

## CHEMICAL CHANGES IN PLAGIOCLASES AND THEIR BEARING ON THE PETROLOGIC HISTORY OF AN AMPHIBOLITE BODY

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### ABSTRACT

Electron microprobe analyses are given for 23 plagioclase crystals from a Precambrian amphibolite body. This mineral has undergone systematic changes in composition, shape, and size as a consequence of adjustment to rising temperatures during metamorphism. The increase in metamorphic grade, reaching the amphibolite facies, seems to be related to a granite intrusion bordering the southeast side of the amphibolite body.

### INTRODUCTION

The main purpose of the present paper is to discuss the chemical composition of plagioclase crystals from an amphibolite body cropping out in the vicinity of Jaraguá, 15 miles northwest of the city of São Paulo. This amphibolite body, occupying an area about one square mile in extent, has been previously investigated by Gomes (1962), Gomes *et al.* (1964), and Gomes (1971). It occurs associated with conglomeratic meta-arkoses, sericite schists, and quartzites, and on the southeast side is in contact with a porphyritic granite, which is younger than the surrounding rocks. It has a trend of about N20W, and seems to be discordant with respect to regional structure (Fig. 1). General information on the regional geology may be found in Coutinho (1955), Cordani *et al.* (1961), and more recently Coutinho (1968).

The origin of these amphibolites, the metamorphosed equivalent of tholeiitic basalt or diabase, was established by Gomes *et al.* (1964) from petrographic features (local relict ophitic structure, and the presence of lath-like complexly twinned plagioclase) and chemical analyses. The analyses were utilized in a petrochemical study of major and trace elements for 20 samples using the same procedure applied by Evans and Leake (1960) for the Connemara amphibolites.

Based on mineralogical and textural characteristics, Gomes *et al.* (1964) distinguished two different zones within the amphibolite body: A) a central-westerly zone characterized by hornblende of low refractive index and light color, and untwinned or simply twinned plagioclase of composition  $An_{13}$ - $An_{55}$ . The rocks are somewhat schistose and fine-grained. B) a south-southeast zone in which the hornblende has high

refractive index and deep color, and the plagioclase is more calcic ( $An_{55}$ - $An_{82}$ ) and commonly shows complex twinning. The rocks are coarse grained and the schistosity is less pronounced than in the first zone.

More recently Gomes (1971) carried out a detailed study by electron microprobe analysis on the chemical composition of the principal minerals of these rocks. The present paper gives a brief description of the feldspar group.

#### ANALYTICAL TECHNIQUE

The analytical work was carried out with an Applied Research Laboratories EMX electron probe microanalyser in the Department of Geology and Geophysics, University of California, Berkeley. Instrumental conditions were: accelerating potential 15 KV, specimen current  $0.05$ - $0.09 \mu \text{A}$ , integration time on scalars 20 seconds, spot size variable from 1 to 20 microns diameter, LiF, ADP and KAP crystal channels detecting X-ray quanta simultaneously. Analysis conditions were adjusted to eliminate loss of K and Na by volatilization. Corrections were made for instrumental drift. The standards used, all natural specimens, were: Tiburon albite (unpublished,  $\text{SiO}_2$ , 68.22 percent;  $\text{Al}_2\text{O}_3$ , 9.90 percent;  $\text{Na}_2\text{O}$ , 11.73 percent), oligoclase E 32 (Ribbe and Smith, 1966), bytownite (unpublished,  $\text{SiO}_2$ , 48.08 percent;  $\text{Al}_2\text{O}_3$ , 32.05 percent;  $\text{CaO}$ , 15.50 percent;  $\text{Na}_2\text{O}$ , 2.73 percent). The accuracy is estimated at between 1 and 2 percent of the amount present for the major elements.

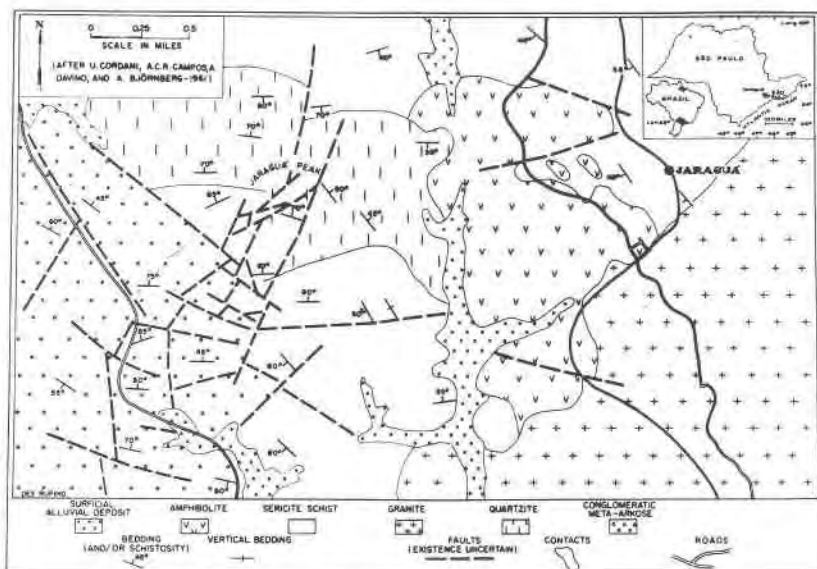


FIG. 1. General geology of the Jaraguá area.

## CHEMICAL COMPOSITION

The plagioclase crystals of the schistose amphibolites, which correspond to Zone A of the body, are fine-grained (variable dimensions from 0.05 to 0.20 mm and averaging 0.10 mm), xenoblastic, and almost devoid of twinning. As given by optical determinations, the anorthite content is low. On the other hand, the plagioclase samples of the non-schistose amphibolites, in Zone B, cropping out near the granite contact at the southern part of the body, are coarse (variable dimensions from 0.10 to 1.00 mm and averaging 0.30 mm), commonly twinned on the albite law, and show a pronounced tendency to develop the lath-like habit that is so common in igneous plagioclase. Other twin laws (pericline, albite-Carlsbad) are also peculiar to these minerals. The plagioclase crystals from the non-schistose rocks are higher in anorthite content than the plagioclases from the schistose Zone A.

Chemical data obtained for 23 samples, 14 from Zone A and 9 from Zone B, are given in Tables 1 and 2 together with formulae calculated on the basis of 32 oxygen atoms. For each sample, data correspond to a mean composition from about 20 spots in different crystals. Zoning is an uncommon feature in these minerals. An average composition for the two zones is presented in Table 3.

Chemical composition of the plagioclase crystals, as indicated by weight percent An, Ab, and Or, is plotted in Figure 2. The zonal distribution of anorthite content in these minerals within the amphibolite body, using the mean values from Tables 1 and 2, is presented in Figure 3.

The analytical results, as emphasized by the histograms from Figures 4 and 5, clearly indicate the more calcium character of the plagioclase samples from Zone B, in agreement with previous conclusions from optical determinations by the author.

As one can see in the tables and better in Figure 2,  $K_2O$  has no important participation in plagioclase crystals composition. No significant contribution is given by  $TiO_2$ ,  $Fe_2O_3$ ,  $MnO$ , or  $MgO$  owing to their low contents.

If the JA-24 values are excluded for reasons stated below, the new compositional fields for Zones A and B could be tentatively fixed as  $An_{18}$ — $An_{51}$  and  $An_{49}$ — $An_{87}$  respectively, despite the great variation in anorthite content shown by the analyzed samples.

As seen in Figure 2, no composition has been determined between  $An_5$ — $An_{17}$ , which corresponds to the peristerite interval according to Laves (1954), and only two analyses (sample JA-7) gave values close to  $An_{20}$ , Christie's (1959) upper limit for the peristerite field.

Table 1  
Chemical composition of plagioclase crystals from Zone A

	JA-4	JA-6	JA-7	JA-20	JA-21	JA-24	JA-26	JA-28	JA-30	JA-31	JA-33	JA-34	JA-35	JA-39
SiO <sub>2</sub>	57.9	58.4	62.9	59.4	56.9	68.3	61.3	56.1	57.1	58.5	57.1	57.6	58.0	59.3
TiO <sub>2</sub>	-	0.01	tr	0.05	0.02	0.03	tr	tr	tr	0.02	0.01	0.02	0.02	0.04
Al <sub>2</sub> O <sub>3</sub>	26.4	26.0	23.3	25.3	26.0	19.9	23.3	26.8	27.5	25.9	26.6	26.4	26.7	25.1
Fe <sub>2</sub> O <sub>3</sub> *	0.31	0.26	0.18	0.32	0.25	0.22	0.19	0.19	0.18	0.31	0.22	0.42	0.36	0.19
MnO	-	tr	0.01	tr	tr	-	-	-	tr	-	tr	tr	tr	-
MgO	-	0.01	0.04	0.04	0.10	-	0.02	0.03	0.01	0.04	0.01	0.04	0.03	0.01
CaO	9.05	6.73	4.66	7.11	7.67	0.61	5.59	8.58	8.70	7.27	7.78	7.25	7.22	6.31
Na <sub>2</sub> O	7.07	7.70	9.15	7.63	7.39	11.7	8.58	6.82	6.65	7.84	7.42	7.12	7.52	7.56
K <sub>2</sub> O	0.06	0.12	0.01	0.03	0.02	0.03	0.05	0.06	0.05	0.03	0.06	0.09	0.02	0.05
Total	100.79	99.23	100.25	99.88	98.35	100.79	99.03	98.58	100.19	99.91	99.20	98.94	99.87	98.56
Structural formulae on the basis of 32 oxygen atoms														
Si	10.328	10.509	11.113	10.617	10.369	10.873	10.998	10.220	10.218	10.480	10.320	10.405	10.386	10.699
Al	5.549	5.513	4.851	5.328	5.583	4.076	4.826	5.753	5.799	5.468	5.665	5.619	5.634	5.336
Fe3+	0.042	0.035	0.024	0.043	0.034	0.029	0.026	0.026	0.024	0.042	0.030	0.057	0.048	0.026
Ti	-	0.001	-	0.007	0.003	0.004	-	-	-	0.003	0.001	0.003	0.003	0.005
Mn	-	-	0.001	-	-	-	-	-	-	-	-	-	-	-
Mg	-	0.003	0.011	0.011	0.027	-	0.005	0.008	0.003	0.011	0.003	0.011	0.008	0.003
Na	2.444	2.685	3.133	2.643	2.610	3.942	2.983	2.408	2.306	2.722	2.599	2.493	2.610	2.643
Ca	1.729	1.297	0.882	1.361	1.497	0.114	1.074	1.674	1.667	1.395	1.506	1.403	1.385	1.219
K	0.014	0.028	0.002	0.007	0.005	0.007	0.011	0.014	0.011	0.007	0.014	0.021	0.005	0.012
Z	15.92	16.06	15.99	15.99	15.99	15.98	15.95	16.00	16.04	15.99	16.02	16.08	16.07	16.07
X	4.19	4.01	4.03	4.02	4.14	4.06	4.07	4.10	3.99	4.13	4.12	3.93	4.01	3.88
Ab	58.4	67.0	78.0	65.9	63.5	97.0	73.3	58.8	57.9	66.0	63.1	63.6	65.3	68.2
An	41.3	32.3	21.9	33.9	36.4	2.8	26.4	40.9	41.8	33.8	36.6	35.8	34.6	31.5
Or	0.3	0.7	0.1	0.2	0.1	0.2	0.3	0.3	0.3	0.2	0.3	0.6	0.1	0.3

\* Iron calculated as Fe<sub>2</sub>O<sub>3</sub>

Table 2  
Chemical composition of plagioclase crystals from Zone B

	JA-9	JA-11	JA-12	JA-13	JA-14	JA-15	JA-16	JA-17	JA-19
SiO <sub>2</sub>	52.0	51.9	50.6	50.5	50.2	47.8	53.5	47.8	53.2
TiO <sub>2</sub>	tr	-	tr	-	tr	tr	0.02	0.02	0.01
Al <sub>2</sub> O <sub>3</sub>	30.5	30.2	31.2	31.4	31.0	33.3	29.9	33.1	29.8
Fe <sub>2</sub> O <sub>3</sub> *	0.07	0.10	0.06	0.26	0.31	0.23	0.07	0.33	0.16
MnO	-	0.01	tr	tr	-	0.01	0.01	0.01	tr
MgO	0.04	0.03	0.04	0.02	0.04	0.03	0.04	0.14	0.03
CaO	11.1	11.4	13.8	10.9	13.4	14.7	9.83	15.3	13.1
Na <sub>2</sub> O	5.30	4.89	3.62	5.28	3.32	2.99	6.23	2.33	4.37
K <sub>2</sub> O	0.05	0.05	0.01	0.03	0.08	0.03	0.05	0.03	0.03
Total	99.06	98.58	99.33	98.39	98.35	99.09	99.65	99.06	100.70
Structural formulae on the basis of 32 oxygen atoms									
Si	9.503	9.527	9.265	9.307	9.274	8.820	9.693	8.822	9.586
Al	6.568	6.532	6.732	6.819	6.748	7.240	6.383	7.198	6.327
Fe <sup>3+</sup>	0.010	0.014	0.008	0.036	0.043	0.032	0.010	0.046	0.022
Ti	-	-	-	-	-	-	0.003	0.003	0.001
Mn	0.002	0.002	-	-	-	0.002	0.002	0.002	-
Mg	0.011	0.008	0.011	0.005	0.011	0.038	0.011	0.038	0.008
Na	1.877	1.740	1.285	1.886	1.189	1.069	2.187	0.833	1.526
Ca	2.172	2.241	2.706	2.151	2.651	2.905	1.907	3.024	2.528
K	0.012	0.012	0.002	0.007	0.019	0.007	0.012	0.007	0.007
Z	16.08	16.07	16.00	16.16	16.06	16.09	16.09	16.07	15.94
X	4.07	4.00	4.05	3.87	3.87	3.99	4.12	3.90	4.07
Ab	46.2	43.6	32.2	46.6	30.8	26.8	53.3	21.5	37.6
An	53.5	56.1	67.8	53.2	68.7	73.0	46.4	78.3	62.2
Or	0.3	0.3	-	0.2	0.5	0.2	0.3	0.2	0.2

\*Iron calculated as Fe<sub>2</sub>O<sub>3</sub>.

## METAMORPHISM

Increase in the anorthite content of plagioclases from metamorphosed basic rocks with increasing grade of metamorphism has been described by many authors (Phillips, 1930; Wiseman, 1934; Dodge, 1942; Engel and Engel, 1962; Binns, 1964). A concomitant rise in grain-size also has been observed in amphibolites from Lead, South Dakota (Dodge, 1942), northwest Adirondack Mountains, New York (Engel and Engel, 1962), and Broken Hill, New South Wales (Binns, 1964). According to Engel and Engel (1962, p. 55), the constituent plagioclase also increases in abundance during the progressive metamorphism of amphibolites from the Adirondack Mountains.

As discussed earlier, the chemical analyses confirm the more calcic composition of the Zone B plagioclase crystals. On the other hand, the petrographic data, as listed in Gomes (1971), indicate that a very pronounced increase in the amount and size of plagioclase samples also takes place in Zone B. Rise in plagioclase content is clearly related to a simultaneous decrease in epidote amount, with mean values from 29 modal analyses giving, for Zone A: pl = 12.2 and ep = 6.8; and for Zone B: pl = 23.4 and ep = 1.8. Similarly, a rise in temperature can explain the larger crystals of hornblende and ilmenite in Zone B. Chemical evidence of deeper metamorphic conditions for Zone B amphibolites are also suggested by the very low water content of the whole rocks (Gomes *et al.*, 1964) as well as by the very high titanium content and very low Si/Al ratios of the hornblendes (Gomes, 1971).

Despite the apparent adjustment of the amphibolite minerals to rising temperatures, failure to attain equilibrium is clearly indicated

TABLE 3. AVERAGE COMPOSITION OF PLAGIOCLASE CRYSTALS

	Zone A	Zone B
SiO <sub>2</sub>	59.2	50.8
TiO <sub>2</sub>	0.02	0.01
Al <sub>2</sub> O <sub>3</sub>	25.4	31.1
Fe <sub>2</sub> O <sub>3</sub>	0.26	0.17
MnO	0.01	0.01
MgO	0.03	0.05
CaO	6.75	12.6
Na <sub>2</sub> O	7.12	4.26
K <sub>2</sub> O	0.04	0.09
Total	98.83	99.09



FIG. 2. Chemical variations in plagioclases from Zone A and B amphibolites as given by weight percent An, Ab, and Or.

by the heterogeneous plagioclase compositions as well as by zoning in amphibole. This latter feature, which has been recognized only in some samples from Zone A, shows crystals commonly having a rim of light green hornblende enveloping a colorless core of actinolite (Gomes, 1971). This zoning is tentatively interpreted as a relict feature, locally

preserved from the metamorphic recrystallization and complete homogenization caused by rising temperatures. Increase in the metamorphic grade of Jaraguá amphibolites from Zone A toward Zone B seems to be related to the Cantareira granitic intrusion. According to many authors, this batholith is responsible for thermal metamorphism of low-grade schists and carbonate rocks in areas adjacent to Jaraguá.

The metasedimentary rocks cropping out in the Jaraguá area are made up essentially of quartz, muscovite, and biotite, and according to Coutinho (1955, p. 33) belong to the greenschist facies (Turner and Verhoogen, 1960). The amphibolites have been also affected by the regional metamorphism and in both zones the mineral assemblages are consistent with the amphibolite facies (Turner, 1968). However, it is believed that the regional metamorphic conditions before the

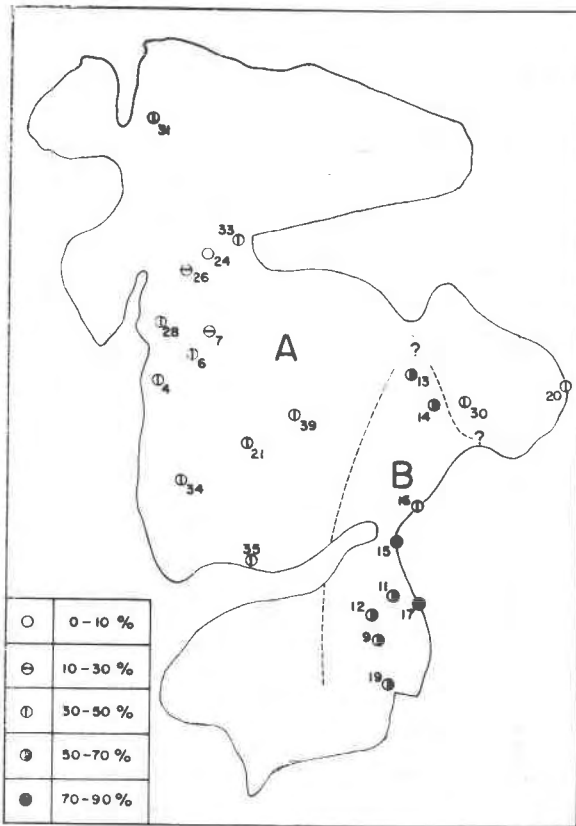


FIG. 3. The zonal distribution of anorthite in plagioclase crystals within the amphibolite body. Sample numbers as listed in Tables 1 and 2.



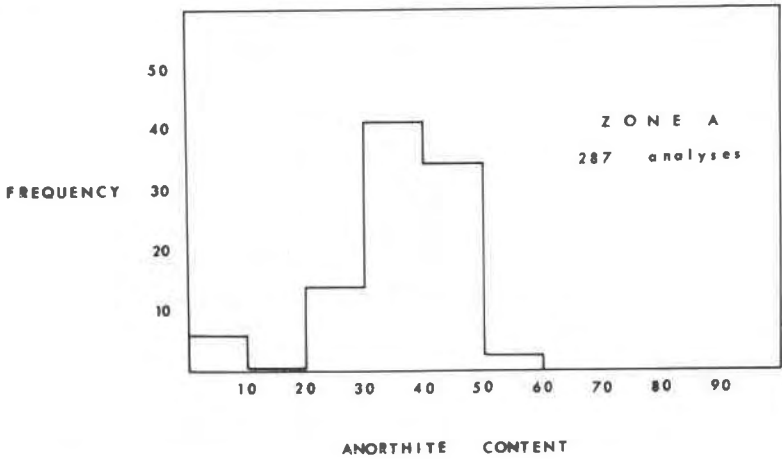


FIG. 4. Composition histogram for plagioclase crystals from Zone A.

granite intrusion were less severe, as suggested by the amphibole zoning. Based on the presence of actinolite, it could be assumed that those conditions were even compatible with the greenschist facies. Adjustment to rising temperatures was indicated by the principal textural and mineralogical changes that have taken place in the amphibolites. Due to its proximity to the granite, the amphibolites from Zone B were submitted to higher temperatures as indicated by the chemical variations in plagioclases, hornblendes, and whole rocks. But even the meta-

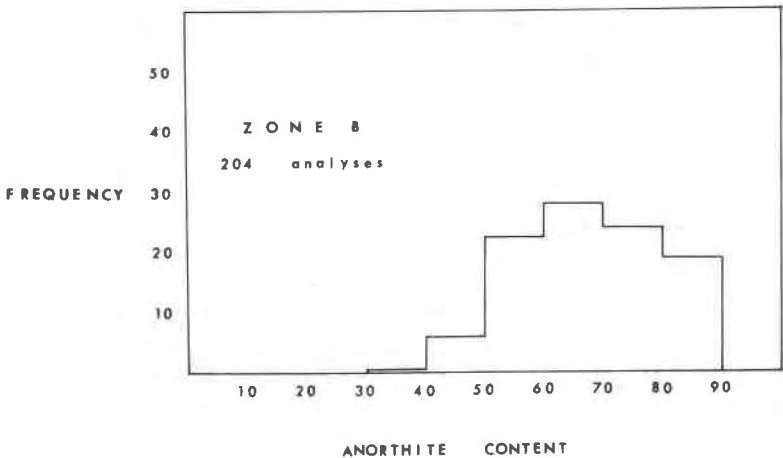


FIG. 5. Composition histogram for plagioclase crystals from Zone B.

sedimentary rocks were affected by this metamorphic event as concluded from the biotite presence instead of chlorite.

It is assumed that ophitic texture and the presence of lathy complexly twinned plagioclase in some rocks from Zone B constitute local remnant features, preserved from destruction by metamorphic recrystallization perhaps as a consequence of the small water content and weak deformation of these amphibolites. Buddington (1939, p. 271–272; 1952, p. 51) has found that metadolerites in the Adirondack Mountains with relict primary ophitic texture have plagioclase crystals which have undergone a change in composition without a change in shape. In some metadolerites from Bakersville–Roan Mountain, Wilcox and Poldervaart (1958) concluded that recrystallization failed to destroy original textures in rocks with low water content. In the presence of water as a free phase, the rocks were completely recrystallized at the same time and at the same temperature. Another interpretation for the preservation of the shape of plagioclase crystals can be given following the same line of reasoning of Vogel and Spence (1969). In the metavolcanic rocks cropping out near Plevna Lake in southeastern Ontario, plagioclase phenocrysts have homogenized compositionally and apparently changed their bulk chemical composition by diffusion in the solid state without recrystallization. In this process the original twin planes and re-entrant angles were preserved.

Local evidence of retrogressive metamorphism within the amphibolite body is indicated by the association albite–hornblende–epidote from JA-24. As seen on the geological map, this sample is located close to a fault-zone. Lower metamorphic conditions affecting this zone are responsible for conversion from a mineral assemblage of the amphibolite facies to a lower-grade assemblage compatible with the greenschist–amphibolite transition facies according to Turner (1968).

#### GENERAL REMARKS

Chemical, mineralogical, and textural data make clear that the Jaraguá amphibolites have varied in composition and texture as a consequence of adjustment to rising temperatures. Although they did not reach complete equilibrium, as indicated by zoning in amphibole and the extreme compositional variation of plagioclase crystals, they responded sufficiently to produce recognizable differences, giving rise to two contrasted petrographic zones within the amphibolite body.

Plagioclase changes as a function of increasing temperature of metamorphism are marked and systematic. They consist essentially of an increase in grain size, abundance, and anorthite content in the Zone B rocks.

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