Mineralogy of Amphibolite Interlayers in the Gneiss Complex, Northwest Adirondack Mountains, New York
Author(s): A. E. J. Engel, Celeste G. Engel, R. G. Havens
Source: *The Journal of Geology*, Vol. 72, No. 2 (Mar., 1964), pp. 131-156
Published by: The University of Chicago Press
Stable URL: http://www.jstor.org/stable/30080947
Accessed: 31/07/2009 10:46

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=ucpress.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.

The University of Chicago Press is collaborating with JSTOR to digitize, preserve and extend access to *The Journal of Geology*.

http://www.jstor.org

VOLUME 72 NUMBER 2

THE JOURNAL OF GEOLOGY

March 1964

MINERALOGY OF AMPHIBOLITE INTERLAYERS IN THE GNEISS COMPLEX, NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK[1]

A. E. J. ENGEL,[2] CELESTE G. ENGEL,[3] AND R. G. HAVENS[4]

ABSTRACT

The progressive metamorphism of amphibolite interlayers in the Adirondack gneiss complex is reflected in the complete transition between the following mineral assemblages: (1) green hornblende-andesine-quartz-ilmenite, stable at an estimated 525° C. at Emeryville, New York, and (2) brown hornblende-labradorite-clinopyroxene-orthopyroxene-ilmenite, stable at approximately 625° C. at Colton, New York.

The hornblende in the Emeryville assemblage is bluish-green, and averages about 70 volume per cent of the amphibolite rock. With increasing grade of metamorphism, the color, density, and composition of the hornblende changes toward a hydroxyl-deficient, brownish-green, denser variety, relatively enriched in Ti, Na, K, F, Cr, V, Sc, Co, and Ni, and depleted in Mn, Zn, and OH. Both Fe_2O_3/FeO, and Fe/Mg decrease with increasing grade of metamorphism.

The coexisting plagioclase increases in An content from An_{54} to An_{60} with increasing grade of metamorphism. This compositional change is accompanied by an increase in grain size, and abundance, but the orthoclase molecule in the plagioclase decreases slightly with rising temperatures and pressures of crystallization.

Ilmenite constitutes 75–95 per cent of the opaque mineral constituent in the amphibolites, ranges up to 9 volume per cent, and averages approximately 2 per cent at both Emeryville and Colton. Analyses of two ilmenites from Emeryville and two from Colton indicate little variation in composition from (in weight per cent) TiO_2 52, total Fe (as FeO) 44.5, MgO 1.2, and MnO 1.4.

A pale-green clinopyroxene first appears in the amphibolites formed at an estimated temperature of 550° C. At Colton clinopyroxene composes from 15 to 52 per cent of the rock, averaging about 20 per cent. Orthopyroxene first appears in the Russell area where temperatures of metamorphism are estimated at 575° C. At Colton orthopyroxene averages about 15 per cent of the rock but constitutes over 30 per cent of a few "amphibolites." The distribution coefficients of $Mg/(Mg + Fe^{++})$ in coexisting pyroxene pairs at Colton are about 0.52, similar to those of pyroxene pairs found in mafic granulites in India, Africa, Scandinavia, and Great Britain. This partitioning of Fe and Mg, along with Ca, is distinctive for metamorphic pyroxenes, and may be employed as both a geologic thermometer and to distinguish metamorphic from igneous mineral assemblages.

The gross distribution patterns of elements between the coexisting minerals of the Colton assemblages reflect (1) the concentration of Al, K, Na, Ba, Ga, Sr, and Pb in the plagioclase and hornblende relative to the pyroxenes, and (2) the greater variety, and complex substitutions of the common ions in hornblende and Ca-rich pyroxene compared to the Ca-poor pyroxene and plagioclase.

In any one area in the belt of progressive metamorphism, the partitioning of specific elements and their distribution coefficients are remarkably uniform. This is indicative of essential equilibrium between the coexisting phases.

The sequence of chemical changes within the associated minerals in the amphibolites metamorphosed between Emeryville and Colton appears to be typical of those in basic rocks reconstituted in the deeply eroded parts of continental crusts, under *P-T* conditions that have induced partial melting in the enveloping, more felsic, paragneiss.

INTRODUCTION

The mineral assemblage in amphibolites of the Adirondack gneiss-amphibolite complex changes systematically in response to

---

[1] Manuscript received June 18, 1962; revised manuscript received October 18, 1962.

[2] University of California, La Jolla, California.

[3] U.S. Geological Survey, La Jolla, California.

[4] U.S. Geological Survey, Denver, Colorado.

increasing grade of metamorphism from green hornblende–calcic andesine–quartz–ilmenite to clinopyroxene–orthopyroxene–brown hornblende–sodic labradorite and ilmenite. The assemblage hornblende-andesine-quartz-ilmenite reflects the reconstitution of a basalt-like system at some 525° C., near Emeryville, New York (fig. 1; see Engel and Engel, 1958, p. 1382–1387). Hereafter this assemblage is referred to as the Emeryville assemblage. Its average mineral composition, in layers devoid of retrograde effects and granitic interpenetrations is (in volume per cent): hornblende 69, andesine 19, quartz 9, and ilmenite 2. The rock is a typical amphibolite, medium grained, faintly to distinctly foliated, with the chemical composition of a saturated basalt (table 1 and fig. 2).

Northeastward along the strike these amphibolites are reconstituted at progressively higher *T* and *P*, with related, systematic changes in composition. At Colton, New York, at the perimeter of the central Adirondack massif, the measured temperatures of metamorphism are ~625° C. (Engel and Engel, 1958, 1960*a*, 1960*b*). The average mineral composition has changed progressively to (volume per cent) plagioclase 36, hornblende 31, clinopyroxene 19, orthopyroxene 11, and ilmenite 2. The chemical composition of the total rock also has changed progressively to that of an olivine basalt (fig. 2 and table 1). At Emeryville the mineral assemblage is typical of the almandine-amphibolite facies; at Colton the assemblage is characteristic of the hornblende-granulite facies. Locally at Colton the volume of hornblende decreases to 5 per cent, and the resulting two pyroxene-labradorite rock is a typical mafic granulite.

These compositional changes in the rock between Emeryville and Colton reflect, and are probably induced by, the regional metamorphism. With increasing grade of metamorphism the rock system is depleted in H_2O, K_2O, and in the ratio Fe^{+++}/Fe^{++}. Consequently CaO and MgO increase, and the ratio K/Ca decreases from 1.3 at Emeryville to 0.4 at Colton. These changes are discussed in conjunction with the field occurrence, lithologic features, and origin of the amphibolites in a separate, complementary publication (Engel and Engel, 1962*a*). In the following discussion emphasis is placed upon the properties of the coexisting minerals and distribution of elements between them.

MINERALOGY

The interrelationships of the two contrasting mineral assemblages and rock compositions at Emeryville and Colton are shown graphically in the ternary plot Ca, Mg + Fe, Al (fig. 3). The data shown in figure 3 are derived from two specific rocks, one from the Emeryville area, the other from Colton. These are amphibolites representative of the apical stages in regional metamorphism in their respective areas. No marked variations from these individual rock and mineral compositions appear in the amphibolite at either of the contrasted areas, except, of course, those induced by emplacement of granite and by spotty retrograde metamorphism.

The three minerals common to both assemblages are hornblende, plagioclase, and ilmenite. At Colton, however, hornblende is largely replaced by coexisting pyroxenes, one calcium-rich (clinopyroxene), the other calcium-poor (orthopyroxene). The properties of all five of these minerals are noted in the following discussion.

HORNBLENDE

The detailed petrochemistry of the hornblendes has been published separately (Engel and Engel, 1961, 1962*b*) and only their salient features are reviewed herein. The amphibole at Emeryville is a bluish-green calciferous (common) hornblende averaging about 70 volume per cent of the rock (tables 1 and 2). Toward Colton, with increasing grade of metamorphism, the amount of hornblende decreases as first clinopyroxene, and then orthopyroxene, become stable, coexisting phases (fig. 2). Color, density, and composition of the hornblende change toward the typical hydroxyl-defi-

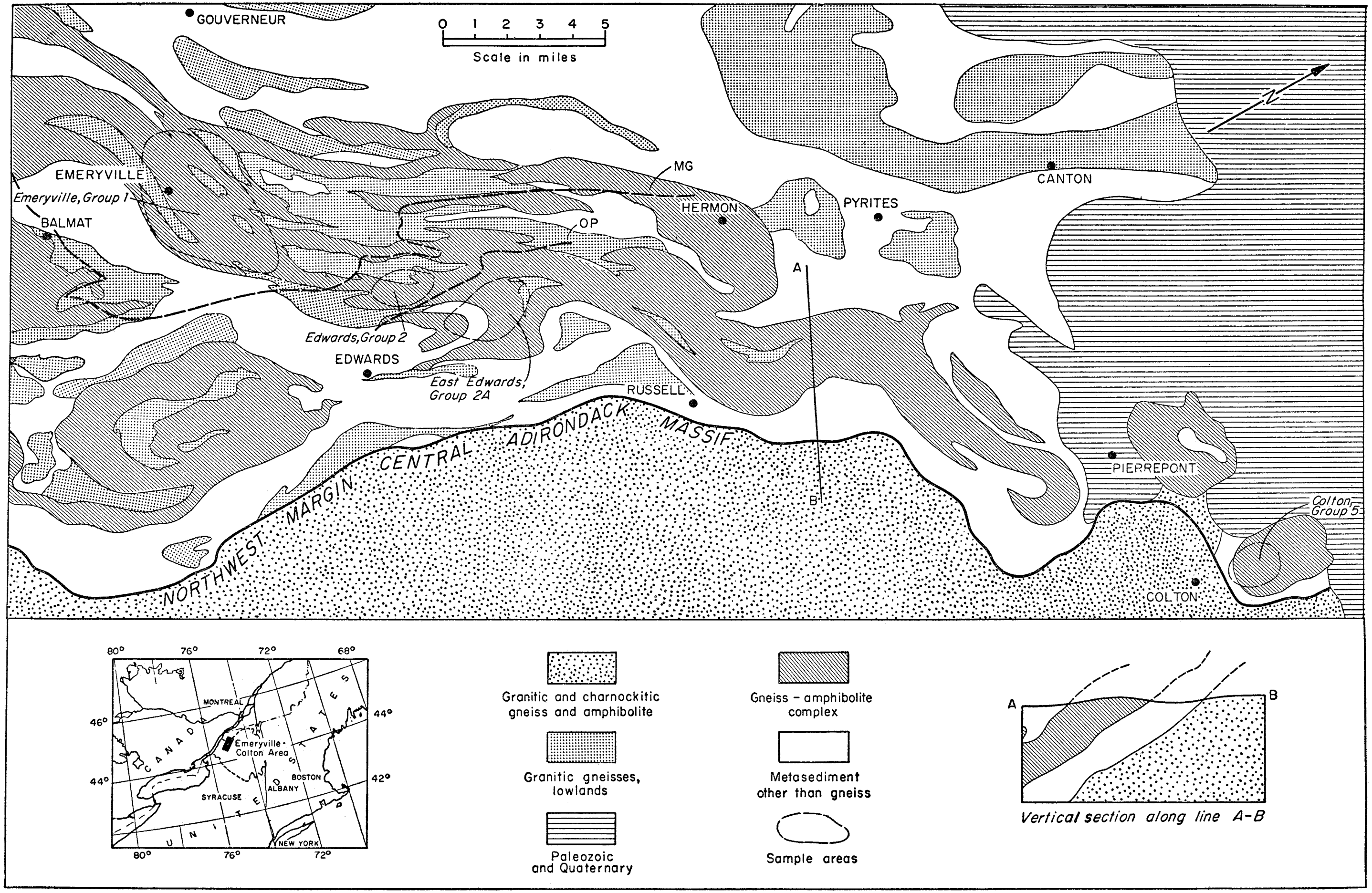

FIG. 1.—Sketch map of the northwest Adirondack Mountains showing the distribution of the several major rock types. The mineral assemblages discussed in the text are from amphibolite rocks that form distinctive lenses and interlayers in the gneiss-amphibolite complex. The dashed line *MG* is the garnet isograd in the paragneiss. The line *OP* is the orthopyroxene isograd in the amphibolite interlayers.

TABLE 1

AVERAGE MINERAL AND CHEMICAL COMPOSITION OF AMPHIBOLITE ROCKS LEAST MODIFIED BY GRANITIC EMPLACEMENT AND RETROGRADE ALTERATION AT EMERYVILLE AND COLTON, NEW YORK

	EMERYVILLE AREA (7 SAMPLES)		COLTON AREA (9 SAMPLES)	
	Mean	Mean Deviation	Mean	Mean Deviation
	Modes, Volume Per Cent			
Quartz	8.6	4.8	0.1	0.02
Plagioclase	18.5	4.5	35.6	4.6
Hornblende	68.6	3.3	31.3	11.0
Clinopyroxene	0.9	0.8	19.2	6.0*
Orthopyroxene	....	....	11.3	....
Opaque minerals	2.1	1.1	2.0	0.7
Biotite	0.6	0.3	0.2	0.1
Sphene	0.4	0.2	....	....
Others†	0.3	0.2	0.3	0.2
	Chemical Analyses			
SiO_2	48.20	1.43	47.89	0.91
TiO_2	1.89	0.39	1.56	0.17
Al_2O_3	14.45	0.81	14.63	0.35
Fe_2O_3	3.50	0.45	1.85	0.58
FeO	10.53	0.73	11.20	0.84
MnO	0.25	0.02	0.25	0.02
MgO	6.62	0.41	7.41	0.24
CaO	10.25	0.71	11.54	0.48
Na_2O	1.94	0.45	2.19	0.14
K_2O	0.96	0.08	0.58	0.12
H_2O^+	1.31	0.06	0.72	0.19
H_2O^-	0.01	0.01	0.03	0.02
P_2O_5	0.18	0.03	0.14	0.03
Total Fe as Fe_2O_3	15.22	1.22	14.29	1.05
	Trace Elements (P.p.m.)			
B	<20	....	<20	....
Ba	100	22	72	22
Co	44	1	45	3
Cr	201	61	353	71
Cu	73	19	61	43
Ga	14	2	13	....
La	<50	....	<50	....
Mo	<10	....	<10	....
Ni	61	4	60	9
Pb‡	8	3	7	3
Sc	56	2	57	4
Sr	226	36	164	19
V	344	49	318	24
Y	59	13	45	2
Zn‡	155	23	151	30
Zr	145	33	104	14

* Mean deviation of total pyroxene content in rock.

† Chiefly apatite, chlorite, calcite, sericite, and zircon.

‡ Colorimetric analyses, analyst H. L. Nieman. All other trace-element analyses are quantitative spectrographic analyses; analysts, Nancy M. Conklin and R. G. Havens.

TABLE 1—*Continued*

	EMERYVILLE AREA (7 SAMPLES)		COLTON AREA (9 SAMPLES)	
	Mean	Mean Deviation	Mean	Mean Deviation
	Norms			
Quartz	0.38	....	....	....
Orthoclase	5.67	....	3.45	....
Albite	16.40	....	18.03	....
Anorthite	27.88	....	28.36	....
Diopside	17.87	....	23.03	....
Hypersthene	21.38	....	8.54	....
Olivine	....	....	11.29	....
Ilmenite	3.65	....	3.01	....
Magnetite	5.08	....	2.69	....
Apatite	0.44	....	0.34	....

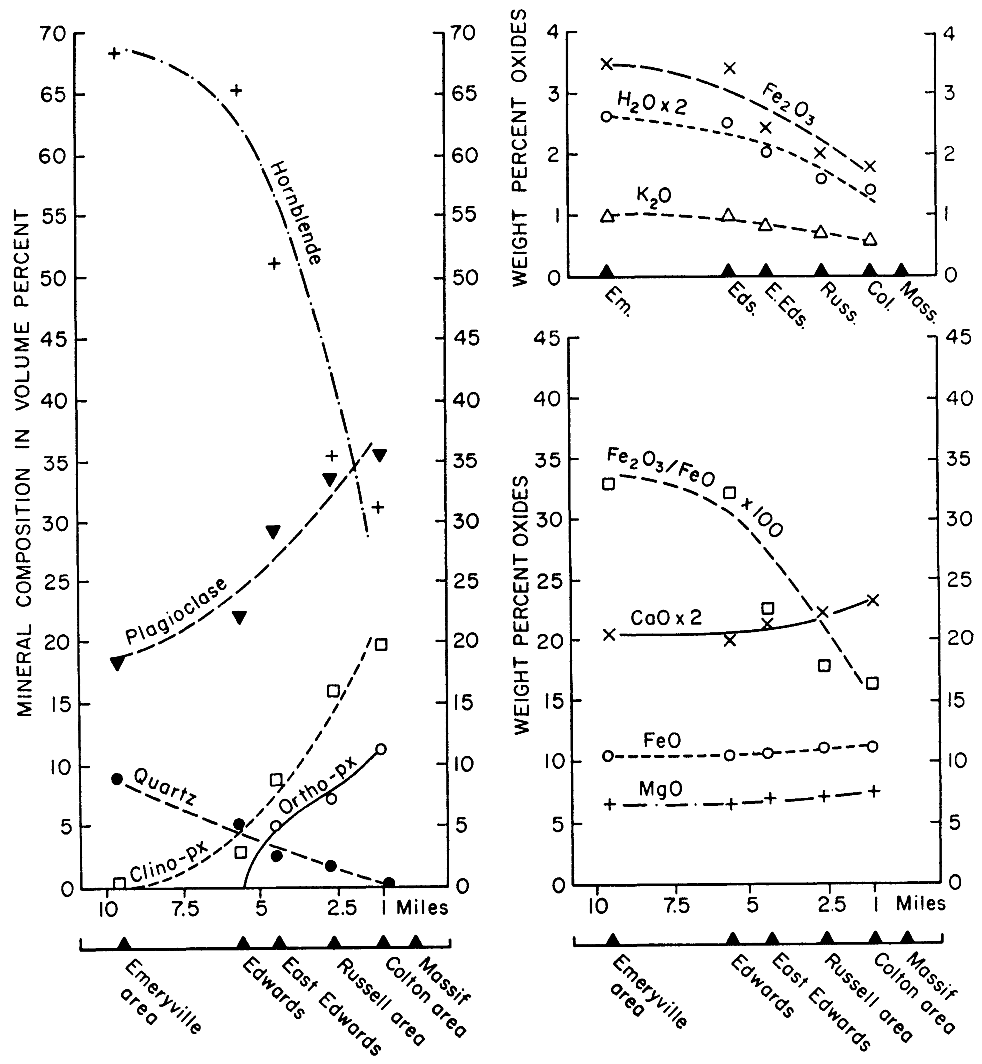

FIG. 2.—Generalized curves indicating the typical progressive changes in minerals and major element compositions of amphibolite rocks between Emeryville and Colton, New York.

cient, brownish, and denser hornblende characteristic of the granulite facies (table 3; see also Engel and Engel, 1961, 1962*b*). Compositionally the changes in hornblende include an increase in Ti, Na, K, F, Cr, V, Sc, Co, and Ni. Decreases occur in the concentrations of Mn, Zn, and OH + F + Cl as well as the ratios Fe_2O_3/FeO and Fe/Mg.

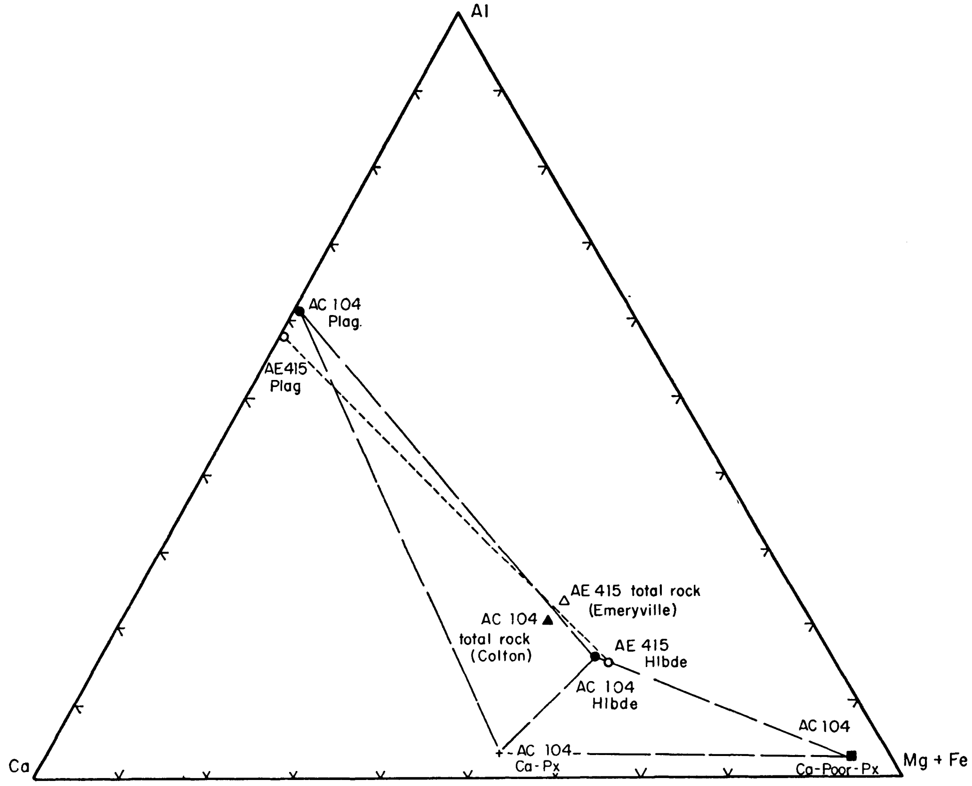

FIG. 3.—Ternary diagram illustrating the variations in total Ca, Mg$^+$Fe, and Al in typical amphibolite rocks and their constituent minerals from the Emeryville and Colton areas, New York.

The increase in amounts of Co, Cr, Ni, Sc, and V with increasing Mg/Fe in the hornblende are graphed in figure 4. A complementary decrease occurs in Mn. Total Si, Ca, and Al in the hornblendes remain essentially constant throughout the probable difference in temperature of metamorphism of 100° C. or more (Engel and Engel, 1958, p. 1382–1387). Indexes of refraction of the hornblendes also remain nearly constant despite the recorded changes in color, composition, and density. It is clear that only slight to moderate changes in physical and chemical properties of hornblendes are induced by the recorded, progressive changes in physical conditions of metamorphism and in the changes in associated mineralogical and chemical composition of the total rock system.

PLAGIOCLASE

The amount, size, and average anorthite content of plagioclase in the amphibolites increase with increasing grade of metamorphism. In the Emeryville assemblage, the mean composition of the plagioclase is near An_{54} and it averages about 19 per cent of the rock, by volume. At Colton the amount of plagioclase is almost doubled and the average composition is about An_{60}. This increase in An content is probably due in

TABLE 2

AVERAGE CHEMICAL COMPOSITION, STRUCTURAL FORMULAS, INDEX OF REFRACTION, DENSITY, AND COLOR OF HORNBLENDES[*] FROM LEAST-ALTERED AMPHIBOLITE ROCKS IN EMERYVILLE AND COLTON AREAS, NEW YORK[†]

	Emeryville Area (7 Samples)		Colton Area (10 Samples)	
	Mean	Mean Deviation	Mean	Mean Deviation
SiO_2	42.46	0.54	42.17	0.34
TiO_2	1.32	.05	2.39	.15
Al_2O_3	12.53	.51	12.22	.33
Fe_2O_3	4.94	.22	3.28	.48
FeO	13.71	.43	14.42	.48
MnO	0.31	.01	0.17	.01
MgO	9.04	.59	9.42	.17
CaO	11.64	.17	11.46	.06
Na_2O	1.32	.05	1.51	.08
K_2O	1.02	.08	1.41	.14
H_2O^+	1.83	.03	1.50	.08
P_2O_5	0.05	.02	0.06	.02
F	0.11[†]	.04	0.17[§]	.02
Cl	0.03[‡]	.00	0.03[§]	.01
Total Fe as Fe_2O_3	20.17	.70	19.30	.40
Fe_2O_3/FeO	0.36	0.015	0.23	0.039
	Trace Elements (P.p.m.)			
Ba	86	32	106	40
Co	47	3	60	2
Cr	249	95	737	116
Cu	17	6	7	4
Ga	18	2	19	2
Ni	57	11	76	13
Pb	6	1	7	3
Sc	77	2	109	10
Sr	46	12	42	12
V	527	66	811	81
Y	72	22	118	22
Yb	9	2	13	....
Zn	216	32	163	21
Zr	97	26	75	8

		Emeryville Area (7 Samples)		Colton Area (10 Samples)	
		Mean	Total	Mean	Total
		Structural Formulas[‖]			
(W)	K	0.194	2.44	0.269	2.56
	Na	0.380		0.439	
	Ca	1.864		1.850	
(X)	Mg	2.015	3.77	2.114	3.95
	Fe^{++}	1.715		1.816	
	Mn	0.038		0.021	
(Y)	Al	0.578	1.28	0.534	1.18
	Fe^{+++}	0.555		0.371	
	Ti	0.147		0.270	
(Z)	Si	6.354	8.00	6.363	8.00
	Al	1.646		1.637	
	OH	1.832	1.89	1.506	1.59
	F	0.051		0.080	
	Cl	0.006		0.006	
	$X+Y$	5.05		5.13	
		Density			
		3.260		3.278	
		Index of Refraction			
	N_x	1.668		1.670	
	N_z	1.689		1.692	
		Pleochroism			
	X	Yellow-green		Light brownish green	
	Y	Green		Yellow-brown	
	Z	Blue-green		Brownish-green	

---

[*] Analyses of hornblendes from the amphibolite rocks summarized in table 1.

[†] Mean deviations of the various oxides and elements are listed alongside the chemical analyses. Trace-element analyses are quantitative spectrographic analyses by R. G. Havens, except that the values for Pb and Zn were determined colorimetrically by H. L. Nieman.

[‡] Mean derived from 4 determinations.

[§] Mean derived from 7 determinations.

[‖] The structural type is taken as $W_{2\text{-}3}(XY)_5(Z_4O_{11})_2$ (OH, F, Cl$)_2$.

TABLE 3

CHEMICAL COMPOSITION AND INDEXES OF REFRACTION OF HORNBLENDES FROM PYROXENE-BEARING AMPHIBOLITE ROCKS, COLTON AREA, NEW YORK*

	A 10	A 67	A 104	A 105	AC 342	AC 358	AC 348	AC 341	A 101	AC 362	Mean	Mean Deviation
SiO_2	42.06	42.05	41.73	42.48	41.61	42.38	42.36	41.67	42.96	42.36	42.17	0.34
TiO_2	2.49	2.26	2.24	2.26	2.61	2.49	2.30	2.71	2.13	2.42	2.39	.15
Al_2O_3	12.50	12.79	12.30	11.34	12.59	12.27	11.86	12.52	11.84	12.20	12.22	.33
Fe_2O_3	2.70	2.86	3.94	3.51	3.15	2.55	4.11	3.52	3.69	2.76	3.28	.48
FeO	14.83	14.36	14.19	14.84	15.03	15.03	13.97	13.84	13.33	14.74	14.42	.48
MnO	0.19	0.18	0.15	0.15	0.17	0.21	0.17	0.17	0.18	0.16	0.17	.01
MgO	9.33	9.41	9.54	9.55	8.87	9.23	9.60	9.27	9.96	9.40	9.42	.17
CaO	11.37	11.48	11.50	11.53	11.40	11.48	11.36	11.40	11.55	11.52	11.46	.06
Na_2O	1.54	1.44	1.28	1.43	1.67	1.65	1.46	1.59	1.51	1.51	1.51	.08
K_2O	1.34	1.42	1.69	1.49	1.49	1.09	1.49	1.58	1.09	1.39	1.41	.14
H_2O^+	1.42	1.43	1.50	1.60	1.32	1.60	1.49	1.45	1.65	1.54	1.50	.08
H_2O^-	0.02	0.05	0.02	0.07	0.01	0.02	0.02	0.03	0.02	0.04	0.03	....
P_2O_5	0.02	0.06	0.02	0.04	0.05	0.03	0.03	0.06	0.03	0.05	0.06	.02
F	0.18	N.d.	N.d.	N.d.	0.19	0.15	0.15	0.22	0.15	0.15	0.17†	.02
Cl	0.02	N.d.	N.d.	N.d.	0.03	0.01	0.03	0.05	0.02	0.03	0.03†	0.009
Subtotal	100.01	99.79	100.10	100.29	100.19	100.19	100.40	100.08	100.11	100.27	....	....
O−F	0.08	....	....	....	0.09	0.06	0.07	0.10	0.07	0.07	....	....
Total	99.93	....	....	....	100.10	100.13	100.33	99.98	100.04	100.20	....	....
Total Fe as Fe_2O_3	19.18	18.81	19.71	20.00	19.85	19.25	19.63	18.90	18.50	19.14	19.30	0.40
Fe_2O_3/FeO	0.18	0.20	0.28	0.24	0.21	0.17	0.29	0.25	0.28	0.19	0.23	.04
Fe/Mg	2.39	2.32	2.40	2.43	2.60	2.42	2.37	2.36	2.16	2.36	2.38	0.07
N_x	1.669	1.668	1.669	1.670	1.670	1.668	1.670	1.675	1.667	1.670	1.670	....
N_z	1.691	1.690	1.691	1.692	1.692	1.690	1.692	1.693	1.691	1.693	1.692	....
$N_z - N_x$	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.018	0.024	0.023	0.022	....
Density	3.276	....	....	3.271	3.296	3.284	....	3.276	3.274	3.272	3.278	....
Purity	98+	99	98+	98+	100	98+	98+	99	98+	99+	....	....

* The compositions of calcium-rich and calcium-poor pyroxenes that coexist with these hornblendes are given in table 8.

† Mean derived from 7 determinations.

TABLE 3—*Continued*

	A 10	A 67	A 104	A 105	AC 342	AC 358	AC 348	AC 341	A 101	AC 362	Mean	Mean Deviation
	Trace Elements (P.p.m.)											
Ba	54	....	180	64	160	97	88	160	71	81	106	40
Co	56	....	57	62	62	62	60	60	58	66	60	2
Cr	500	....	740	930	520	780	860	760	600	940	737	116
Cu	7	....	8	5	3	1	8	2	18	10	7	4
Ga	19	....	22	21	21	18	20	14	15	18	19	2
Ni	80	....	63	50	62	72	83	87	88	100	76	13
Pb‡	6	....	N.d.	N.d.	4	14	5	N.d.	5	5	7	3
Sc	100	....	110	130	97	110	110	98	100	130	109	10
Sr	33	....	38	42	78	66	46	53	28	36	42	12
V	840	....	780	940	750	720	800	830	640	1,000	811	81
Y	110	....	140	140	110	94	140	81	93	150	118	22
Yb	12	....	15	15	12	11	14	10	11	15	13	0.2
Zn‡	150	....	N.d.	N.d.	170	220	145	N.d.	135	160	163	21
Zr	75	....	60	64	88	81	76	86	61	82	75	8
	Structural Formulas§											
(*W*) K	0.257	0.272	0.324	0.286	0.287	0.206	0.285	0.303	0.206	0.266	0.269	
(*W*) Na	0.450	0.421	0.373	0.416	0.490	0.477	0.425	0.465	0.436	0.439	0.439	
(*W*) Ca	1.841	1.857	1.860	1.862	1.853	1.838	1.831	1.846	1.851	1.859	1.850	
(*X*) Mg	2.102	2.117	2.147	2.145	2.006	2.055	2.153	2.089	2.220	2.109	2.114	
(*X*) Fe^{++}	1.874	1.813	1.791	1.871	1.907	1.877	1.758	1.750	1.667	1.856	1.816	
(*X*) Mn	0.023	0.022	0.019	0.019	0.020	0.026	0.020	0.020	0.022	0.019	0.021	
(*Y*) Al	0.587	0.630	0.495	0.423	0.573	0.542	0.483	0.538	0.517	0.548	0.534	
(*Y*) Fe^{+++}	0.307	0.324	0.446	0.396	0.359	0.285	0.465	0.399	0.415	0.311	0.371	
(*Y*) Ti	0.282	0.255	0.254	0.255	0.297	0.279	0.259	0.308	0.239	0.273	0.270	
(*Z*) Si	6.360	6.354	6.306	6.408	6.320	6.382	6.379	6.306	6.430	6.383	6.363	
(*Z*) Al	1.640	1.646	1.694	1.592	1.680	1.618	1.621	1.694	1.570	1.617	1.637	
OH	1.431	1.439	1.510	1.607	1.335	1.593	1.494	1.461	1.645	1.544	1.506	
F	0.085	....	....	....	0.091	0.070	0.070	0.104	0.071	0.070	0.080	
Cl	0.004	....	....	....	0.007	0.001	0.007	0.012	0.004	0.007	0.006	
$X+Y$	5.18	5.16	5.16	5.11	5.16	5.07	5.14	5.11	5.08	5.11	5.13	

‡ Colorimetric analyses; analyst, H. L. Nieman. All other trace-element analyses are quantitative spectrographic analyses by R. G. Havens.

§ The structural type is taken as $W_{2-3}\ (XY)_5\ (Z_4O_{11})_2$ (OH, F, Cl)$_2$.

some part to the increased temperature of metamorphism, but also probably reflects to some degree the increase in Ca in the total rock.

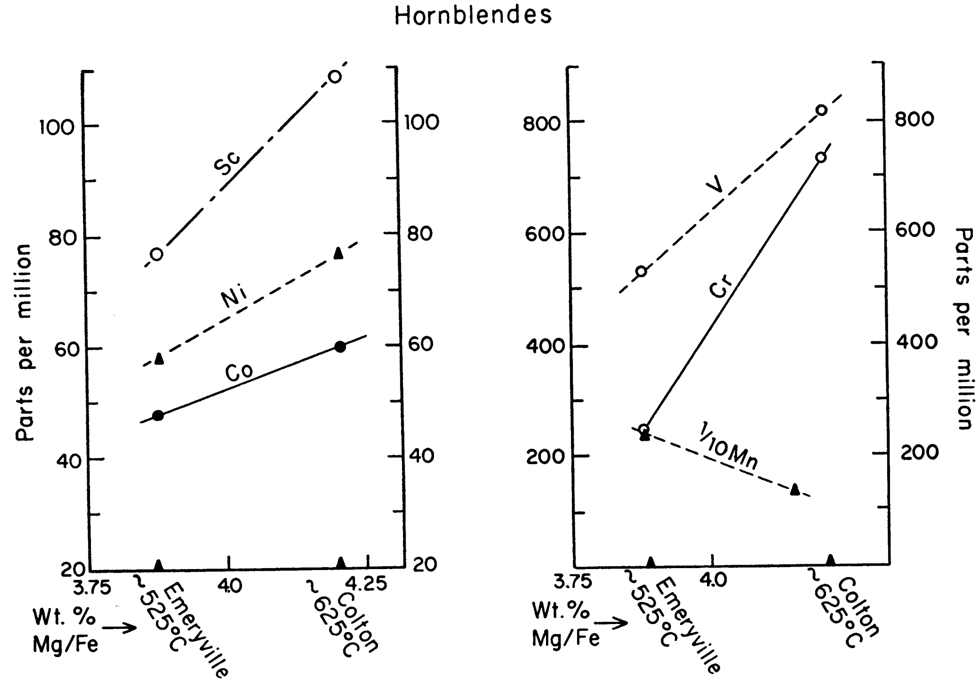

FIG. 4.—Variations in the amounts of Co, Cr, Ni, Sc, and V related to increasing Mg/Fe in hornblendes between Emeryville and Colton, New York.

TABLE 4

CHEMICAL ANALYSES OF PLAGIOCLASE FELDSPARS FROM AMPHIBOLITES AT EMERYVILLE AND COLTON, NEW YORK*

	EMERYVILLE AREA	COLTON AREA	
	AE 415	AC 362	A 104
SiO_2	55.38	54.01	53.35
TiO_2	0.02	0.01	0.01
Al_2O_3	28.49	29.21	29.42
Fe_2O_3	0.19	0.40	0.36
MgO	0.03	0.02	0.06
CaO	10.04	11.55	11.99
Na_2O	5.55	4.63	4.57
K_2O	0.34	0.18	0.20
Total	100.04	100.01	99.96

* Analyst: C. G. Engel.

Chemical analyses of plagioclase feldspars from amphibolites at Emeryville and at Colton are given in table 4. Determinations of alkalis and trace elements were made on additional plagioclases, seven from the amphibolites at Emeryville, and seven from the rocks at Colton. These analyses are grouped in table 5. The analyses of plagioclases at Emeryville are complicated by the presence as impurities of minor quartz and traces of sericite. Corrections have been made for these contaminants in all tables; but because of the possible errors, it is unwise to place complete faith in rigorous comparisons of amounts of certain trace elements, especially K and B, between the plagioclases of the two localities.

The data suggest that the K content, and hence the orthoclase molecule, decrease with an increase in temperature of crystal growth and in anorthite molecule. Data on analogous "low-temperature" plagioclases

TABLE 5

Molecular Compositions, Alkali, and Other Trace Elements in Plagioclases from Amphibolites and Pyroxene-bearing Amphibolites of the Emeryville and Colton Areas, New York*

	Emeryville Area								Colton Area							
	A 3	AE 317	AE 415	AE 334	AE 337	AE 326	AE 338	Mean	A 10	A 104	A 105	AC 358	AC 341	A 101	AC 362	Mean
	Parts per Million															
Ba	62	60	32	56	75	55	40	54	46	120	40	62	11	63	54	57
Be	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	3	<2	<2	<2	~1
Ga	17	12	17	10	16	15	12	14	18	22	24	20	18	18	23	20
Li	5	5	<1	<1	2	5	3	~3	<1	1	<1	<1	2	<1	<1	~1
Mn	39	30	35	40	36	32	35	35	26	46	26	27	26	21	15	27
Pb	19	16	18	15	20	18	16	17	14	12	12	36	8	12	10	15
Sr	580	570	525	530	420	600	320	506	350	560	420	530	510	340	350	437
Ti	165	160	95	120	140	100	130	130	94	85	68	64	79	65	51	72
Zr	79	79	140	120	130	110	150	115	23	30	29	51	47	21	31	33
	Weight Per Cent															
Na_2O	4.97	5.13	5.35	5.41	4.91	5.24	....	5.17	4.67	4.57	4.89	4.37	5.16	4.76	4.63	4.72
K_2O	0.33	0.38	0.37	0.26	0.24	0.24	....	0.30	0.17	0.20	0.22	0.11	0.18	0.19	0.18	0.18
An	55	53	52	52	56	54	54	54	60	61	58	62	56	58	60	59

* Concentrations of other trace elements: B <40, Cs <50, Co <20, Cr <20, Ni <40, Rb <10, Sc <20, V <20, Y <20, Yb, <2, Zn <300. Analysts: Na_2O and K_2O, C. G. Engel; trace elements, R. G. Havens.

from the inclosing paragneiss (Engel and Engel, 1960*a*), from the Stillwater complex (Hess, 1960, table 10), and from diverse granitic, gneissic, and mafic rocks (Smith, 1960, table 52) also indicate a decrease in the content of orthoclase molecule with increasing anorthite content of low-temperature plagioclases. In contrast, however, analyses obtained by Sen (1959, 1960) on plagioclases from metamorphic rocks led him to conclude that the K, Ba, Sr, Fe, and Ti contents of plagioclases of the amphibolite and granulite facies increase with increasing temperature of formation and anorthite content of the plagioclase. Other analyses of plagioclases, from Indian charnockites (Howie, 1955, p. 745), and from Appalachian amphibolites (Wilcox and Poldervaart, 1958, p. 1358) indicate higher absolute amounts of K in plagioclases than we find in the Adirondack samples. In table 6 we have compiled average concentrations of CaO, Na_2O, K_2O, Ba, Sr, Ti, and Fe from the plagioclases in the Emeryville and Colton amphibolites along with the mean concentrations of these elements in plagioclases of analogous rock types, as reported by Sen (1959, tables 2 and 3; 1960, table 2). The changes in amounts of trace elements in plagioclases from the Adirondack amphibolites are small and, with the exception of Ba, in the opposite direction from those suggested by Sen. That is, K, Sr, Ti, Mn, and Zr may decrease slightly with increasing temperature of metamorphism and anorthite molecule. The apparent increase in Fe is equivocal because of traces of secondary hematite on and in the plagioclases at Colton.

TABLE 6

AVERAGE AMOUNTS OF ALKALIS, CA, TI, AND FE IN PLAGIOCLASES FROM AMPHIBOLITE ROCKS OF THE EMERYVILLE AND COLTON AREAS, WYOMING, AND OTHER TERRANES

	AMPHIBOLITE FACIES		HORNBLENDE-GRANULITE FACIES	
	Emeryville*	Other†	Colton*	Other‡
CaO.......	10.8	5.34	12.0	5.5
Na_2O......	5.17	6.98	4.72	5.7
K_2O.......	0.30	0.13	0.18	0.63
	Parts per Million			
Ba.........	54	29	57	346
Sr.........	506	496	437	916
Ti.........	130	289	72	87
Fe.........	2,100	1,200	2,600	1,200

* Average of 7 samples from each area except K_2O at Emeryville. The mean of K_2O at Emeryville is of 6 samples.

† Average of analyses of 8 plagioclase feldspars from hornblende-andesine-quartz amphibolites of other terranes, largely Laramie Mountains, Wyoming (Sen, 1960, table 1, samples 6-51-Cl, 6-51-L, 6-50-E, 6-51-94, 6-9-B, 6-70-A, 6-50-K, 7-9-H).

‡ Average of analyses of 6 plagioclase feldspars from pyroxene-hornblende-plagioclase-bearing gneisses (Sen, 1960, table 2, samples R-32, R-75, 5649, 37606, R-175, 5643).

Plagioclases from many metamorphic rocks tend to be altered, clouded with imperfections or inclusions, and difficult to separate from associated, equally coarse-grained quartz, sericite, and K feldspar. In view of these difficulties, the errors of analysis, and the probable variations in composition and temperature in the various terranes, the variations in the data are quite understandable. Probably, however, the K_2O content recorded in the literature for many plagioclases is high by a factor of 2, and reported amounts of Fe, Ti, Sr, and other trace elements may be in error by at least 25 per cent.

X-ray studies were undertaken of the plagioclases in amphibolites of the Emeryville and Colton areas to determine the angular separation between the $(1\bar{3}1)$ and the (131) reflections. These values, along with equivalent data for plagioclases from the enveloping paragneiss, are plotted against composition in figure 5. This figure also shows, in a general way, the observed relationship between metamorphic and plutonic igneous plagioclases and those formed synthetically and in volcanic environments (Smith and Yoder, 1956). The data are consistent with the conclusions that (1) the degree of inversion of plagioclases toward some undefined low-temperature state varies with the physical environment during crystallization; and (2) plagioclases in deep-seated regionally metamorphosed rocks undergo about the maximum inversion commonly observed.

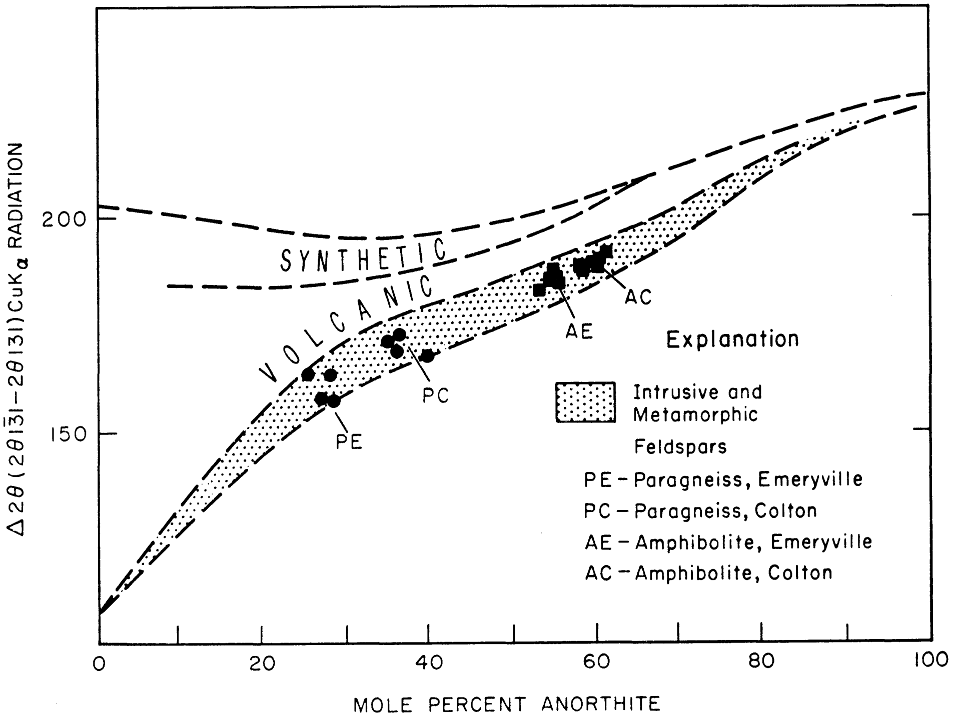

FIG. 5.—Variations in 2Θ (131)–2Θ (131) with composition of plagioclases in the amphibolites and enclosing paragneiss of the Emeryville and Colton areas, New York. Zonal patterns indicate in a general way the distribution patterns of plagioclases formed in (1) regional metamorphic and intrusive igneous rocks, (2) volcanics, and (3) experimental dry-heating experiments (after Smith and Yoder, 1956).

ILMENITE

The principal opaque mineral in the amphibolites is ilmenite. It comprises more than 90 per cent of all opaques except for secondary veinlets of pyrite (see table 1). Ilmenite occurs as ameboid blebs and irregular grains intergrown with, and filling irregular openings between, silicates.

Studies of polished sections and with an electron probe indicate only scattered, small amounts of hematite and other coexisting or exsolved Fe- and Ti-rich oxides, so commonly observed with ilmenite (Buddington, Fahey, and Vlisidis, 1955; Howie, 1955; Vincent and Phillips, 1954). Magnetite is rare. Probably much of the magnetite reported to occur in amphibolites actually is ilmenite, misidentified in thin-section studies. The scarcity of magnetite in many amphibolites seems to be due to the ferrophile nature of the constituent hornblende and to the resulting, highly asymmetrical partitioning of Fe between it and the coexisting oxides.

TABLE 7

PARTIAL ANALYSES* OF ILMENITE IN AMPHIBOLITE INTERLAYERS IN THE GNEISS COMPLEX, EMERYVILLE AND COLTON AREAS, NEW YORK, AND FROM MAFIC GRANULITE, MADRAS, INDIA (HOWIE, 1955)

	EMERYVILLE AREA		COLTON AREA		MADRAS, INDIA† (2941)
	AE 334	AE 326	A 10	AC 342	
TiO_2	52.02	51.98	52.70	52.61	47.63
FeO‡	44.82	44.67	44.36	44.05	48.96
MnO	1.34	1.60	1.12	1.48	0.45
MgO	1.1	1.1	1.3	1.4	0.99
Al_2O_3	N.d.	N.d.	N.d.	N.d.	Nil
Fe/Ti	1.12	1.11	1.09	1.09	1.33
	Trace Elements (P.p.m.)				
Co	56	61	70	99	100
Cr	62	110	550§	340	500†
Cu	69	34	52	96	N.d.
Ni	30	39	58	140	150
Sc	16	20	44	34	N.d.
V	560	730	1,000§	780	1,800§
Zr	390	320	300	300	300

* Major element analyses by Celeste G. Engel; analyses of trace elements by R. G. Havens.

† Ilmenite from mafic granulite ("norite") containing plagioclase, hornblende, hypersthene, augite, ilmenite and magnetite (Howie, 1955, p. 98, table 1, sample 24).

‡ All Fe calculated as FeO.

§ High values probably due to magnetite impurity.

Amounts of ilmenite vary in different amphibolites at Emeryville and Colton from nil up to 9 per cent (by volume). The average is about 2 per cent ilmenite at both Emeryville and Colton; but the Ti content of the total rocks may decrease slightly between Emeryville and Colton. There is no clear indication of increased concentrations of ilmenite formed as hornblende (the major other Ti-bearing mineral) decreases in volume. This is because, as the hornblende content of the rock is halved, its Ti content is almost doubled (see tables 1 and 2). If the Ti of these mafic granulites is eventually concentrated in ilmenite as suggested by Ramberg (1948), it is only after hornblende becomes an accessory mineral or disappears from the assemblage.

Much of the ilmenite in amphibolites at Emeryville is partly or wholly rimmed by sphene, presumably formed as a (late ?) metamorphic reaction product. The sphene disappears with increasing grade of metamorphism in the Edwards area. The disappearance of sphene is essentially coincident with the disappearance of sericite in plagioclase, but this may be an accidental relationship.

Results of partial analyses of ilmenites from the amphibolites at Emeryville and Colton are shown in table 7 along with the analysis of an ilmenite from a layer of pyroxene-hornblende-plagioclase charnockite from Madras, India, analyzed by Howie

(1955). Limitations of sample size prevented precise determinations of Fe_2O_3 in the Adirondack samples. Total Fe is reported as FeO. Presumably Fe_2O_3 totals between 3 and 5 weight per cent.

The concentrations of trace elements in the ilmenites are in certain respects like those measured in the coexisting hornblendes and pyroxenes (cf. tables 2, 7, and 8). For example, amounts of Co and Ni in the ilmenite, hornblende, clinopyroxene, and orthopyroxene are essentially the same within the limits of analytical error. The largest deviations observed are in V and Zr. Both ilmenite and hornblende contain two or more times as much V as do the pyroxenes, and there is over three times as much Zr in the ilmenites as in the coexisting mafic silicates.

Except for the above-cited analysis of ilmenite from charnockite, there are almost no data on the composition of ilmenites in amphibolites with which to compare these analyses. The ratio of Fe/Ti in the Adirondack ilmenites is $\sim$1.1, compared to Fe/Ti of 1.3 found by Howie for ilmenites in the charnockites of Madras, India (table 7).

The amounts of trace elements reported by Howie from the Madras ilmenite are essentially the same as those found in the Emeryville and Colton ilmenites. This is especially true if, as we suspect, the Madras ilmenites and the ilmenite A 10 from Colton contain magnetite impurity. Commonly magnetite contains from 2 to 10 times more V and Cr than ilmenite.

The magnetic properties of amphibolites, from the Emeryville-Colton region are induced largely by ilmenite, and are tabulated and discussed by Balsley and Buddington (1958, p. 783).

QUARTZ

Most of the quartz is confined to the pyroxene-poor amphibolites, reconstituted below $\sim$575° C. Quartz comprises from 2 to 20 per cent (by volume) of the amphibolites at Emeryville and appears in the norm of about one-half of the twenty amphibolites that have been analyzed from the Emeryville area (Engel and Engel, 1962*a*). As clino- and orthopyroxene appear at successively higher temperatures of metamorphism, the quartz content diminishes to nil, and the norms of the Colton amphibolites contain from 3 to 14 per cent olivine (see fig. 1 and table 1).

Probably the total SiO_2 content of the amphibolites also decreases from an average of about 49 per cent at Emeryville to approximately 47 per cent at Colton. This difference is not clear in the forty-two analyses made by classical techniques that are summarized in table 1, but emerges from a study of more than 200 amphibolites and pyroxene-amphibolites from Emeryville and Colton, employing both classical and fluorescent X-ray analyses.

CLINOPYROXENE

The first pyroxene to appear in the amphibolites with increasing metamorphic grade is calcium-rich (clinopyroxene). The threshold temperature at which this Ca-rich pyroxene forms is about 550° C. (about 5 miles northeast of Emeryville, New York; see fig. 1; see also Engel and Engel, 1960, 1962*a*). The appearance of clinopyroxene is essentially coincident with (1) the disappearance of sphene in the rocks, (2) an abrupt decrease in quartz, and (3) an increase in amount of An content of the plagioclase.

The increase in abundance of clinopyroxene with progressively higher temperatures of metamorphism is rapid, and at Colton it constitutes about 20 per cent of the rock, varying in abundance in separate amphibolites from about 15 to 52 volume per cent. The Ca-rich pyroxene is typically pale green in thin section, and lacks visible pleochroism. There are no obvious exsolution laminae.

The chemical compositions of six clinopyroxenes from amphibolites at Colton are listed in table 8 alongside the coexisting Ca-poor orthopyroxene. These clinopyroxenes are similar to those from pyroxene-amphibolites and pyroxene-plagioclase-hornblende gneisses in India, Africa, Scandi-

TABLE 8

CHEMICAL ANALYSES AND STRUCTURAL FORMULAS OF COEXISTING PYROXENES FROM PYROXENE-BEARING AMPHIBOLITES OF THE COLTON AREA, NEW YORK*

	A 10-Cl	A 10-Or	A 104-Cl	A 104-Or	A 105-Cl	A 105-Or	AC 358a-Cl	AC 358a-Or	AC 341-Cl	AC 341-Or	AC 362-Cl	AC 362-Or	MEAN	
													Cl	Or
	Weight Per Cent													
SiO_2	50.95	50.12	50.82	50.28	50.75	50.23	50.85	50.24	50.84	50.24	50.80	50.21	50.84	50.32
TiO_2	0.35	0.72†	0.38	0.32	0.32	0.76†	0.36	0.42	0.39	0.30	0.34	0.21	0.36	0.46
Al_2O_3	2.14	1.30	2.56	2.25	2.12	2.09	2.34	1.71	2.21	1.64	2.17	1.43	2.26	1.74
Fe_2O_3	1.60	0.98	1.72	1.44	1.96	0.89	1.70	1.11	1.77	1.15	1.40	0.84	1.69	1.07
FeO	11.28	29.29	10.62	26.75	11.67	28.76	11.14	28.53	10.38	27.57	11.61	29.93	11.12	28.47
MnO	0.33	0.80	0.29	0.73	0.32	0.70	0.32	0.71	0.33	0.76	0.31	0.62	0.32	0.72
MgO	11.83	15.50	11.53	15.67	11.52	14.70	11.65	15.61	12.04	16.52	11.81	15.55	11.73	15.59
CaO	20.91	1.03	21.16	1.98	20.54	1.56	20.97	1.32	21.06	1.33	20.98	0.83	20.94	1.34
Na_2O	0.34	0.08	0.50	0.17	0.50	0.18	0.44	0.16	0.48	0.14	0.37	0.10	0.44	0.14
K_2O	0.06	0.06	0.04	0.07	0.05	0.06	0.05	0.06	0.05	0.07	0.05	0.06	0.05	0.06
Total	99.79	99.88	99.62	99.66	99.75	99.93	99.82	99.87	99.55	99.72	99.84	99.78	....	....
	Trace Elements (P.p.m.)													
Ba	6	4	8	13	6	6	6	5	8	9	5	4	7	7
Co	45	73	45	77	48	72	44	68	44	75	45	75	45	73
Cr	160	68	400	200	400	170	260	100	320	130	400	130	323	133
Cu	29	71	51	35	25	33	4	5	21	10	27	64	26	36
Ga	6	7	8	10	6	9	6	7	6	8	6	7	6	8
Ni	57	68	49	50	60	50	38	40	61	62	64	70	55	57
Sc	96	23	130	36	120	36	100	20	98	23	120	32	111	28
Sr	10	<10	16	14	14	12	12	<10	14	<10	10	<10	13	<10
V	290	99	370	150	380	140	260	87	320	99	410	100	322	113
Y	28	<20	50	<20	38	<20	28	<20	28	<20	41	<20	36	<20
Yb	3	<5	<5	<5	4	<5	3	<5	3	<5	4	<5	3	<5
Zn	<300	510	<300	520	<300	530	<300	690	<300	560	<300	540	<300	558
Zr	61	32	100	55	80	40	94	34	69	34	76	38	80	39

* The properties of coexisting hornblendes are given in table 3.

† High value probably due to ilmenite impurity.

TABLE 8—*Continued*

	A 10-Cl	A 10-Or	A 104-Cl	A 104-Or	A 105-Cl	A 105-Or	AC 358a-Cl	AC 358a-Or	AC 341-Cl	AC 341-Or	AC 362-Cl	AC 362-Or	MEAN	
													Cl	Or
	Structural Formula on Basis of Six Oxygens													
Si	1.934	1.950	1.928	1.942	1.932	1.956	1.929	1.948	1.929	1.944	1.929	1.947	1.929	1.950
Al	0.066	0.050	0.072	0.058	0.068	0.044	0.071	0.057	0.071	0.056	0.071	0.043	0.071	0.050
Al	0.029	0.009	0.042	0.044	0.026	0.051	0.033	0.025	0.027	0.018	0.025	0.022	0.029	0.029
Ti	0.009	0.021	0.010	0.009	0.009	0.022	0.008	0.012	0.010	0.008	0.009	0.006	0.010	0.013
Fe^{+++}	0.045	0.028	0.048	0.041	0.055	0.012	0.048	0.032	0.050	0.033	0.039	0.024	0.047	0.031
Fe^{++}	0.357	0.925	0.336	0.864	0.371	0.852	0.353	0.925	0.329	0.892	0.368	0.975	0.352	0.922
Mn	0.010	0.026	0.009	0.023	0.010	0.022	0.010	0.023	0.010	0.024	0.009	0.020	0.010	0.023
Mg	0.668	0.898	0.651	0.901	0.653	0.852	0.658	0.901	0.680	0.952	0.668	0.903	0.663	0.899
Ca	0.849	0.042	0.859	0.081	0.837	0.065	0.852	0.054	0.856	0.055	0.853	0.034	0.850	0.055
Na	0.024	0.005	0.036	0.012	0.036	0.013	0.031	0.011	0.035	0.010	0.026	0.007	0.031	0.010
K	0.002	0.002	0.001	0.003	0.002	0.002	0.002	0.002	0.002	0.003	0.002	0.002	0.002	0.002
z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
$x+y$	1.993	1.983	1.992	1.978	1.999	1.975	1.997	1.985	1.999	1.995	1.999	1.993	1.994	1.984
Ca	44.3	2.2	45.3	4.3	43.7	3.5	45.1	2.8	44.7	2.8	44.2	1.8	44.4	2.9
Mg	34.8	46.8	34.4	47.7	34.1	45.7	34.9	47.6	35.5	49.3	34.7	46.6	34.7	47.1
Fe	20.9	51.0	20.3	48.0	22.2	50.8	20.0	49.6	19.8	47.9	21.1	51.6	20.9	50.0

navia, and Great Britain (Howie, 1955, 1958; O'Hara, 1960), Australia (Wilson, 1960), North America (Norton and Clavan, 1959; and Subramaniam, 1962). The nearly identical counterpart of the Colton clinopyroxene is described by Howie, from a pyroxene amphibolite in the Sudan, which is very similar in other features to the Colton amphibolite (Howie, 1958, table 1).

The range and mean concentrations of trace elements in the Ca-rich pyroxenes at Colton are given in table 8. These values for specific elements are remarkably uniform, reflecting the uniformities in amounts of major elements. In table 9 the mean concentrations of trace elements from the Colton pyroxenes are compared with mean values from Ca-rich pyroxenes in pyroxenic metamorphic rocks of widely divergent terranes, as reported by Howie (1955), DeVore (1955), and Moxham (1960). The data reported by Moxham are for trace elements in clinopyroxenes in skarns in Ontario and Quebec, Canada. Those reported by DeVore are from Ca-rich pyroxenes in pyroxenites from Greenland, North Carolina, and Maryland (1955, p. 489). The divergences that exist in the numbers are very large, but it is not possible to state whether these are due principally to differences in the several rock systems, to impurities, or to errors in analyses. The data cited from Howie (1955) are analyses of trace elements in pyroxenes from mafic layers associated with charnockites near Madras, India, which are very like the Colton rocks in composition and, possibly, in origin. In this instance the concentrations of trace elements reported by Howie (1955) are essentially those found in the Colton pyroxenes.

TABLE 9

TRACE ELEMENTS REPORTED FOR CLINOPYROXENES IN WIDELY SEPARATED, BASIC METAMORPHIC ROCKS (P.P.M.)*

	Colton (1)	Canada (2)	India (3)	India (4)	Others (5)
Ba	7	11	5	...	...
Co	45	12	50	65	24– 40
Cr	323	31	300	75	378–3,850
Ga	6	10	10	7	2– 6
Mn	2,300	1,348	1,500	1,900	...
Ni	55	13	70	50	120– 256
Sc	111	9	100	80	33– 98
Sr	13	80	10	Tr.	25– 115
V	322	31	400	400	150– 231
Y	36	9	40	40	Tr.– 40
Zr	80	38	150	...	Tr.– 105

* Col. (1): average of analyses of 8 clinopyroxenes in amphibolites of the Colton area, Adirondack Mountains (see table 8 for individual analyses); col. (2): weighted average of analyses of trace elements in clinopyroxenes from metamorphic rocks, largely skarns, in Ontario and Quebec, Canada (Moxham, 1960, table 6, p. 537); cols. (3) and (4): analyses of trace elements in clinopyroxenes nos. 2941 and 4642A from "norite" and "hypersthene diorite," India (Howie, 1955, table 11, p. 758); col. (5): range in amounts of trace elements reported for three clinopyroxenes from pyroxenites from Greenland, North Carolina, and Maryland (DeVore, 1955, table 13, p. 489).

ORTHOPYROXENE

The first appearance of orthopyroxene in the Adirondack amphibolites is at temperatures of metamorphism of ~575° C., northeast of Edwards, New York (see fig. 1). From this point northeast to the perimeter of the Adirondack massif at Colton, orthopyroxene increases rapidly in abundance in the amphibolite layers. At Colton, orthopyroxene averages some 14 volume per cent of the amphibolites, but the range in abundance is large. It is absent in a very few amphibolites and comprises over half of a few others.

Typical orthopyroxene is pleochroic, pale green to pale pink in thin section, and devoid of lamellae. The intensity of pleochroism varies considerably between specimens. Microscopic inclusions appear in a few grains as rectangular, elliptical, and rod-shaped bodies aligned along either or both of the dominant cleavages. These inclusions vary in color and abundance but rarely constitute over 0.5 volume per cent of the total pyroxene sample.

The composition of six orthopyroxenes from typical pyroxene amphibolites near Colton is given in table 8, alongside the compositions of the Ca-rich pyroxene. There is an equally strong similarity in composition of the Colton orthopyroxenes with Ca-poor orthopyroxenes in mafic granulites and pyroxene-amphibolites from Africa (Howie, 1958, table 1), India (Howie, 1955, p. 754–757; Howie and Subramaniam, 1957, p. 579; Subramaniam, 1962, table 2, sample Ch 132), Pennsylvania and Delaware (Clavan, McNabb, and Watson, 1954), and elsewhere. The previously cited investigation of Howie (1955, tables 1 and 2) of a pyroxene-amphibolite from the Sudan permits the most exacting comparisons, because of the completeness of Howie's data on both rock and constituent minerals.

DISTRIBUTION OF ELEMENTS BETWEEN MINERALS

The distribution of elements between the minerals in metamorphic rocks may be indicative of the degree to which equilibrium has been approached, the *T* and *P* conditions extant during the reconstitution process, and the permeability and composition of the rock system. The measured distributions for elements like Mg and Fe, expressed as a distribution coefficient or fitted to theoretical functions, also suggest the nature of the solid solutions (Ramberg and DeVore 1951; Kretz, 1959, 1961; Mueller, 1960, 1961; Bartholomé, 1962). The extended treatment of the subject in recent years has been stimulating and enlightening, but is featured by an excessive reworking of both inadequate and inaccurate data. Most participants now seem to have agreed that optical constants are not a substitute for good chemical analyses, but there is still too little critical evaluation of field relations, the composition of the total rock assemblage, and the quality of the chemical analyses of minerals, especially the partial analyses obtained by use of the emission spectrograph.

The extended recent manipulations of the analyses of pyroxene originally published by Clavan *et al.* (1954) represent an example of uncritical use of questionable data. Seven pairs of pyroxenes from southeastern Pennsylvania and Delaware were analyzed by them. They recognized that most analyses of minerals are made by techniques evolved for rocks and not completely adequate for minerals such as pyroxenes—in which there is a most unequal distribution of oxides, and where MgO plus total Fe may amount to as much as 50 per cent of the total oxides. In an attempt to fit techniques to needs, Clavan *et al.*, in their studies of the orthopyroxenes, attempted new analytical procedures (1954, p. 570–574). Using these new procedures they obtained values for Al_2O_3 ranging from 0.00 to 0.57 with a mean of 0.10 weight per cent Al_2O_3.

The concentration of Al reported for some of these pyroxenes is probably low by a factor of 10 or more, and certainly there is some Al in all of them. When these pyroxene analyses are calculated to the structural formula where $Z(\mathrm{Si} + \mathrm{Al})$ must total 2.00 they are deficient. This lack of fit of these analyses with a well-established structural formula strongly suggests that the analyses are inferior. This conclusion may be independently arrived at from the fact that other accepted methods of analyses of pyroxenes from granulite facies rocks yield >0.5 Al_2O_3.

In 1959 Norton and Clavan studied clinopyroxenes from the same rocks that yielded the orthopyroxenes discussed above. This composite work produced the pyroxene pairs so widely cited in subsequent studies. It is of considerable interest to note that in the second study, on clinopyroxenes, Clavan abandoned his own methods of analysis and returned to more conventional techniques. The results are analyses that do fit the structural formula for pyroxenes.

The distribution of most elements between the coexisting minerals in the average amphibolite from Emeryville and Colton, New York, is given in terms of volume and density in table 10, A and B. Graphical representations of specific distributions of major elements appear in figures 6, 7, 9, and 10. Equilibrium appears to have been closely approached during metamorphic recrystallization, a fact indicated here by the remarkably uniform distribution of various elements within the coexisting phases of the amphibolites in any one of the extensively sampled areas.

The gross distribution patterns in the silicates reflect (1) the high concentrations of Al, Na, K, Ba, Ga, Sr, and Pb in the plagioclase and hornblende compared to that found in the pyroxenes, and (2) the relative abundance and complex substitutions of the common ions in hornblende and Ca-rich pyroxene as compared with Ca-poor pyroxene and plagioclase.

The first cited feature is directly related to the expulsion of Na and K, along with H_2O, from the rock as the pyroxenes and more calcic plagioclase displace hornblende, andesine, and quartz (Engel and Engel, 1962*a*). From the regional data on these rocks, especially in the central Adirondack massif (Engel and Engel, 1962*a*) we may

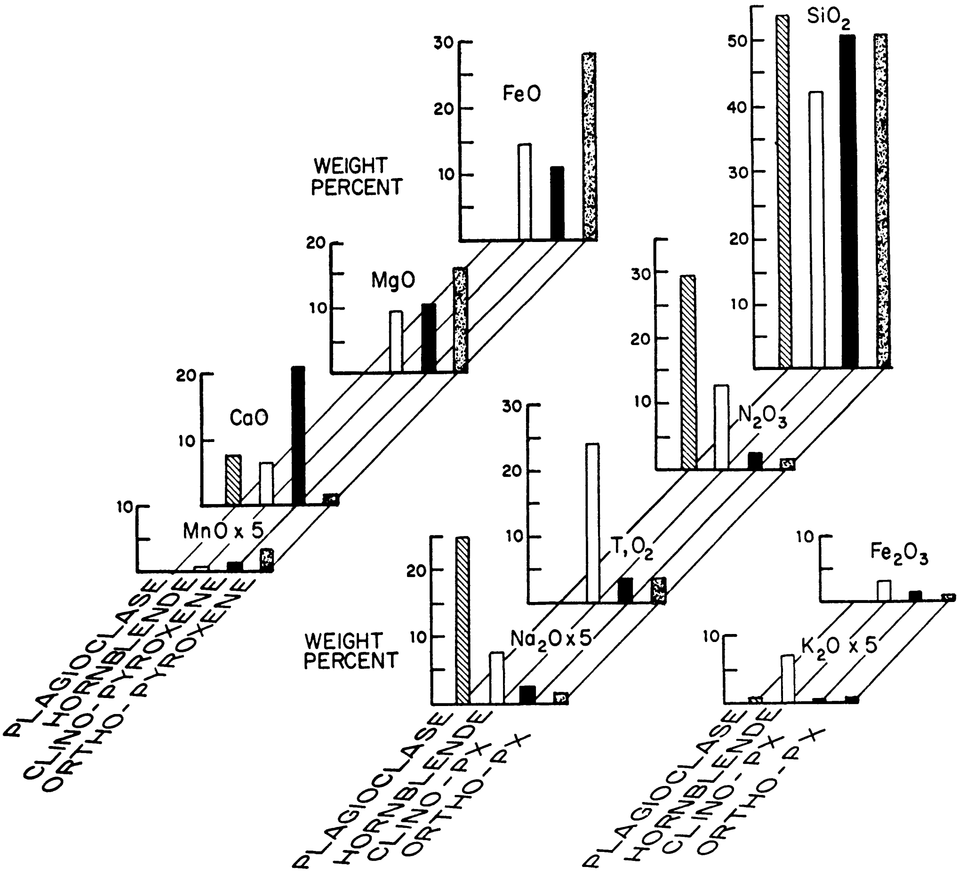

FIG. 6.—Amounts in weight per cent of the major constituent oxides in coexisting plagioclase, hornblende, clinopyroxene, and orthopyroxene from the average amphibolite rock in the gneiss complex, Colton area, New York.

TABLE 10

PARTITIONING OF ELEMENTS BETWEEN COEXISTING MINERALS IN THE AVERAGE AMPHIBOLITE ROCK AT EMERYVILLE AND COLTON, NEW YORK

A. PARTITIONING OF ELEMENTS IN MINERALS

	SiO_2	Al_2O	Fe_2O	FeO	CaO	MgO	Na_2O	K_2O	MnO	TiO_2	H_2O
	Average Rock, Emeryville Area										
Quartz	7.70	......	......	......	......	......	......	......	......	......	......
Albite	5.02	1.42	......	......	......	......	0.86	......	......	......	......
Anorthite	3.76	3.19	......	......	1.75	......	......	......	......	......	......
Hornblende	30.45	8.98	3.54	9.82	8.36	6.48	0.95	0.73	0.22	0.95	1.31
Ilmenite	......	......	0.04	1.00	......	0.03	......	......	.03	1.20	......
Other*	0.81	0.72	......	......	......	0.05	0.02	.19	......	......	0.01
Total (from minerals)†	47.74	14.31	3.58	10.82	10.11	6.56	1.83	.92	.25	2.15	1.32
Total (rock analysis)‡	48.20	14.45	3.50	10.53	10.25	6.62	1.94	0.96	0.25	1.89	1.31
	Average Rock, Colton Area										
Albite	8.17	2.32	......	......	......	......	1.40	......	......	......	......
Anorthite	8.07	6.86	......	......	3.75	......	......	......	......	......	......
Hornblende	14.17	4.10	1.12	4.73	3.86	3.07	0.51	0.47	0.06	0.80	0.50
Clinopyroxene	10.49	0.45	0.36	2.14	4.33	2.38	0.09	.01	.06	0.08	......
Orthopyroxene	6.49	0.21	0.14	3.47	0.17	2.13	0.02	.01	.10	0.04	......
Ilmenite	......	......	0.04	0.95	......	0.03	......	......	.03	1.15	......
Other*	0.32	0.26	0.05	0.08	......	0.14	......	......	......	......	.12
Total (from minerals)†	47.71	14.20	1.71	11.37	12.11	7.75	2.02	.49	.25	2.07	.62
Total (rock analysis)‡	47.89	14.63	1.85	11.20	11.54	7.41	2.19	0.58	0.25	1.56	0.72

* Largely sericite and traces of chlorite at Emeryville; traces of hematite, chlorite, and serpentine at Colton.

† Chemical composition of the rock calculated from compositions and densities of constituent minerals.

‡ Composition of the rock determined by direct chemical analyses (see table 1).

B. MINERALOGICAL DATA

Mineral	Mode	Density	Weight Equivalent	Weight Per Cent
	Average Rock, Emeryville Area			
Quartz	9.0	2.65	23.85	7.7
Albite	8.7	2.62	22.79	7.3
	An54			
Anorthite	9.8	2.76	27.04	8.7
Hornblende	68.6	3.26	223.63	71.8
Ilmenite	1.5	4.72	7.08	2.3
	Average Rock, Colton Area			
Albite	14.3	2.62	37.46	11.9
	An60			
Anorthite	21.4	2.76	59.06	18.7
Hornblende	32.2	3.28	105.94	33.6
Clinopyroxene	19.2	3.38	64.89	20.6
Orthopyroxene	11.3	3.61	40.79	12.9
Ilmenite	1.5	4.72	7.08	2.2

predict further expulsion of these elements, along with Ti and Mn, with reconstitution at progressively higher *T* and *P* in the crust.

Considering the coexisting pyroxenes, the Ca-rich pyroxene has a higher Fe^{+++}, Ti, Na, Al, Cr, V, and Mg/(Mg + Fe) ratio relative to the coexisting orthopyroxene.

The distribution of major ions in coexisting pyroxenes has been illustrated schematically (see esp. the discussion by Bartholomé, 1962) as

$$\begin{array}{ccccccc} (\mathrm{CaFeSi_2O_6})_{\text{Ca-r}} & + & (\mathrm{MgSiO_3})_{\text{Ca-p}} & \rightleftharpoons & (\mathrm{CaMgSi_2O_6})_{\text{Ca-r}} & + & (\mathrm{FeSiO_3})_{\text{Ca-p}} \\ \text{hedenbergite} & + & \text{enstatite} & \rightleftharpoons & \text{diopside} & + & \text{orthoferrosilite ,} \\ & & \text{(or clinoenstatite)} & & & & \text{(or ferrosilite)} \end{array}$$

where Ca-r = calcium-rich pyroxene and Ca-p = calcium-poor pyroxene. Under equilibrium conditions

$$(a_{\mathrm{CaMgSi_2O_6}}/a_{\mathrm{CaFeSi_2O_6}})_{\text{Ca-r}} \times (a_{\mathrm{FeSiO_3}}/a_{\mathrm{MgSiO_3}})_{\text{Ca-p}} = K_p(T)\,,$$

where a = activity of the various components.

If the coexisting pyroxenes are ideal solutions, it is possible to equate activities of

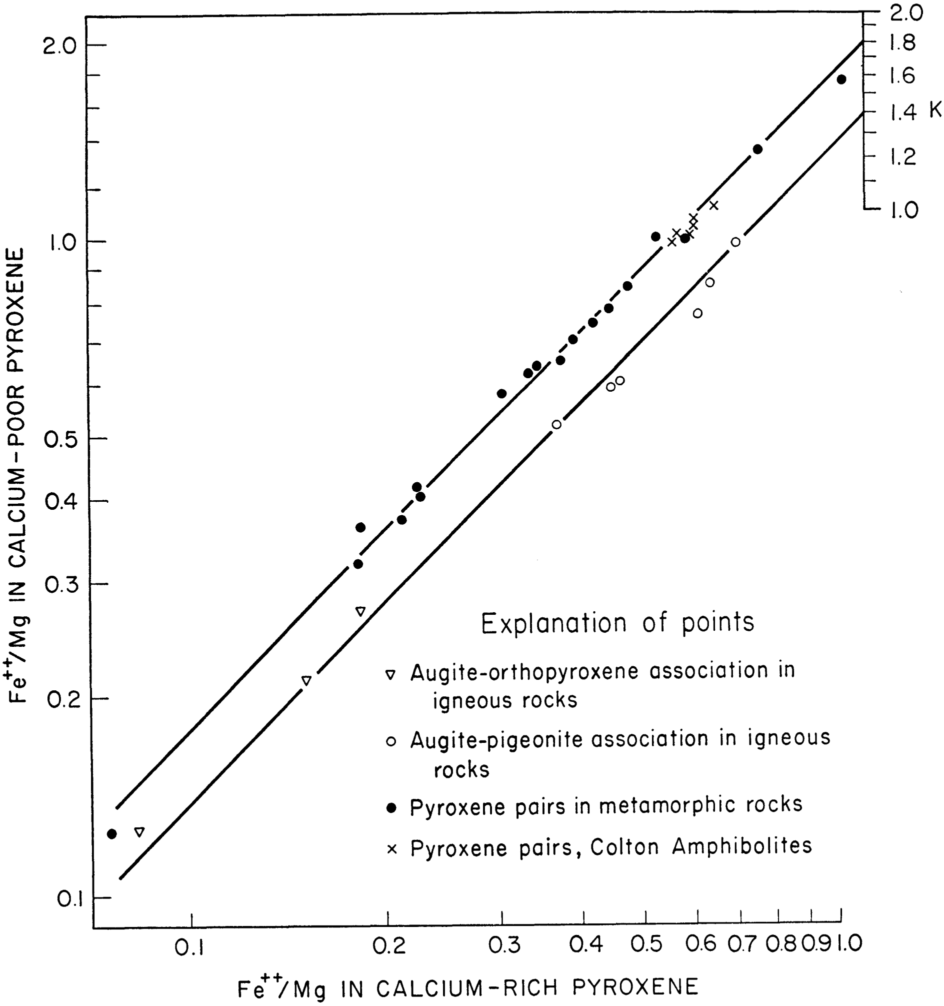

FIG. 7.—Graphical log-log plot indicating the distribution of Fe^{++}/Mg in coexisting pyroxenes in mafic igneous rocks compared with those in the Colton amphibolites and other mafic granulites (diagram after Bartholomé, 1962).

the components with their mole fractions (Sahama and Torgeson, 1949; Turner and Verhoogen, 1960, p. 21; Bartholomé, 1962). Thus

$$(a_{\mathrm{CaFeSi_2O_6}}/a_{\mathrm{CaMgSi_2O_6}})_{\mathrm{Ca\text{-}r}} = (\mathrm{Fe^{++}/Mg})_{\mathrm{Ca\text{-}r}},$$

and

$$(a_{\mathrm{FeSiO_3}}/a_{\mathrm{MgSiO_3}})_{\mathrm{Ca\text{-}p}} = (\mathrm{Fe^{++}/Mg})_{\mathrm{Ca\text{-}p}},$$

and the equilibrium condition becomes

$$(\mathrm{Fe^{++}/Mg})_{\mathrm{Ca\text{-}p}} = (\mathrm{Fe^{++}/Mg})_{\mathrm{Ca\text{-}r}} \times K_p(T).$$

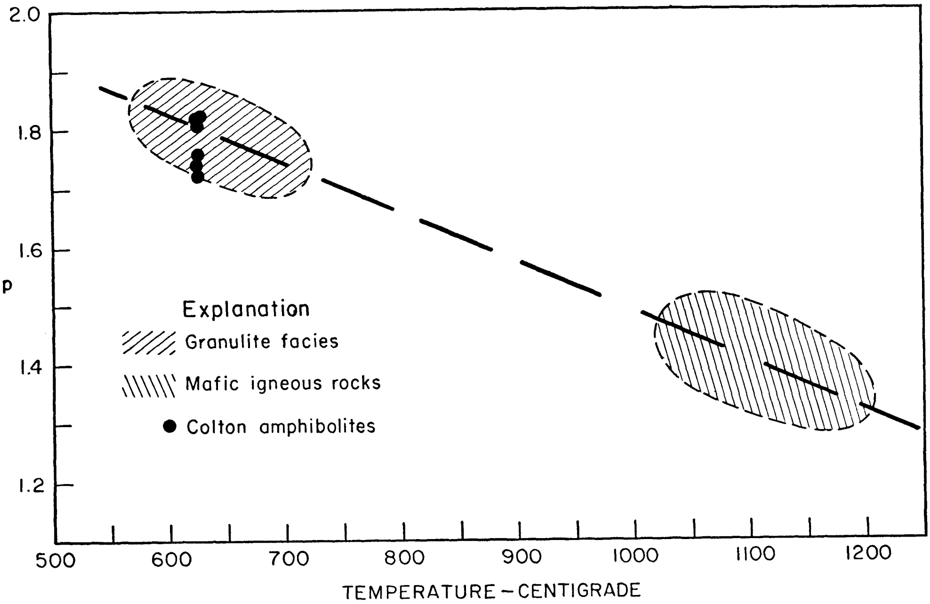

FIG. 8.—Approximate distribution of K_p in coexisting pyroxenes in mafic metamorphic and igneous rocks, as a function of temperature of crystallization.

The distribution coefficients of Mg and Fe in the coexisting pyroxenes at Colton fit the function derived by Mueller (1961) on the assumption that the two pyroxenes are essentially ideal solid solutions of their Mg and Fe end members.

Kretz (1961) and Bartholomé (1962) also note, in support of the above-cited relationship, an interesting relationship between rock environment and the K_p values obtained for coexisting pyroxenes (Bartholomé, 1962, p. 6–11). The K_p value of pyroxenes in igneous rocks, especially the stratiform sheets, are clearly lower by about 0.4 than K_p values of coexisting pyroxenes of mafic granulites and pyroxene amphibolites. This separation in K_p values of pyroxenes from igneous and metamorphic environments is shown in figures 7 and 8. Data on pyroxenes from the pyroxenite from Sutherland and the "granulite" from Ardnamurchan published by Muir and Tilley (1958) are omitted because they may be of igneous rather than metamorphic origin (see Bowes, Wright, and Park, 1961).

The positions of the K_p value for the coexisting pyroxenes from the Colton amphibolites conform with the curve derived from other metamorphic pyroxenes (fig. 7).

The relationship between K_p value of these pyroxenes and the mole fraction of $\mathrm{CaSiO_3}$ (hereafter *m*) in the clinopyroxene also appears to be a function of the environment of the parent rock. Bartholomé has noted that where the $K_p > 1.6$, $m > 0.45$; where $K_p < 1.6, m < 0.45$. In general, $m > 0.45$ for the pyroxenes in metamorphic rocks and $m < 0.45$ for pyroxenes in mafic igneous rocks. The question has been raised whether these differences are largely due to the differing temperatures at which the pyroxene-bearing metamorphic and igneous rocks crystallized. The variation of K_p with temperatures of crystallization appears to have the approximate slope indicated in figure 8. The K_p values for the coexisting pyroxenes at Colton are plotted on this curve using as temperatures of crystallization the data from several geothermom-

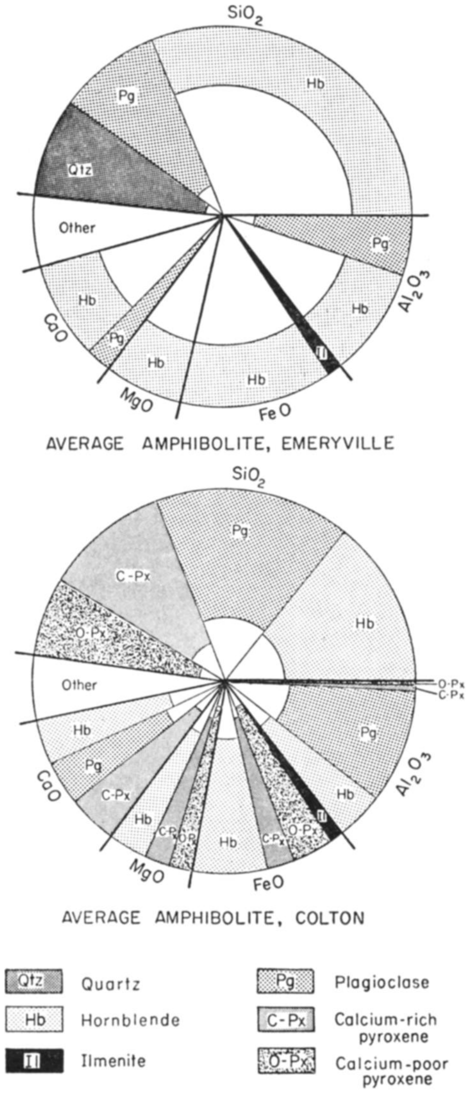

FIG. 9.—Diagrams showing the interrelations of the average modal and chemical compositions of the amphibolite rocks at Emeryville and Colton, and the partitioning of major elements between the coexisting phases. The volume per cent of each mineral species is indicated by the length of the radius of the inner, pattern-free segments, relative to the radius of the main, enclosing circles (neglecting "other"). Each partitioned arcuate segment of the main circle indicates the per cent of major oxide in the indicated mineral, relative to other minerals.

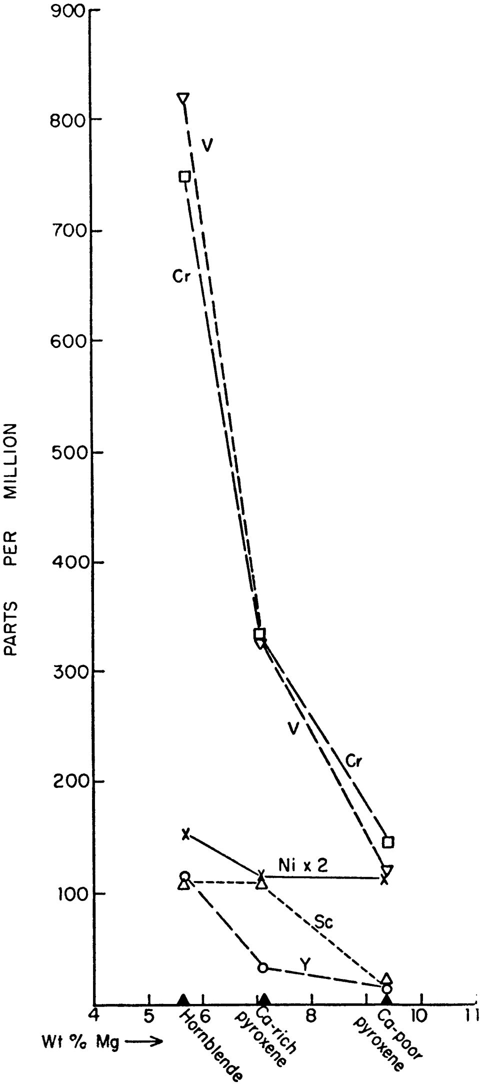

FIG. 10.—Relation between total Mg and the amounts of Cr, Ni, Sc, V, and Y in co-existing hornblende, clinopyroxene, and orthopyroxene in the amphibolites at Colton, New York. The data are averages from tables 2 and 8.

eters (Engel and Engel, 1958, p. 1382–1387; Hess, 1961, p. 144–146). It should be noted that 625° C. is the minimum estimated from geothermometers for the metamorphism at Colton. The maximum temperature could be at least 50° higher. Obviously, this sort of curve-fitting is not sufficiently demanding to require more than approximate temperatures or K_p values. Demonstrably inaccurate analyses of pyroxenes will fit this curve, and the complicating effects of pressure and composition of the rock system are yet to be evaluated rigorously.

In a more general way, the distribution of elements between the coexisting minerals and the relation of this distribution to the mode and densities of the coexisting phases in the Emeryville and Colton amphibolites are illustrated in figure 9. The upper circular diagram in figure 9 represents the relations in the average amphibolite at Emeryville; the lower circle depicts the relations at Colton. In each circle the inner, unshaded, arcuate segment indicates, by the length of its radius relative to length of the radius of the large circle, the abundance of each mineral. The span of the outer arc defined by the oxides indicates the partitioning of the several major elements in the rock, weighted according to the volume per cent and density of each mineral species.

The relations between total Mg in the three mafic silicates (hornblende, clinopyroxene, and orthopyroxene) and the concentrations of Cr, V, Ni, Sc, and Y in these minerals are graphed in figure 10. In general the correlation appears to be systematic, but negative! There appears to be no simple, positive correlation between the concentrations of these trace elements and concentrations of Fe, Mg, or the ratio Fe/Mg.

In conclusion it is clear that the partitioning of elements in the amphibolites is in general accordance with the classical concepts of chemical coherence outlined by Goldschmidt (1937); but detailed deviations occur from simple, predictable relations, and the explanation of these apparent anomalies will require more precise and accurate measurements and sophisticated theoretical analyses.

ACKNOWLEDGMENTS.—These studies were made possible through financial support of the National Science Foundation (Earth Sciences, Grant 14177), the U.S. Geological Survey, and the University of California.

Michael Fleischer, Ralph Kretz, George Phair, and David Wones were kind enough to review the manuscript. Their critical suggestions for its improvement are very much appreciated.

REFERENCES CITED

BALSLEY, J. R., and BUDDINGTON, A. F., 1958, Iron-titanium oxide minerals, rocks, and aeromagnetic anomalies of the Adirondack area, New York: Econ. Geology, v. 53, p. 777–805.

BARTHOLOMÉ, P., 1962, The iron-magnesium ratio in associated pyroxenes and olivines: Geol. Soc. America, Buddington Volume, p. 1–20.

BOWES, D. R., WRIGHT, A. E., and PARK, R. G., 1961, Field relations of rocks containing coexisting pyroxenes: Geol. Mag., v. 98, p. 530–531.

BUDDINGTON, A. F., FAHEY, J., and VLISIDIS, ANGELINA, 1955, Thermometric and petrogenic significance of titaniferous magnetite: Am. Jour. Sci., v. 253, p. 497–523.

CLAVAN, W. S., MCNABB, W. M., and WATSON, E. H., 1954, Some hypersthenes from SE Pennsylvania and Delaware: Am. Mineralogist, v. 39, p. 566–580.

DEVORE, G. W., 1955, Crystal growth and the distribution of elements: Jour. Geology, v. 63, p. 471–494.

ENGEL, A. E. J., and ENGEL, CELESTE G., 1958, Progressive metamorphism and granitization of the major paragneiss, northwest Adirondack Mountains, New York, Part 1, Total rock: Geol. Soc. America Bull., v. 69, p. 1369–1414.

——— — ——— 1960*a*, Progressive metamorphism and granitization of the major parageneiss, northwest Adirondack Mountains, New York, Part 2, Mineralogy: *ibid.*, v. 71, p. 1–58.

——— — ——— 1960*b*, Migration of elements during metamorphism in the northwest Adirondack Mountains, New York: U.S. Geol. Survey Prof. Paper 400-B, p. 465–470.

——— — ——— 1961, Variations in properties of hornblendes formed during progressive metamorphism of amphibolites, northwest Adirondack

Mountains, New York: U.S. Geol. Survey Prof. Paper 425-C, p. 313–316.

Engel, A. E. J., and Engel, Celeste G., 1962*a*, Progressive metamorphism of amphibolites, northwest Adirondack Mountains, New York: Geol. Soc. America, Buddington Volume, p. 37–82.

——— — ——— 1962*b*, Hornblendes formed during progressive metamorphism of amphibolites, northwest Adirondack Mountains, New York: Geol. Soc. America Bull., v. 73, p. 1499–1514.

Goldschmidt, V. M., 1937, The principles of distribution of chemical elements in minerals and rocks: Jour. Chem. Soc. London, p. 655–675.

Hess, H. H., 1960, Stillwater igneous complex, Montana, a quantitative mineralogical study: Geol. Soc. America Mem. 80, 225 p.

Howie, R. A., 1955, The geochemistry of the charnockite series of Madras, India: Trans. Roy. Soc. Edinburgh, v. 62, p. 725–768.

——— 1958, African charnockites and related rocks: Congo Belge, Serv. géol. Bull., v. 8, p. 1–14.

——— and Subramaniam, A. P., 1957, The paragenesis of garnet in charnockite, enderbite, and related granulites: Mineralog. Mag., v. 31, p. 565–586.

Kretz, R., 1959, Chemical study of garnet, biotite, and hornblende from gneisses of south-western Quebec, with emphasis on distribution of elements in coexisting minerals: Jour. Geology, v. 67, p. 371–402.

——— 1961, Correspondence: Mineralog. Mag., v. 98, p. 31–32.

Moxham, R. L., 1960, Minor element distribution in some metamorphic pyroxenes: Canadian Mineralogist, v. 6, p. 522–545.

Mueller, R. F., 1960, Compositional characteristics and equilibrium relations in mineral assemblages of a metamorphosed iron formation: Am. Jour. Sci., v. 2, p. 449–497.

——— 1961, Analysis of relations among Mg, Fe and Mn in certain metamorphic minerals: Geochim. et Cosmochim. Acta, v. 25, p. 267–296.

Muir, I. D., and Tilley, C. E., 1958, The composition of co-existing pyroxenes in metamorphic assemblages: Geol. Mag., v. 95, p. 403–408.

Norton, D. A., and Clavan, W. S., 1959, The optical mineralogy, chemistry and X-ray crystallography of ten clinopyroxenes from the Pennsylvania and Delaware Piedmont Province: Am. Mineralogist, v. 44, p. 844–874.

O'Hara, M. J., 1960, Co-existing pyroxenes in metamorphic rocks: Geol. Mag., v. 97, p. 498–503.

Ramberg, H., 1948, Titanic iron ore formed by dissociation of silicates in granulite facies: Econ. Geology, v. 43, p. 553–570.

——— and DeVore, G. W., 1951, The distribution of Fe^{++} and Mg^{++} in coexisting olivines and pyroxenes: Jour. Geology, v. 59, p. 193–210.

Sahama, Th. G., and Torgeson, D. R., 1949, Some examples of the application of thermochemistry to petrology: Jour. Geology, v. 57, p. 255–262.

Sen, S. K., 1959, Potassium content of natural plagioclases and the origin of antiperthites: Jour. Geology, v. 67, p. 479–495.

——— 1960, Some aspects of the distribution of barium, strontium, iron, and titanium in plagioclase feldspars: *ibid.*, v. 68, p. 638–665.

Smith, J. R., 1960, Optical properties of low-temperature plagioclase: Geol. Soc. America Mem. 80, Appendix, p. 191–219.

Smith, J. V., and Yoder, H. S., 1956, Variations in X-ray powder diffraction patterns of plagioclase feldspars: Am. Mineralogist, v. 41, p. 632–647.

Subramaniam, A. P., 1962, Pyroxenes and garnets from charnockites and associated granulites: Geol. Soc. America, Buddington Volume, p. 21–36.

Turner, F. J., and Verhoogen, J., 1960, Igneous and metamorphic petrology: New York, McGraw-Hill Book Co.

Vincent, E. A., and Phillips, R., 1954, Iron-titanium oxide minerals in layered gabbros of the Skaergaard intrusion, East Greenland, Part 1, Chemistry and ore-microscopy: Geochim. et Cosmochim. Acta, v. 6, p. 1–26.

Wilcox, R. E., and Poldervaart, A., 1958, Metadolerite dike swarm in Bakersville-Roan Mountain area, North Carolina: Geol. Soc. America Bull., v. 69, p. 1323–1368.

Wilson, A. F., 1960, Co-existing pyroxenes: Some causes of variation and anomalies in the optically derived compositional tie-lines, with particular reference to charnockitic rocks: Geol. Mag., v. 97, p. 1–17.