly throughout garnet or pyroxene-rich areas and also in small stringers or lenses in the pyroxene-rich areas.

Hematite occurs rarely as single or clusters of grains. The grains are polycrystalline and formed from 6–10 crystals in radial growth. In several cases the radial growth of hematite is centered on relict cores of pyrite.

Apatite is a minor accessory mineral, locally (in quartz patches) forming quite large subhedral crystals.

It is inferred that the assemblage garnet, pyroxene, quartz, scapolite, clinozoisite+paragonite (or lawsonite) rutile, hematite, apatite was a primary mineral assemblage representing equilibrium or a close approach thereto. Calcite may have inverted from aragonite.

A.N.U. 2833 (JPL J-291)

This eclogite contains much more garnet than the previous example and quartz is absent. Garnet is euhedral and medium-grained (0.5–3 mm) and the pyroxene is finer grained (0.05–0.3 mm) subhedral, and shows a strong preferred orientation. Garnet has a deeper pink color in the cores of crystals than at the margins and some pyroxene crystals are also distinctly zoned. Optical properties of both minerals vary from rim to core (Table 1). Rutile and apatite are common accessory minerals and there are very rare laths of glaucophane, either in association with pyroxene or included in the garnet crystals.

TABLE 1. CHEMICAL COMPOSITIONS, CIPW NORMS AND APPROXIMATE MODES OF GUAJIRA "ECLOGITES"

Analyses				Norms		
	2832	2833			2832	2833
SiO_2	59.47	47.45		Qz	6.8	—
TiO_2	0.32	0.77		Or	0.1	0.4
Al_2O_3	14.09	14.61		Ab	59.2	24.2
Fe_2O_3	4.04	2.4^{b}	(5.33)^{a}	Ne	—	4.2
FeO	5.21	12.6^{b}	(9.76)^{a}	An	7.0	22.7
MnO	0.17	0.27		Di	9.7	24.2
MgO	2.44	6.69		Hy	7.3	—
CaO	5.16	10.48		Ol	—	18.5
Na_2O	7.00	3.80		Ilm	0.6	1.4
K_2O	0.01	0.06		Mt	5.9	3.5
P_2O_5	0.26	0.04		Ap	0.6	—
H_2O^+	0.50	0.58		Calcite	1.9	—
H_2O^-	0.03	0.05		Rest	0.5	0.6
CO_2	0.84	0.01		APPROXIMATE MODES		
Cr_2O_3	0.002	0.003		Qz	22	—
				Cpx	57	58
	99.54	99.81		Ga	17	41.5
				Rest	4	0.5
$\frac{100\,Mg}{Mg+Fe^{2+}}$ (atomic ratio)	45.5	49				
Normative plagioclase components	$Ab_{90}An_{10}$	$Ab_{56}An_{44}$				

[a] FeO, Fe_2O_3 contents determined by chemical analysis.
[b] FeO, Fe_2O_3 contents calculated from mineral analyses and mode.

Unlike the previous example, specimen 2833 shows quite extensive but very patchy secondary alteration of garnet, pyroxene and rutile. The alteration products do not show the characteristic kelyphitic intergrowth frequently observed in eclogites. The most common secondary minerals are albite, epidote, blue-green hornblende, and sphene. Some garnets are partly altered to hornblende but others are almost completely replaced by areas of albite, epidote and hornblende. The rare crystals of glaucophane also show marginal alteration to blue-green hornblende. Rutile is commonly rimmed or completely replaced by sphene.

CHEMICAL COMPOSITIONS OF ROCKS AND MINERALS

The whole-rock compositions of the two specimens (2832 and 2833) are given in Table 1, together with their CIPW. norms and approximate modes calculated from the rock and mineral analyses. Specimen 2832 is virtually unaltered and the Fe_2O_3 and FeO contents calculated from the mineral analyses are in good agreement with the analyzed FeO and Fe_2O_3 contents. The observed secondary alteration in specimen 2833 is apparently accompanied by oxidation of the FeO since the measured Fe_2O_3 content is considerably greater than that calculated from the mode and mineral analyses.

The composition of specimen 2832 is unique in comparison with other garnet+pyroxene or garnet+pyroxene+quartz assemblages. The high SiO_2 content coupled with very high Na_2O and low CaO and MgO contents denote a composition which cannot be classified, even loosely, as basaltic. This is further reinforced by the calculation of the CIPW. norm. On the other hand, apart from the K_2O content, the composition and CIPW. norm of 2832 are comparable with compositions of sodic trachytes or possibly benmoreite. There are no relict textures preserved but the observed tendency for calcite to occur in lenticular patches suggests that calcite amygdules may originally have been present.

Eclogitic rocks showing similarity in some components with 2832 include a banded pyroxene-bearing glaucophane schist from California (Coleman, Lee, Beatty and Brannock, 1965, p. 490 56-CZ-59), an oligoclase-omphacite-garnet-quartz "eclogite" from East Sudetes (Kozlowski, 1958, p. 726) and an eclogite inclusion in a basaltic diatreme from Utah (O'Hara and Mercy, 1966a, p. 342). None of these examples share with 2832 the combination of high Na_2O and high SiO_2 content and all differ in mineralogical detail from 2832.

The chemical composition of specimen 2833 is similar to many other eclogites in the literature, and, except for its very low K_2O content is typically "basaltic." More specifically the chemical composition and CIPW. norm of 2833 are closely comparable with hawaiite. Low K_2O content is a common characteristic of many eclogitic rocks and may be due to mobility of this component during garnet+pyroxene crystallization.

Garnet compositions. It was possible in both specimens to obtain garnets of very high purity, the only observed contaminant being minor, very small needles of rutile. The two garnets are of remarkably similar composition (Table 2), despite differences in bulk chemical composition of the host rocks. Both are characterized by very high FeO, moderate MnO and low MgO contents. Calculation of structural formulae gives a satisfactory check on the analyses, but requires that some Fe^{3+} enter the divalent ion positions. This is commonly found in almandine garnet analyses (*cf.* Deer, Howie and Zussman, 1961, p. 86) but may be due to the difficulty of getting garnet completely into solution under inert atmosphere conditions.

Both analyzed garnets are almandines with low to moderate grossular +andradite contents, low pyrope and very low spessartine contents. Almandine contents are higher, grossular contents are lower and pyrope contents are similar to those in garnets reported by Coleman *et al.*, (1965) from eclogites associated with glaucophane schists (Fig. 2). On the other hand, the garnets analyzed by O'Hara and Mercy (1966) from inclusions in basaltic diatremes have lower grossular contents than the Colombian garnets, lower almandine contents and higher pyrope contents (fig. 2).

Samples were hand-picked from the core and rim of the coarse garnet in 2832 to determine the narure of the strong color zoning. Comparison of the measured values of refractive index and unit-cell dimension from rim and core (Table 2) with the diagrams of Sriramadas (1957) indicates that the cores are enriched in almandine and depleted in pyrope relative to the rims. The compositional zoning in garnet 2832 is probably similar.

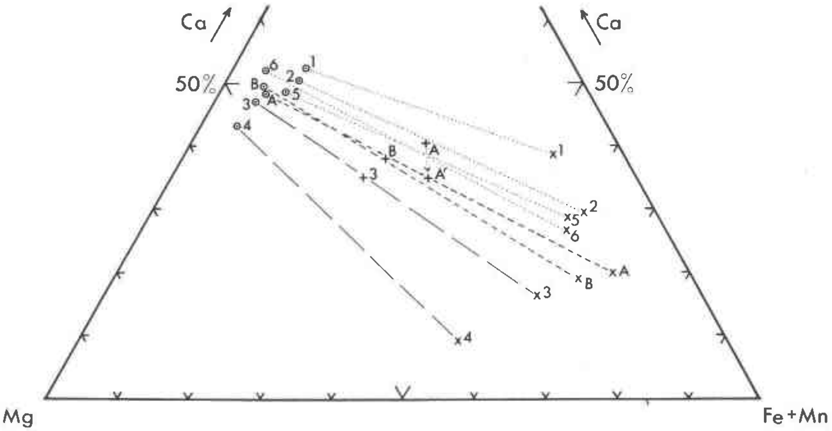

FIG. 2. Ca-Mg-(Fe+Mn) diagram (atomic proportions) illustrating the compositions of coexisting garnet (×), clinopyroxene (⊙) and host-rock (+) in eclogites of "low temperature type"

A. Colombia specimen 2832 (A'-replot without Ca as $CaCO_3$)
B. Colombia specimen 2833
1. California No. 113-RGC-58. Coleman et al 1965.
2. New Caledonia No. 36-NC-62, Coleman et al 1965.
5. California No. 100-RGC-58, Coleman et al 1965.
6. Urals, U.S.S.R. Shubina Village, Chesnokov, 1959.
3. Arizona No. G.R.1, O'Hara and Mercy, 1966a.
4. Arizona No. G.K. 6, O'Hara and Mercy, 1966a.

TABLE 2. CHEMICAL COMPOSITIONS, STRUCTURAL FORMULAE AND PROPORTIONS OF GARNET END-MEMBERS IN GARNETS FROM GUAJIRA "ECLOGITES"

	2832 Ga	2833 Ga			2832 Ga	2833 Ga
SiO_2	37.67	37.98	Z	Si	3.008	3.005
TiO_2	0.46	0.49		Al	—	—
Al_2O_3	20.63	20.69	Y	Al	1.942	1.929
Fe_2O_3	2.31	1.79		Ti	.024	.026
FeO	28.41	27.53		Fe^{3+}	.034	.045
MnO	0.58	0.67	X	Fe^{3+}	.105	.061
MgO	2.49	3.91		Fe^{2+}	1.897	1.822
CaO	6.66	6.48		Mn	.039	.045
Na_2O	0.13	0.08		Mg	.297	.461
K_2O	n.d.	n.d.		Ca	.570	.550
P_2O_5	0.087	0.025		Na	.020	.012
Cr_2O_3	n.d.	n.d.			*Molecular Proportions*	
H_2O^-	0.53	0.04		Almandine	69	64
				Andradite	2	2
	99.96	99.69		Grossular	18	16.5
				Pyrope	10	16
				Spessartine	1	1.5
					Physical Properties	
$\frac{100\ Mg}{Mg+Fe^{2+}}$ (atomic)	13	20		n_{rim}	1.789±0.002	1.786±0.003
				n_{core}	1.802±0.002	1.800±0.003
				$a_{o_{rim}}$	11.588±0.002	
				$a_{o_{core}}$	11.603±0.002	
Mg/Fe^{2+} (atomic)	0.16	0.25		$a_{o_{aver}}$	11.595±0.002	11.589±0.002

Pyroxene compositions. The extremely fine grain-size of specimen 2832 prevented complete purification of the clinopyroxene. Optical and X-ray powder examination showed the presence of quartz and rare apatite and rutile. Plagioclase was not detected. The analyzed concentrate (>90% pyroxene) was corrected by subtracting 0.2% apatite (indicated by the P_2O_5 content of 0.11% in the analyses) and 7.8% quartz (determined by calculation of the analysis to an ideal pyroxene composition+excess quartz). A pure pyroxene concentrate was obtained from specimen 2833.

Although both pyroxenes are rich in jadeite+acmite and both have very high $Mg/Mg+Fe^{2+}$ ratios (Table 3), they are very different chemically and reflect the different total rock compositions. The pyroxene from specimen 2833 is an omphacite, closely comparable with pyroxenes in eclogites associated with glaucophane schists of California and New

TABLE 3. CHEMICAL COMPOSITIONS, STRUCTURAL FORMULAE AND PROPORTIONS OF PYROXENE END-MEMBERS IN PYROXENES FROM GUAJIRA "ECLOGITES"

	2832 Px (Impure[a])	2832 Px (Corrected[a])	2833 Px
SiO_2	59.61	56.35	55.36
TiO_2	0.30	0.32	0.21
Al_2O_3	16.74	18.15	10.32
Fe_2O_3	4.81	5.22	2.86
FeO	0.70	0.75	2.05
MnO	0.03	0.03	0.007
MgO	2.60	2.83	8.73
CaO	4.02	4.23	13.49
Na_2O	11.16	12.11	6.56
K_2O	0.015	0.016	0.028
P_2O_5	0.11	0.00	0.005
Cr_2O_3	0.002	0.002	
H_2O^+	0.06	—	—
H_2O^-	—	—	0.03
	100.16	100.0	99.65
$\frac{100\ Mg}{Mg+Fe^{2+}}$ (atomic)		87	88.5
Mg/Fe^{2+} (atomic)		6.7	7.6

	2832 Px	2833 Px
Si	1.964	1.977
Al^z	.036	.023
Al^y	.709	.411
Ti	.008	.005
Fe^{3+}	.137	.077
Fe^{2+}	.022	.061
Mn	.001	.000
Mg	.147	.465
Ca	.158	.516
Na	.818	.454
K	.000	.001
XY	2.000	1.990

Molecular Proportions

	2832 Px	2833 Px
Acmite	14	8
Jadeite	68	38
Tschermak's silicate	3	2
Diopside	13	46
Hedenbergite	2	6

Optical Properties

	2832 Px	2833 Px
α (minimum)	1.671±0.002	1.672±0.002
β (average)	1.676±0.002	1.679±0.003
γ (maximum)	1.686±0.002	1.697±0.002
$2V_z$	73±0.5°	68–70°C[c]
$Z\wedge c$	49±1°	48–60°C

Unit cell parameters[b]

	2832 Px	2833 Px
a	9.494±.002 Å	9.596±.001 Å
b	8.623±.001 Å	8.783±.002 Å
c	5.223±.001 Å	5.266±.002 Å
β	107°26′±1′	106°54′±1′

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[a] The analyzed pyroxene concentrate (column 1) has been corrected for an admixture of 7.8% Quartz, 0.2% Apatite to yield the composition of column 2. [b] Unit cell values determined using USGS computer program No. 9214 (Least Squares Unit Cell Refinement) and an IBM 7090 computer at the Stanford University Computation Center. [c] In zoned crystals, $2V_{core} > 2V_{rim}$ and $Z\wedge c_{core} > Z\wedge c_{rim}$.

Caledonia (Coleman *et al.* 1965). The pyroxene falls near the maximum jadeite content of the eclogitic pyroxenes described by Coleman et al. The pyroxene from specimen 2832 is a jadeite (68 mole % jadeite) which has minor acmite (14%) and diopside-hedenbergite (15%) solid solution. We know of no previous report of such jadeitic pyroxene coexisting with garnet and quartz, but in its chemical composition, the jadeite is similar to the Clear Creek, New Idria, jadeite (Coleman 1961) and to other jadeite described by Coleman (1965) and Coleman *et al.* (1965). These examples of jadeite are not associated with garnet but commonly occur with glaucophane, albite, and crossite in tectonic inclusions in serpentinite. The most sodic pyroxenes coexisting with almandine-pyrope garnet previously described are those containing 9.01% Na_2O (50% Jd, 12% Ac) and 8.80% Na_2O (50% Jd, 10% Ac) from basaltic diatremes in Arizona and Utah (O'Hara and Mercy, 1966a). The latter two pyroxene compositions lie between the two Colombian examples—this is well illustrated on a triangular Jd–Ac–(Di+He+Tsch) plot (Coleman *et al.* 1965). The Guajira rocks thus greatly extend the compositional range of jadeite-bearing pyroxenes occurring in eclogitic rocks, *i.e.* in equilibrium with almandine-pyrope garnet and in the absence of plagioclase. It is emphasized that the high jadeite content of pyroxene 2832 is attributed directly to the particular bulk chemical composition of the rock 2832 and does not necessarily imply $p-T$ conditions of crystallization different from those of the eclogites and pyroxenes described by Coleman *et al.* (1965).

MATERIAL PARAGENESES AND ELEMENT PARTITION

Mg, Fe partition: The values of the partition coefficient $K'_{Mg,Fe}$[1] for the Guajira eclogites are 43 (2832) and 30 (2833) and are similar to those of the glaucophane schist terrane eclogites (range 11–38, average 21, Banno and Matsui 1965; Banno, unpublished).

The eclogites described by O'Hara and Mercy (1966a) have $K'_{Mg,Fe}$ values of 13 (GK6) and 21 (GR1) *i.e.*, within the range of the eclogites of glaucophane schist terranes or transitional towards those of amphibolite facies terranes. The presence of lawsonite (Watson, 1960) in eclogites from this locality is further evidence for a relatively low temperature of crystallization of the Arizona-Utah eclogites.

Ca, Mg, Fe distribution between garnet and pyroxene, and the role of zoisite: Coleman *et al.* have argued that eclogites from glaucophane schist terranes (Group C eclogites) contain garnets of characteristically high

[1] $$K'_{Mg,Fe} = \frac{(Mg^{2+}/Fe^{2+})_{cpx}}{(Mg^{2+}/Fe^{2+})_{ga}}.$$

almandine and high grossular+andradite contents. The Guajira eclogites contrast with those described by Coleman *et al.* in having garnets with much lower contents of grossular+andradite and the eclogites described by O'Hara and Mercy (1966a) appear to continue this trend with garnets of even lower Ca-content. The use of a Ca-Mg-(Fe+Mn) (atomic proportions) plot (Fig. 2) illustrates the relative compositions of coexisting garnet and pyroxene and the control that total rock chemistry plays in determining the Ca-content of garnet. The differences in Ca, Mg, Fe distribution between the Group C eclogites (Coleman *et al.* 1965), the Guajira eclogites and the Arizona eclogites are attributed to differences in bulk chemical composition rather than to different conditions of crystallization.

The latter point is more clearly illustrated in an ACF plot ($A=Al_2O_3+Fe_2O_3-(Na_2O+K_2O)$; $C=CaO$; $F=FeO+MgO+MnO$ (Fig. 3). The presence of clinozoisite[1] as a separate phase in some eclogites implies that the rock composition lies in field A of Figure 3 and the coexisting garnet should contain the maximum grossular content for the particular $p-T$ conditions. In the three clinozoisite or epidote bearing eclogites plotted in Figure 3 (A, 1, 2) the rock compositions lie well on the Ca-Al side of the garnet-clinopyroxene join, consistent with the interpretation of the clinozoisite or epidote as a stable, essential phase. These three clinozoisite-bearing eclogites should contain garnets with maximum grossular content, but, as shown in Figure 3, the grossular+andradite content varies from 20 mole % (A or 2832) to 29% (No. 2) or 39% (No. 1) Either the three assemblages represent very different $p-T$ conditions of equilibrium or other chemical factors, not evident in Figure 3, determine the Ca-content of garnet. The analysis by Banno (1967) of factors determining the Ca-content of garnet in the analogous assemblages of kyanite eclogite favors the latter interpretation. In the case of kyanite eclogites, the maximum grossular content of garnet may be greater in quartz-free eclogite than in quartz-bearing kyanite eclogite (O'Hara and Mercy, 1966b). In the clinozoisite eclogites plotted in Figure 3, assemblage 1 (113-RGC-58) does not contain quartz and has the highest grossular content while both assemblages 2 and A contain free quartz. Banno has also shown, following Sobolev, Zyuzin and Kuznetzova (1965), that the grossular content of garnet is strongly dependent on the Na_2O content of the coexisting pyroxene, and for garnets with greater than 60 percent pyrope+almandine the grossular content of garnet *decreases* with increasing Na_2O content of pyroxenes. Assemblages 1 and 2 contain similar Na_2O contents in their respective pyroxenes (5.9% and 6.5%) but as-

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[1] Lawsonite may be expected to play a similar role to clinozoisite.

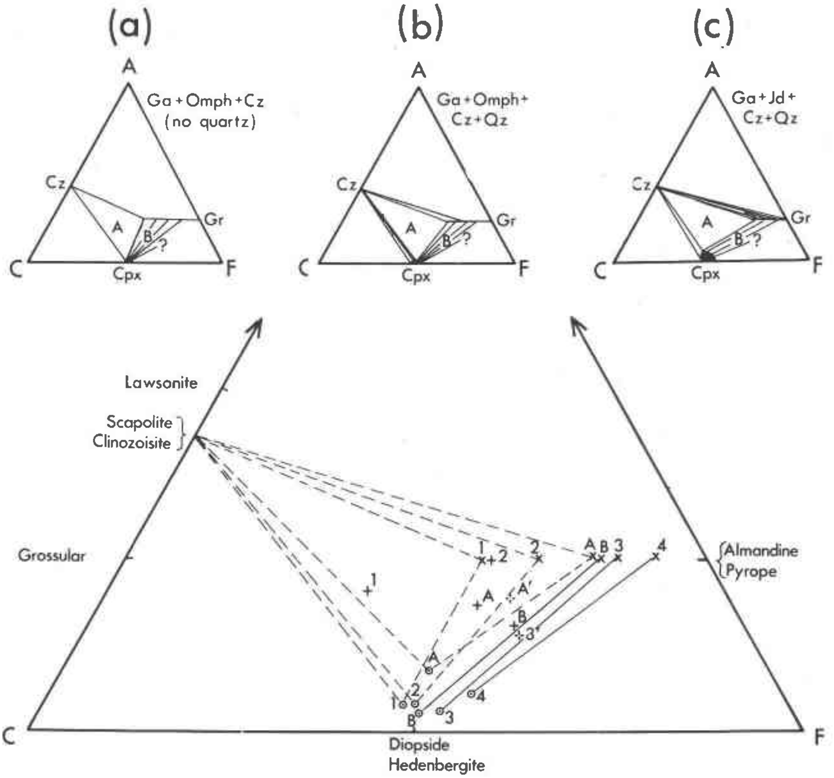

FIG. 3. ACF diagram (mol. proportions) for zoisite eclogites (1, 2, A) and simple garnet +pyroxene eclogites from Colombia (B) and Arizona (3, 4). Symbols and numbers as in Fig. 2. A′ is a replot of whole rock composition 2832(a) corrected for CO_2 content, assuming the presence of $CaCO_3$. B′ and 3′ are whole rock compositions derived by correcting the analyzed FeO, Fe_2O_3 contents to values derived from the mineral analyses and the approximate mode.

Figs. 3a, 3b, 3c illustrate the deduced variation in maximum solid solution of grossular in garnet and the position of the ga-px-cz field in quartz-free eclogite (3a) in quartz-bearing eclogite (3b) and in a garnet+jadeite+quartz (3c) assemblage.

semblage A with 12.1 percent Na_2O in the pyroxene, in accord with Banno's arguments, has a lower grossular content. Thus we consider that the positions of the two-phase garnet+pyroxene and three-phase garnet +pyroxene+clinozoisite fields in ACF diagrams of the eclogite facies are sensitively dependent on the presence or absence of quartz and on the jadeite+acmite content of the coexisting pyroxene (Figs. 3a–c). The two-phase garnet+pyroxene assemblages of 2833 (B in Fig. 3) and GK6, GR1 (O'Hara and Mercy, 1966a) lie within the appropriate two-phase field and on the (Fe+Mg)-rich side of the garnet-pyroxene join of specimen 2832.

The data presented show that the mineral compositions and parageneses of the Guajira rocks are generally similar to those of the Group C eclogites of Coleman *et al.* (1965) *i.e.*, eclogites associated with glaucophane schists. The observed differences in mineral compositions are attributed to differences in total rock chemical composition and to mineral partition relationships. The presence of traces of glaucophane in specimen 2833, the absence of kelyphitic alteration of garnet and pyroxene, and the distinctive textures of these rocks (sharply euhedral, zoned garnets enclosed in much finer grained lepidoblastic pyroxene±quartz) are further points of similarity to the Group C eclogites.

The Guajira eclogites also have similar mineralogical characteristics to the Arizona-Utah eclogites (Watson, 1960; O'Hara and Mercy, 1966a) but the latter ecologites occur as xenoliths in a volcanic diatreme. They are associated with xenoliths of crustal sedimentary and metamorphic rocks, and ultramafic rocks ranging from harzburgite to talc schists. Their mode of occurrence has invited comparison of these eclogites with those occurring in diamond-bearing kimberlite pipes but their mineralogy, element partition relationships and bulk chemical compositions are unlike the rather restricted group of eclogites occurring in kimberlites. It is suggested that the Arizona-Utah eclogites are accidental xenoliths of low-temperature eclogites similar to those of California.

CONDITIONS OF METAMORPHISM

From the mineralogical data presented it is possible to place some limits on the p, T conditions of the Guajira eclogites by comparison with various experimental studies (Fig. 4). The clinopyroxene 2832 contains 15 percent diopside and 15 percent acmite solid solution and the pressure required for its stability in the presence of quartz is below that required for its stability in the presence of quartz is below that required for the albite$\rightleftharpoons$jadeite+quartz reaction (Birch and Le Comte, 1960; Kushiro, 1965; Coleman, 1965). The field association in California of similar jadeitic pyroxene+quartz assemblages with aragonite rather than calcite (Coleman, 1965) suggests conditions of crystallization between 7 and 11 kbars for an assumed temperature of 300°C.

The association of clinozoisite+quartz and the presence of paragonite place some limits on the temperature of crystallization (Holdaway 1966, Eugster and Yoder 1955) but the suggestion that the intimately associated clinozoisite and paragonite have replaced lawsonite places a more severe restriction on the initial conditions of crystallization of specimen

2832 (Newton and Kennedy, 1963). The coupled reaction of lawsonite with jadeite and the probability that $p_{H_2O} \ll p_{total}$ (as indicated by the absence of amphibole and chlorite from 2832) would effectively lower the breakdown temperature of lawsonite (Fig. 4).

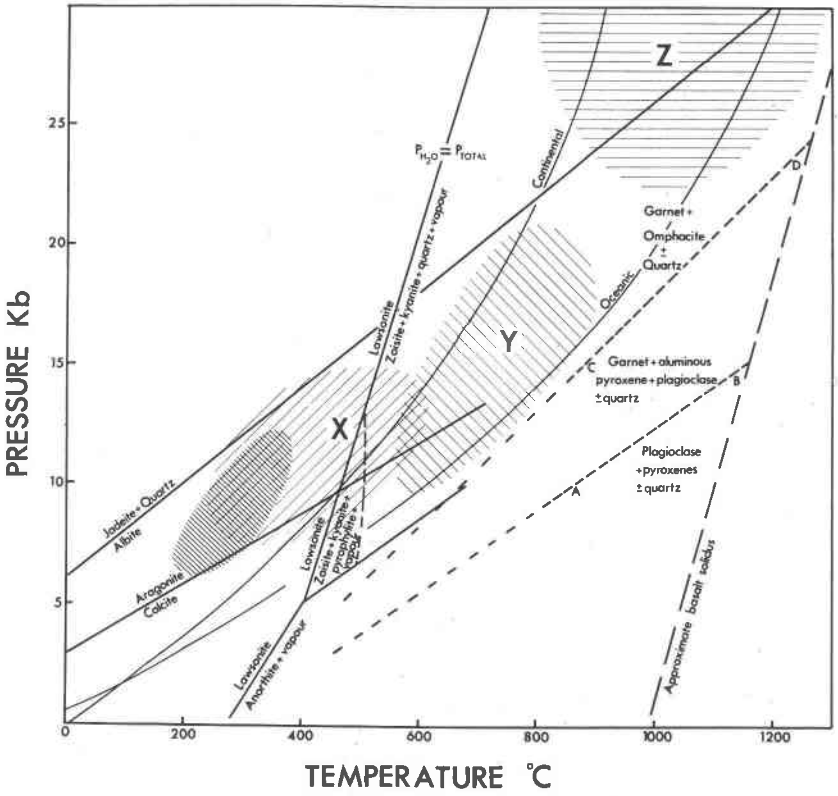

FIG. 4. Diagram illustrating the estimated p_{total}, T field of crystallization (heavily shaded area) of the almandine-jadeite-quartz-clinozoisite assemblage of specimen 2832. The lines AB and CD are from Green and Ringwood (1967) and represent the appearance of garnet and disappearance of plagioclase respectively in a dry quartz tholeiite composition with 100 $Mg/Mg+Fe^{++}=60$. The P, T field on the high pressure side of CD is regarded as the field of stability of eclogite under dry conditions. The positions of the albite $\rightleftharpoons$jadeite+quartz, calcite$\rightleftharpoons$aragonite and the stability relations of lawsonite are taken from the literature (see text). The fields X, Y, Z are estimated P, T fields for formation of eclogites in glaucophane schist terranes (X), in amphibolite or high grade metamorphic terranes such as Norway, Germany, France (Y) or as xenolithic inclusions in diamond-bearing kimberlite pipes (Z) (cf. Green, 1966). The positions of estimated geothermal gradients in oceanic and continental regions are also shown.

The available data on mineral stability fields and the rather distinctive mineral paragenesis of specimen 2832 yield an estimate of the conditions of crystallization of this assemblage as $T = 200-400°C$, $p_{total} = 7-12$ kbars and $0 < p_{H_2O} \ll p_{total}$ (Fig. 4). The accompanying specimen (2833) may have crystallized in the same p, T environment or under somewhat lower pressure conditions. The stability of these assemblages relative to hydrated assemblages such as glaucophane schists or amphibolites is attributed to local water pressures being very much less than total pressure.

ACKNOWLEDGMENTS

We are grateful to Drs. S. Banno, E. D. Ghent and K. S. Heier for critically reading the manuscript. James Papike and Norman Page of the U.S. Geological Survey gave valuable advice concerning unit cell determination techniques for the clinopyroxenes.

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Manuscript received, May 15, 1967; accepted for publication, April 8, 1968.