

Geochemistry of coexisting biotites and Ca-amphiboles from Zaker granitic rocks of Zanjan District, northwest Iran

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ABSTRACT

The coexisting biotites and amphiboles from Zaker granitic rocks have low Fe^{3+} content which suggests low oxygen fugacities. The absorption colour variations of biotite and amphibole are greatly affected by their Ti/Fe^{2+} and $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ ratios. The variations in the distribution coefficient of the coexisting biotites and amphiboles suggest that they were crystallised under variable conditions of temperature and pressure and also suggest the presence of a chemical disequilibrium stage between them. The low $K_{\text{DFeMg}}^{\text{H-B}}$ values in the coexisting biotites and amphiboles indicate that the investigated minerals and their host rocks were crystallised under low temperature and pressure. The low Ti content of Zaker amphiboles also confirmed the low crystallisation temperature of the hornblende and edenite. The contents of Sr in biotites and Ga, Cu and Ba in the amphiboles show some irregularities in their concentrations during the chemical gradations of the host rocks towards the felsic end member. The high K/Rb ratios in the biotites and the low values of Ti in the amphiboles suggest a metamorphic origin for both minerals.

INTRODUCTION

Zaker batholith forms one of the numerous granitic intrusions in the western part of Tarom District nearest to Zanjan District (Fig. 1). The batholith covers about 80 km² and is located between latitudes 36°34' and 36°42'N and longitudes 48°35' and 48°50'E. The geology of Zanjan area received much attention from several workers in the Geological Survey of Iran (Hirayama *et al.* 1965, 1966; Alavi *et al.* 1969). Hirayama *et al.* (1966) mentioned that Zanjan District is mainly occupied by Eocene pyroclastic rocks, lavas and sedimentary rocks in addition to numerous granitic intrusions of post-Miocene age. However, the basal conglomerate of the younger Tertiary strata contain no granodiorite pebbles. These granitic intrusions range in composition from granites to diorites passing through granodiorites which form the main rock unit in these batholiths. The same authors divided the main part of the Eocene strata (Karaj Formation) into two members: the Kordkand Member (lower units) and the Amand Member (higher units). The Amand Member comprises 9 main units, of which 3 are intruded by Zaker granitic batholith. These are: (1) andesite, porphyrite, sandstone and mudstone; (2) tuff breccia and lapilli tuff; and (3) porphyrite, andesite tuff and sandstone. Alavi *et al.* (1969) mentioned that some of the Eocene Amand Member

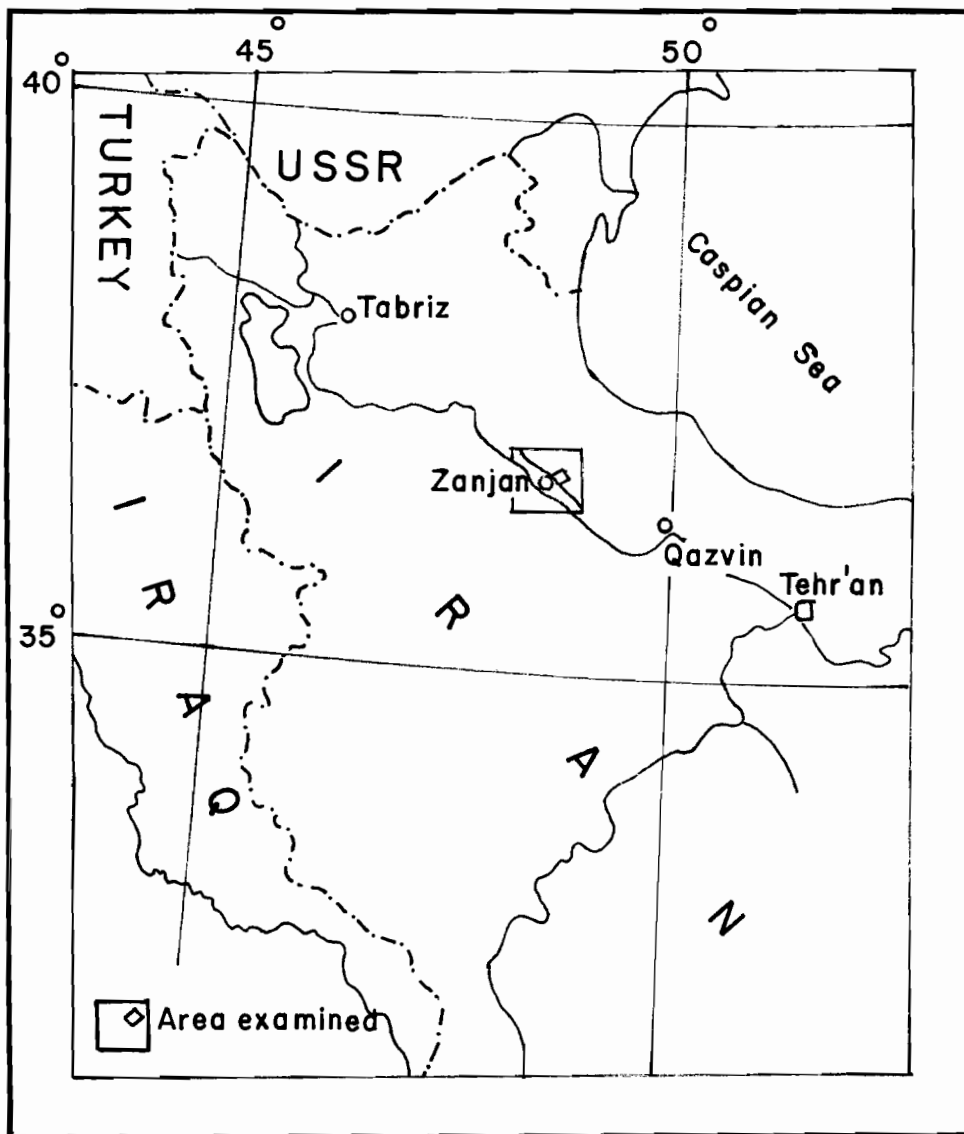


Fig. 1. Location map.

strata have been altered hydrothermally or contaminated along the contact surfaces of granitic intrusions giving rise to altered lava, porphyrite, hornfelse and gabbroid rocks.

More recently, the mineralogical classification and the geochemistry of feldspars of Zaker granitic rocks were given by Refaat (1975, 1976). The geochemistry of coexisting biotite and chlorite from Zaker granites was studied also by Refaat & Abdallah (1979). It is evident that chlorite has formed as a net result of a chloritisation process of biotites which began to alter at a late magmatic stage of Zaker granite batholith during solid solution reaction. The granitic rocks of Zaker batholith consist mainly of grey, white,

pink and red granites in addition to adamellites, granodiorites and diorites (Fig. 2). The granodioritic rocks form the main rock type within the study area. On the basis of field observations, the batholith shows a very rough zonal form. The innermost zones, occupying the core of the granodiorite, are characterised by greyish green diorites. Granite and adamellites crop out at the margins of the granodiorites. All granitic rocks grade imperceptibly into each other with rather indefinite contacts. The granitic rocks are dissected by very few andesite dykes running in various directions. Zaker granitic rocks intruded some of the Eocene Amand Member (andesite, rhyolitic volcanic tuff, sandstone and mudstone) causing some contact effects. The altered (volcanic) rocks, hornfelses and contaminated gabbroid rocks are encountered along the contacts of Zaker intrusion. A gradational contact can be observed in very rare places around Zaker intrusion in which some granite rocks grade into a mixed zone of metasediments (argillaceous and arenaceous materials) and volcanic rocks (propylite and aplite). Zaker granitic rocks enclose few small subangular xenoliths of propylite, diorite, gabbro, pyroclastic rock and sandstone. Some of these xenoliths show sharp contacts and no sign of replacement between both rocks (dioritic xenolith), whereas the other xenoliths are of heterogeneous nature and show gradational contacts.

The purpose of this paper is to study the geochemistry of coexisting biotites and hornblendes in Zaker granitic rocks.

PETROGRAPHY

Zaker granitic rocks consist essentially of plagioclase, perthite, orthoclase, quartz, biotite, hornblende, muscovite and chlorite. Monoclinic pyroxenes are represented in some granodiorite and diorite samples. Iron ores, apatite, sphene, monazite, epidote and zircon are present as accessories. This study comprises 11 pairs of coexisting biotites and hornblendes in which 4 pairs were separated from granites, 2 pairs from adamellites, 3 pairs from granodiorites and one pair only from quartz diorites. The volume percentages of biotites and hornblendes in granitic rocks range from 2.1 to 14.9 and from 7.9 to 19.1 respectively (Refaat 1975). Most of the examined biotite and hornblende occur as associated crystals of both mafic minerals. Either biotite or hornblende is considered the sole ferro-magnesian mineral in some granitic samples. Biotite flakes contain inclusions of apatite, epidote, zircon, sphene and iron ores. Hornblendes form euhedral prismatic crystals which may enclose iron ores and quartz as inclusions. Few biotite flakes are altered along the cleavage planes to blue chlorite. The pleochroic formula of biotite is X=pale yellowish green and Y=Z=dark brown to dark greenish brown. The hornblende crystals are also strongly pleochroic with X=yellowish green, Y=pale green and Z=green to dark green. Some large hornblende crystals are partly poikilitic, i.e. the hornblende crystals are sieved by quartz grains. Coarse twinned crystals of green hornblende show zonal structure. Intergrowths between biotite and hornblende are observed in rare granitic samples. Some replacement of hornblende by biotite took place in some granitic samples suggesting that such samples have been affected by metasomatic process. Both biotite and hornblende are characterised by rather high elongation indices ranging from 2.5 to 3.5 especially in the granite samples.

In some granodioritic samples, euhedral crystals of pale green augite and diopside are present in the core of some green hornblende which shows that these hornblende crystals are crystallised in reaction relationship with pyroxene and melt.

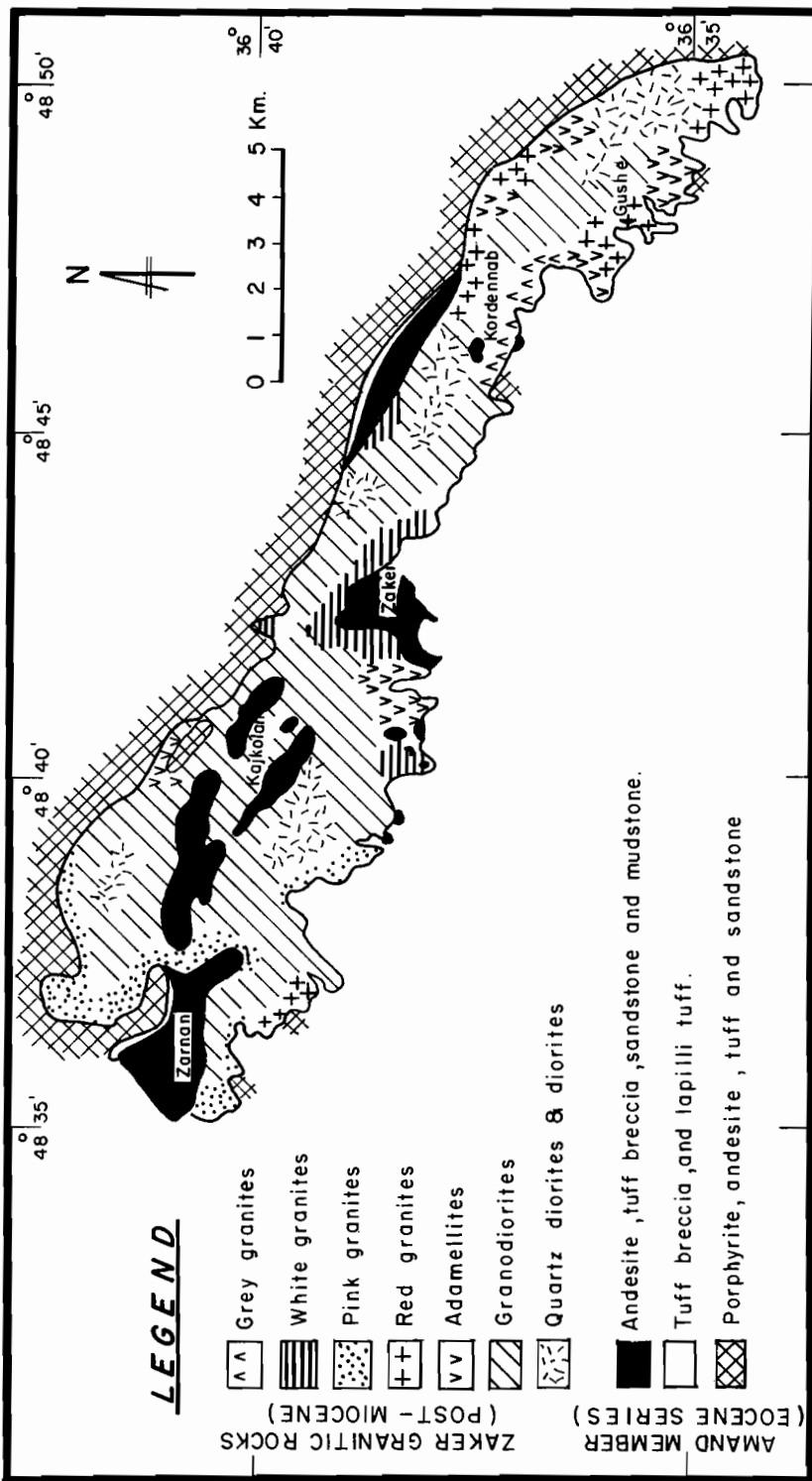


Fig. 2. Generalised geological map of Zaker District.

SAMPLE PREPARATION

The great similarity between the specific gravity of biotite and hornblende causes some difficulties during the separation of both mafic minerals from each other. Therefore, many slabs (5 cm in thickness) were cut in different surfaces in every granitic sample. A thin section was prepared from each slab and then studied under the microscope to determine the slab which was most concentrated in biotite or hornblende. The purpose of this technique is to choose the slab which comprises biotite or hornblende as sole mafic mineral. The selected slabs were crushed to pass through 120 mesh sieve. The washed crushed powders were treated with bromoform which gave rise to two separate fractions of light and heavy minerals. The heavy fractions are mainly represented by biotite or hornblende. Each heavy fraction was passed through an isodynamic separator to increase the concentrations of biotite or hornblende. The final purification of biotite and hornblende was carried out by centrifuging in heavy liquids. The purity of both examined mafic minerals was mostly more than 97%. The purity of biotite and hornblende was carefully tested under the microscope. It was observed that very little impurities of iron ores, epidote and composite grains of biotite-hornblende formed the main inclusions of both mafic minerals investigated.

THE STRUCTURAL FORMULAE

The major elements (Table 1) of biotites and hornblendes (11 samples of each) were determined by using volumetric and gravimetric methods of silicate analysis (Bennet & Reed 1971). The major elements of biotite were recalculated on the basis of 24 (O, OH) and the structural formulae and some compositional ratios are listed in Table 2. The structural formulae of hornblendes were calculated from their major elements on the basis of 24 (O, OH). Table 3 shows the structural formulae of hornblende and some compositional ratios.

The tetrahedral coordinated Z group in both biotite and hornblende consists entirely of Si and Al to provide the theoretical 8 atoms in the tetrahedral sites. The numbers of atoms in the Y group vary from 5.542 to 6.188 (Table 2) in all the examined biotites. This range is nearly identical with the theoretical 6 atoms of trioctahedral micas. The coordinated large cations of the X group (Ca, Na, K) range from 1.574 to 2.334 (Table 2) compared to 2 in the ideal mica. In all the examined biotites K atoms constitute over 85% of the X ions. The octahedral atoms in the hornblende range from 4.912 to 5.591 (Table 3) compared with 5 in the ideal amphibole formula, while the X atoms vary from 1.874 to 2.312 (Table 3). The Ca atoms form over 90% of the X ions in the investigated hornblendes. The ferric contents of our biotites and hornblendes vary from 0.073 to 0.166 (Table 2) and from 0.209 to 0.438 (Table 3) respectively suggesting low oxygen fugacities (Semet 1973). The Fe^{3+} content in biotite is less than the Fe^{3+} atoms of hornblende reflecting that oxygen fugacities decrease from hornblende to biotite during a fractional crystallisation process of granitic melts.

The relationship between the $X_{\text{Al}^{iv}}^{\text{B}}$ and $X_{\text{Al}^{iv}}^{\text{H}}$ in the examined coexisting biotite and hornblende is somewhat different from that of Gorbatshev (1970) who mentioned that the $X_{\text{Al}^{iv}}^{\text{B}} = 0.24 + 0.35 X_{\text{Al}^{iv}}^{\text{H}}$ in the coexisting hornblendes and biotites from gneisses.

The present authors applied the above equation to the chemical data of the examined coexisting biotite and hornblende from granitic rocks. The net results do not

agree with Gorbatshev's equation except only in sample number 11 in which both sides of the equation equal 0.295 (Table 4). It is argued that the discordance of Zaker chemical data with Gorbatshev's equation is due to the great difference between the nature of the bulk chemical composition in igneous and metamorphic rocks. This discordance may also reflect a type of chemical disequilibrium between both Zaker mafic minerals during the crystallization process.

COMPOSITION OF BIOTITES AND AMPHIBOLES

The plots of octahedral cations (Table 2) in Fig. 3a (Foster 1960) show that the biotites of tonalites, granodiorites and adamellites are rich in Mg whereas those of granites are rich in Fe^{2+} , i.e. both magnesium biotite and iron biotite are represented in Zaker granitic rocks.

The composition of the examined amphibole has been established with respect to Al^{VI} and the total values of $\text{Al}^{\text{VI}} + \text{Fe}^{3+} + \text{Ti}$ (Table 3) in Fig. 3b (Deer *et al.* 1966). These amphiboles plot within the field of hornblende except one sample from granite and two samples from adamellite which belong to the hornblende–edenite zone. The edenite can be derived from hornblende by the addition of Na atoms in the X position.

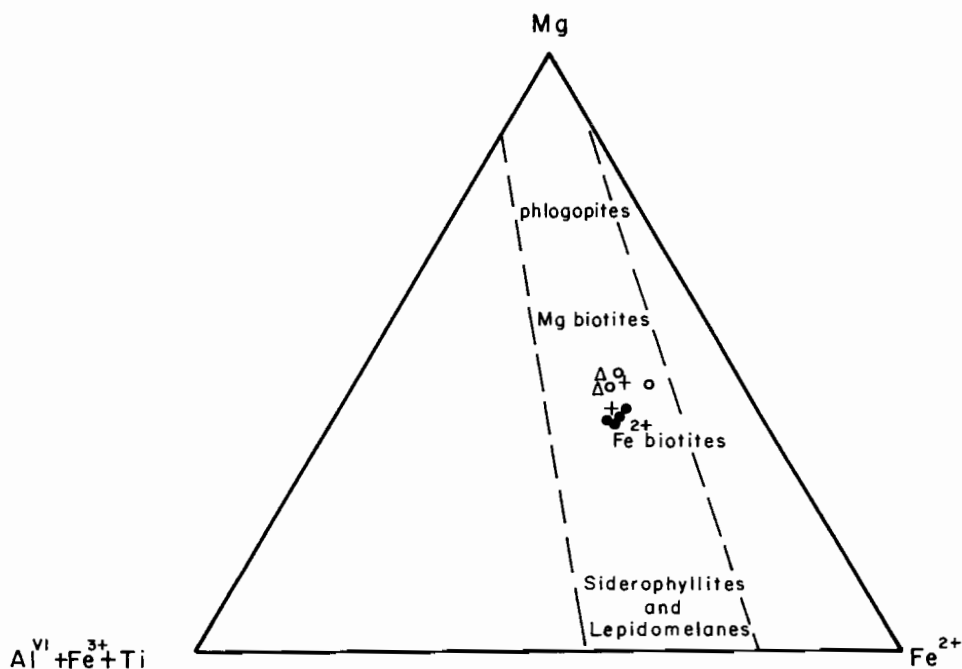


Fig. 3a. Relation between octahedral cations in the biotites (after Foster 1960).

Legend

- , Biotite and/or amphibole from granites.
- +, Biotite and/or amphibole from adamellites.
- , Biotite and/or amphibole from granodiorites.
- △, Biotite and/or amphibole from quartz–diorites.

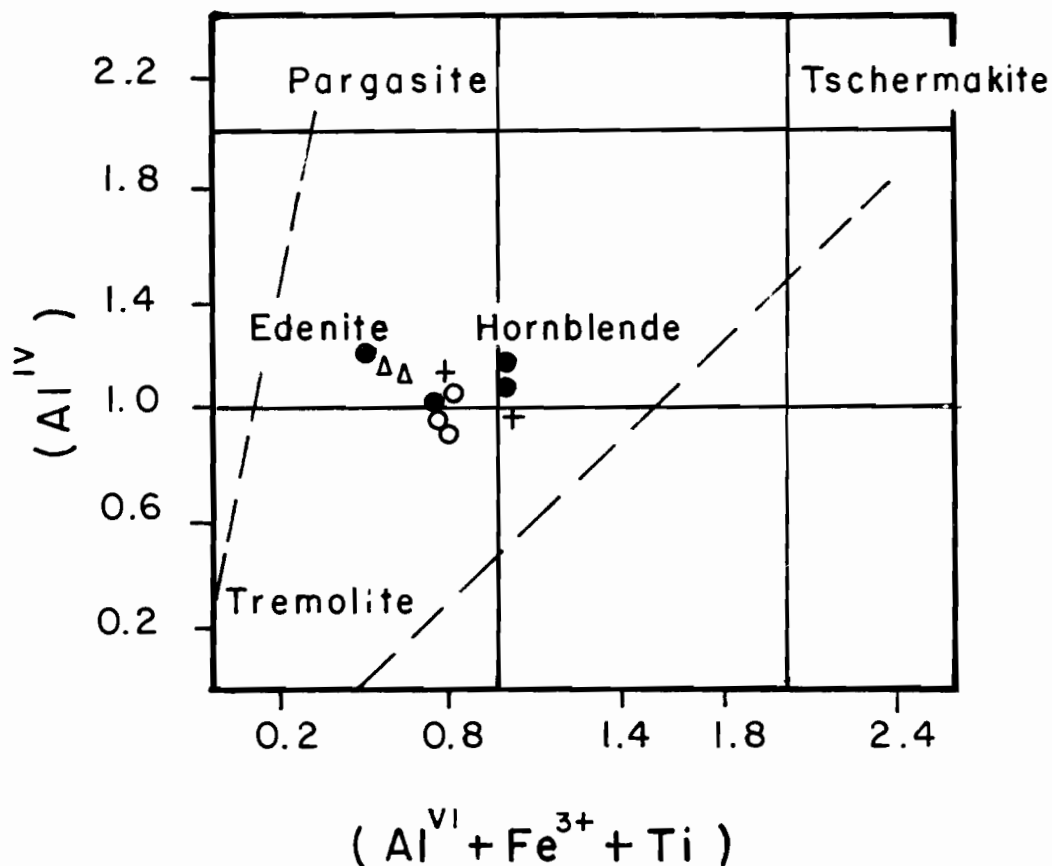


Fig. 3b. The chemical variation of amphiboles expressed as the number of $(Al^{VI} + Fe^{3+} + Ti)$ and (Al^{IV}) atoms per formula unit (after Dear *et al.* 1966). Legend as in Fig. 3a.

Moreover, a substitution of Al for Si takes place in the Z position. All the examined amphiboles are termed calcic amphiboles.

Pleochroic formulae of biotite and hornblende

The pleochroic formulae of biotites have been discussed by Hall (1941), Hayama (1959, 1964) and Engel & Engel (1960). Hayama (1959) correlated the change in the absorption colour of biotite to the behaviour of TiO_2 and $Fe_2O_3/(FeO + Fe_2O_3)$ values. He concluded that the biotites of higher Ti and lower $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ values were characterised by red-brown absorption colour in the Y and Z directions and that those of lower Ti and higher $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ values were characterised by brown absorption colour in the Y and Z directions. The examined biotites are strongly pleochroic with X=pale yellowish green and Y=Z=dark brown to dark greenish brown. According to the structural formulae (Table 2) of the biotites, the Ti/Fe^{2+} ratios are low whereas the ratios of $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ are rather high. Therefore, these biotites fall in the brown field of the Y and Z absorption colours (Fig. 4a). The variation in absorption colour of hornblende along the X, Y and Z directions was studied by Engel

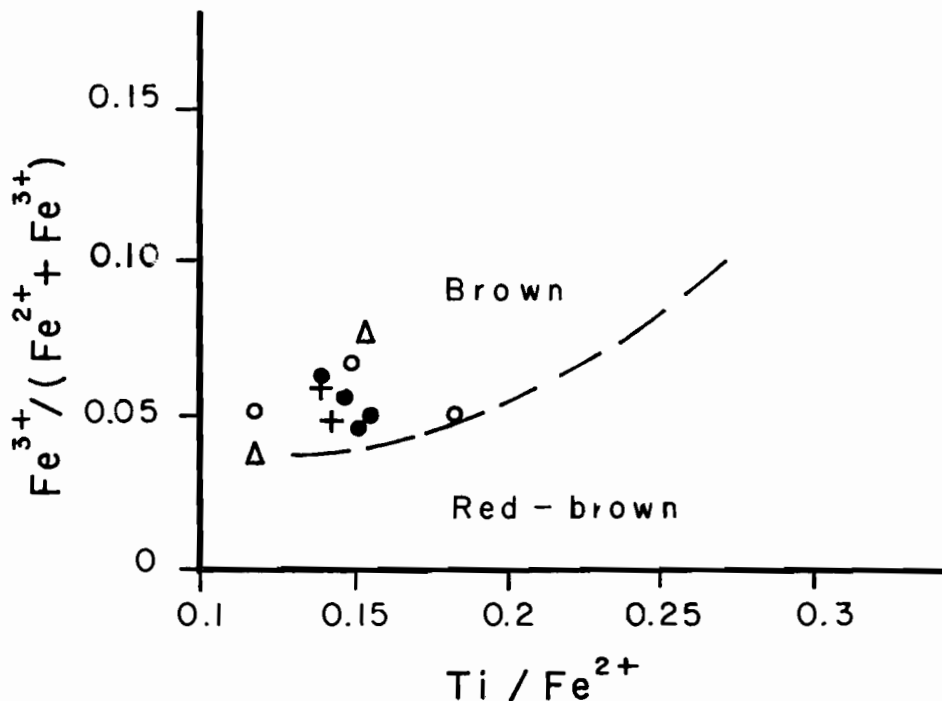


Fig. 4a. Relation between Y and Z absorption colour of biotites and their $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ and Ti/Fe^{2+} ratios (after Hayama 1959). Legend as in Fig. 3a.

& Engel (1962) and Binns (1965). These authors attributed the variation in absorption colour along the Z direction in hornblendes to the Ti and Fe^{3+} contents. Binns (1965) mentioned that the continuous variation in absorption colour in hornblende from blue-green to green, to dark green and to green brown along the Z direction is due to the increase in Ti/Fe^{2+} ratios and decrease in Fe^{3+} contents. Generally, the examined amphiboles have low ratios of Ti/Fe^{2+} and low Fe^{3+} contents (Table 3). Therefore, their absorption colours along Z direction vary from green to dark green (Fig. 4b). It can be observed that most of the hornblendes from granodiorites and tonalites are of dark green colour along the Z direction. This absorption colour is due to the low Fe^{3+} content as related to the high Fe^{3+} content in the hornblende from granites and adamellites in which the Z absorption colour is green. Both types of hornblende have little variation in Ti/Fe^{2+} ratio ranging from 0.043 to 0.071 (Table 3).

DISTRIBUTION COEFFICIENTS

The distribution coefficients of some elements in the coexisting biotite and hornblende are presented in Table 4. The distribution of elements between coexisting minerals has been discussed by several authors (De Vore 1957; Kretz 1961; Albuquerque 1971, 1973; Stephenson 1977). The distribution coefficient of some elements between the examined coexisting biotite and hornblende is calculated according to the following equation:

$$K_{DA}^{a-b} = \frac{X_A^a}{1 - X_A^a} \times \frac{1 - X_A^b}{X_A^b} \quad (\text{Stephenson 1977}).$$

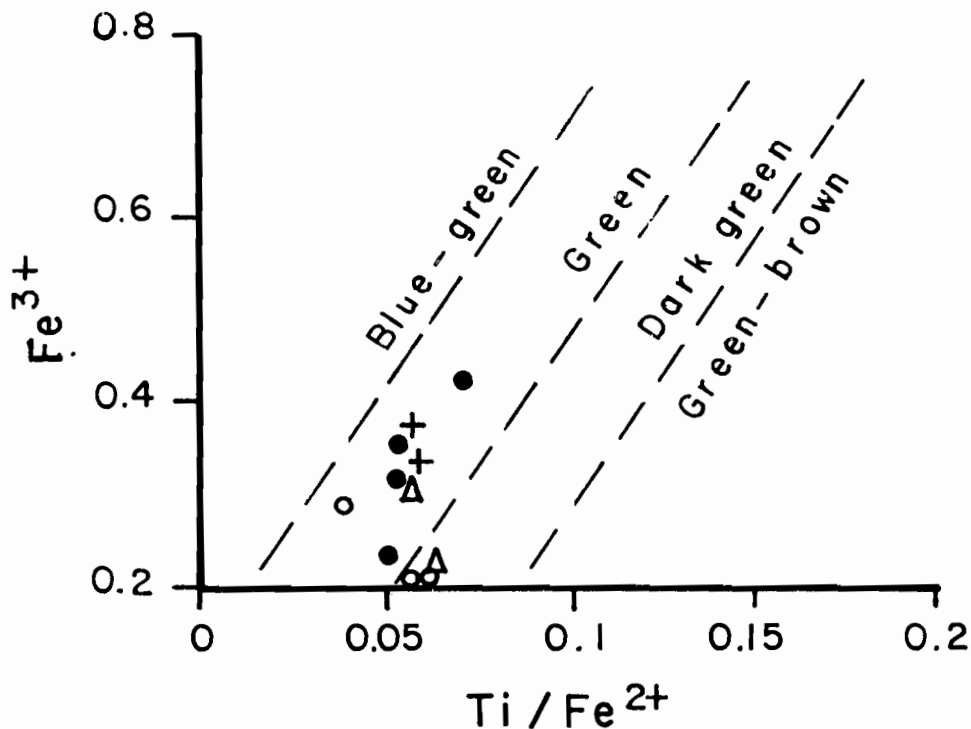


Fig. 4b. Relation between Z absorption colours of amphiboles and their Fe³⁺ content and Ti/Fe²⁺ ratios (after Binns 1965). Legend as in Fig. 3a.

where K_D = distribution coefficient, A = element, a - b = coexisting minerals and X_A = atomic ratio of the element (A) to the sum of major elements occupying some sites in the coexisting minerals (a and b). The values of K_D for any element may be constant if both coexisting minerals behaved as ideal mixtures and attained chemical equilibrium under uniform conditions of temperature and pressure whereas the difference in these conditions for both coexisting minerals reflects a marked variation in the K_D (Stephenson 1977). In the present study three distribution coefficients (Table 4) are calculated, namely $K_{DA^{iv}}^{B-H}$ (1.992-3.660), $K_{D_{Fe^{2+}+Mg}}^{B-H}$ (1.553-2.249) and $K_{D_{(Al^{vi}+Ti+Fe^{3+})}}$ (0.821-1.648). It is remarked that the values of every K_D alone are highly variable suggesting that both mafic minerals were crystallised under variable conditions of temperature and pressure.

The present authors ascribe the formation of both minerals under variable conditions to the chemical variation in their host rocks which grade from granites to diorites passing through adamellites and granodiorites. The relationship between $K_{DA^{iv}}^{B-H}$ and $X_{A^{iv}}^H$ is shown in Fig. 5. It is evident that $K_{DA^{iv}}^{B-H}$ increases with the decrease of $X_{A^{iv}}^H$, i.e. the systematical variations in $K_{DA^{iv}}^{B-H}$ are related to the Al^{iv} content of the hornblende (Gorbatshev 1969). Fig. 6 is a plot of the Fe/Mg ratios (Tables 2 and 3) of the coexisting biotite and amphibole (Kretz 1963; Hietanen 1971). Zaker biotites are characterised by high Fe/Mg ratios relative to the hornblendes.

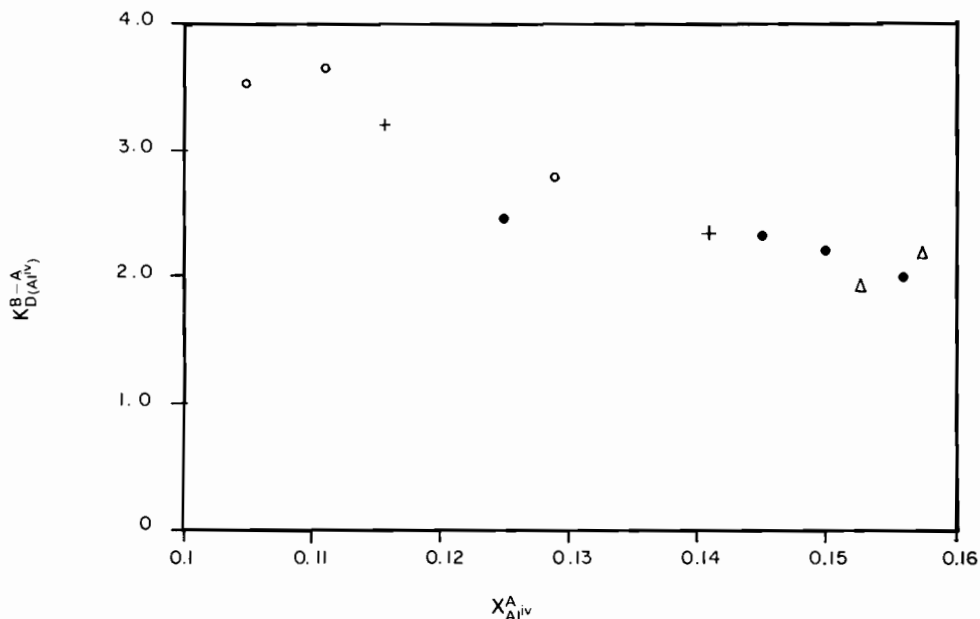


Fig. 5. Relation of the distribution of Al^{IV} between coexisting amphiboles (A) and biotites (B) to the atomic ratio of Al^{IV} in amphiboles. Legend as in Fig. 3a.

The K_D values

$$\left(K_D = \frac{(\text{Fe/Mg}) \text{ hornblende}}{(\text{Fe/Mg}) \text{ biotite}} \right)$$

for the amphibole–biotite pairs have been calculated according to Dodge *et al.* (1968, 1969) and Albuquerque (1971, 1974). The values of K_D for the examined coexisting amphibole–biotite pairs vary from 0.444 to 0.642 (Table 4) with an average of 0.524. This average (0.524) is low compared with the $K_{D_{Fe:Mg}}^{H-B}$ average of amphibole–biotite pairs from the southern California batholith (Larsen & Draisin 1950) which is 0.83. It can be concluded that Zaker biotite–amphibole pairs have low values of K_D suggesting that the host rocks of both ferromagnesian minerals were crystallised under low temperature and pressure (Albuquerque 1971, 1973).

GENESIS OF MAFIC MINERALS

Figure 7a shows the relationship between $Rb\%$ and the K/Rb ratios (Table 5) of biotites. The diagram is divided by Stavrov (1971) into two fields comprising biotite in differentiated granitic complexes and biotite in metamorphic complexes. The examined biotites fall in the field of metamorphic complexes. Fig. 7b shows the relationship between Si and Ti (Table 3) in the examined amphiboles. Leake (1965) divided the diagram into two fields, the first represents the igneous amphiboles and the second represents the metamorphic amphiboles. The investigated amphiboles plot within the field of metamorphic amphiboles. It can be concluded that both the coexisting biotites and amphiboles fall in the field of metamorphic complexes in which

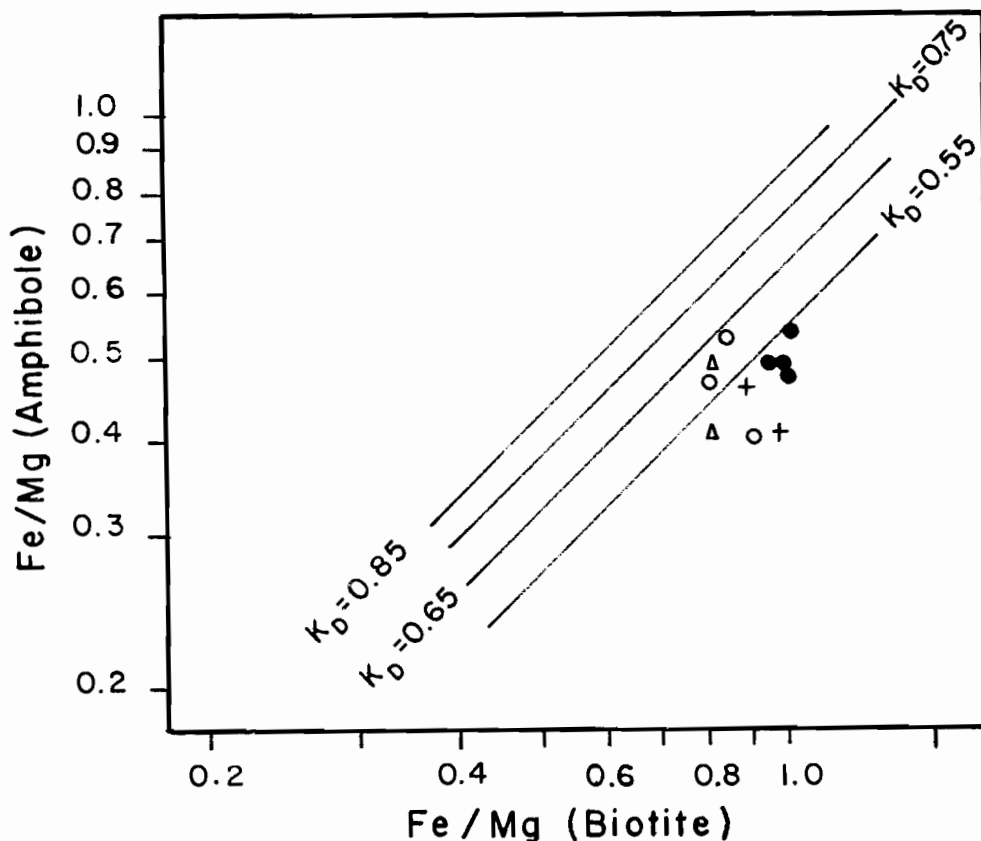


Fig. 6. Distribution of Fe/Mg ratio between coexisting biotites and amphiboles (after Kretz 1963; Hietanen 1971). Legend as in Fig. 3a.

the biotites tend to have low Rb contents varying from 250 to 550 ppm (Table 5) and high ratios of K/Rb ranging from 151 to 318 (Table 5), i.e. the investigated biotites contain high K values (1.31–2.11, Table 2). The examined hornblendes are characterised by low Ti contents (0.062–0.087, Table 3) and slightly high Si contents (6.75–7.15, Table 3). The low Ti contents in Zaker hornblendes are related to the low crystallisation temperature of these amphiboles because high temperature favours the entry of Ti in the structure of the amphiboles (Green & Ringwood 1968; Holloway & Burnham 1972). The present authors relate the geochemical characters (Figs 7a and 7b) of Zaker biotites and hornblendes to a late hydrothermal granitisation process (Mehnert 1968) which took place at low temperature.

DISTRIBUTION OF TRACE ELEMENTS

The trace elements in both the examined mafic minerals (Table 5) were estimated by using a spectrographic method. The trace element contents in the coexisting biotite–hornblende pairs are plotted in Fig. 8. Ga, Ba and Ni (Table 5) are more concentrated in the biotites than in the amphiboles. From the chemical point of view, Ga and Ba must follow Al and K respectively because of the great similarity between their ionic

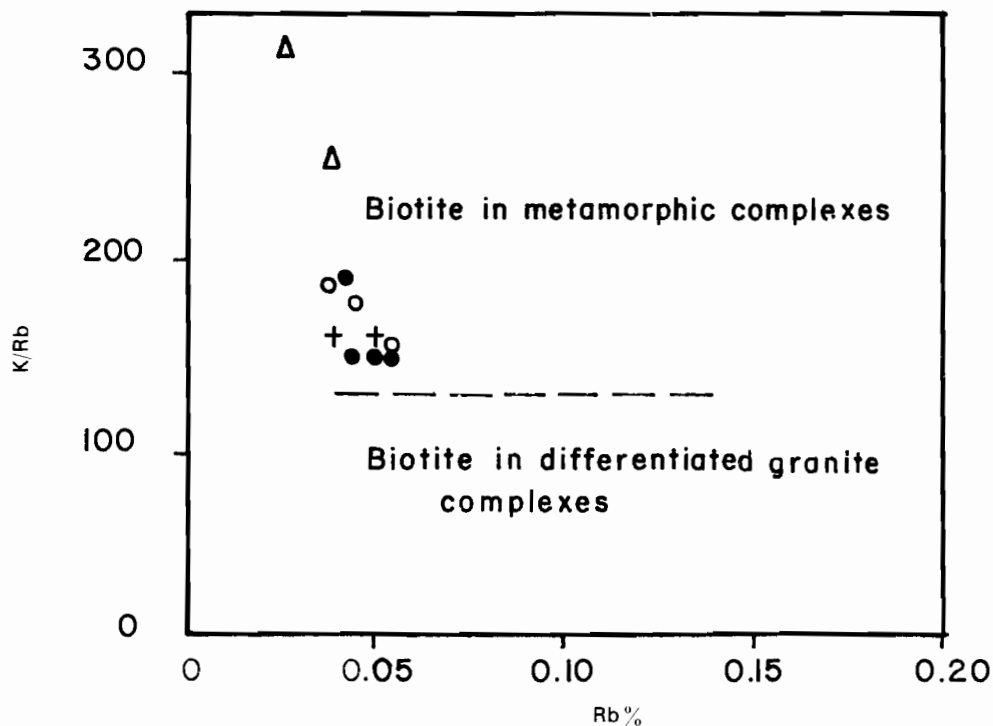


Fig. 7a. Relation between Rb% and K/Rb ratio in biotites (after Stavrov 1971). Legend as in Fig. 3a.

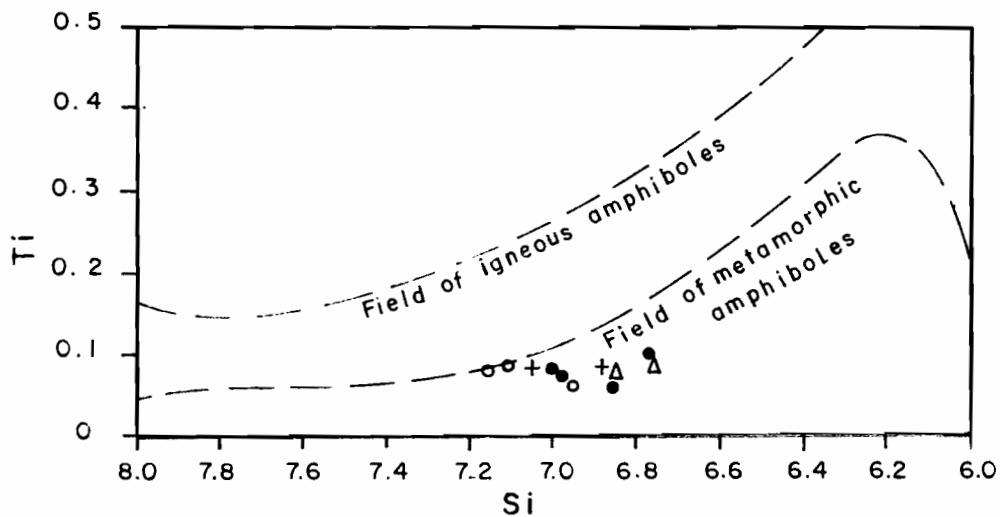


Fig. 7b. Relation between Ti and Si in amphiboles (after Leake 1965). Legend as in Fig. 3a.

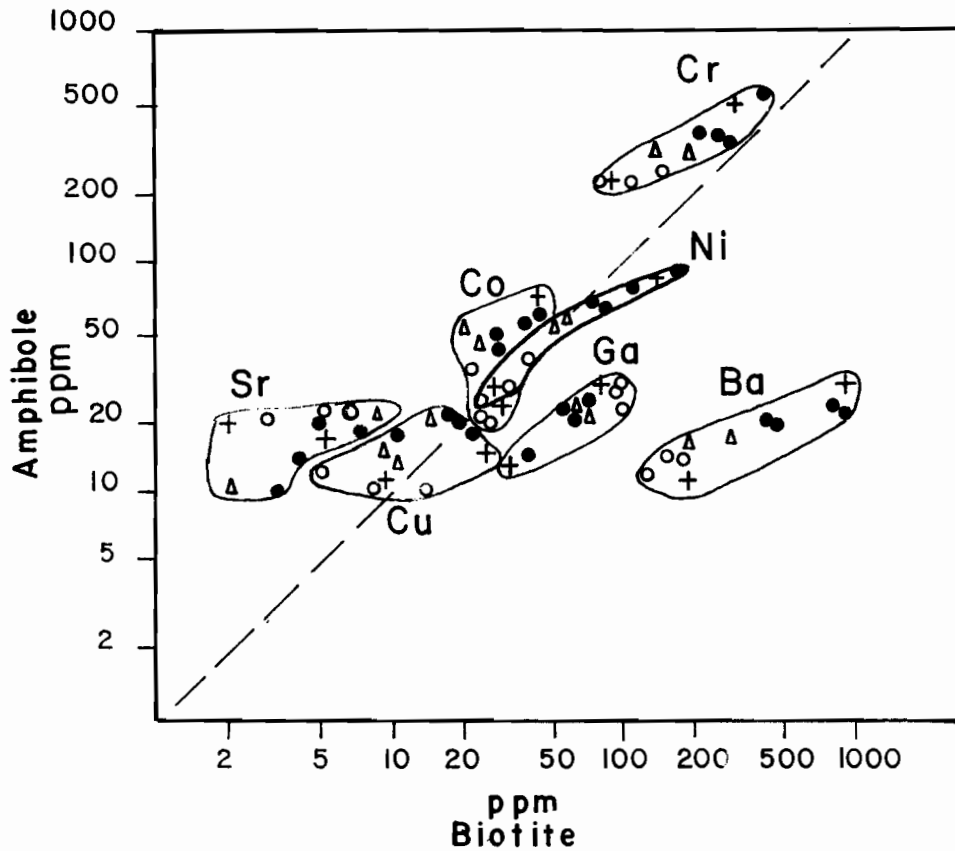


Fig. 8. Distribution of trace elements in coexisting biotites and amphiboles. Legend as in Fig. 3a.

radii and this explains the enrichment of biotite in Ga and Ba. The examined amphiboles have high contents of Sr, Cr and Co (Table 5) as compared to biotites; this is attributed to the enrichment of amphiboles in Ca, Fe^{3+} , and Mg.

The trace elements of the coexisting biotites and amphiboles are plotted against the values of the function $Fe_t/(Fe_t + Mg)$ (Table 1), of both the examined mafic minerals (Fig. 9). Ga agrees with the variation of Al and both elements increase in the biotites toward the felsic end member. Cr, Ni and Co in both biotites and amphiboles decrease as their host rocks pass from tonalites to granites. Cu and Ba of the biotites decrease as their host rocks become more felsic. Sr increases in hornblendes as host rocks vary from tonalite to granite passing through adamellite and granodiorite. The plotting of Ga, Cu and Ba in hornblendes and Sr in biotites against $Fe_t/(Fe_t + Mg)$ values shows considerable scattering which suggests that these elements were affected greatly by the impurities which were introduced in both biotites and hornblendes during late hydrothermal action.

CONCLUSION

The investigated biotites range in composition from Mg to Fe^{2+} biotites (Foster 1960) whereas the amphiboles are termed calcic amphiboles comprising hornblende and edenite (Deer *et al.* 1966).

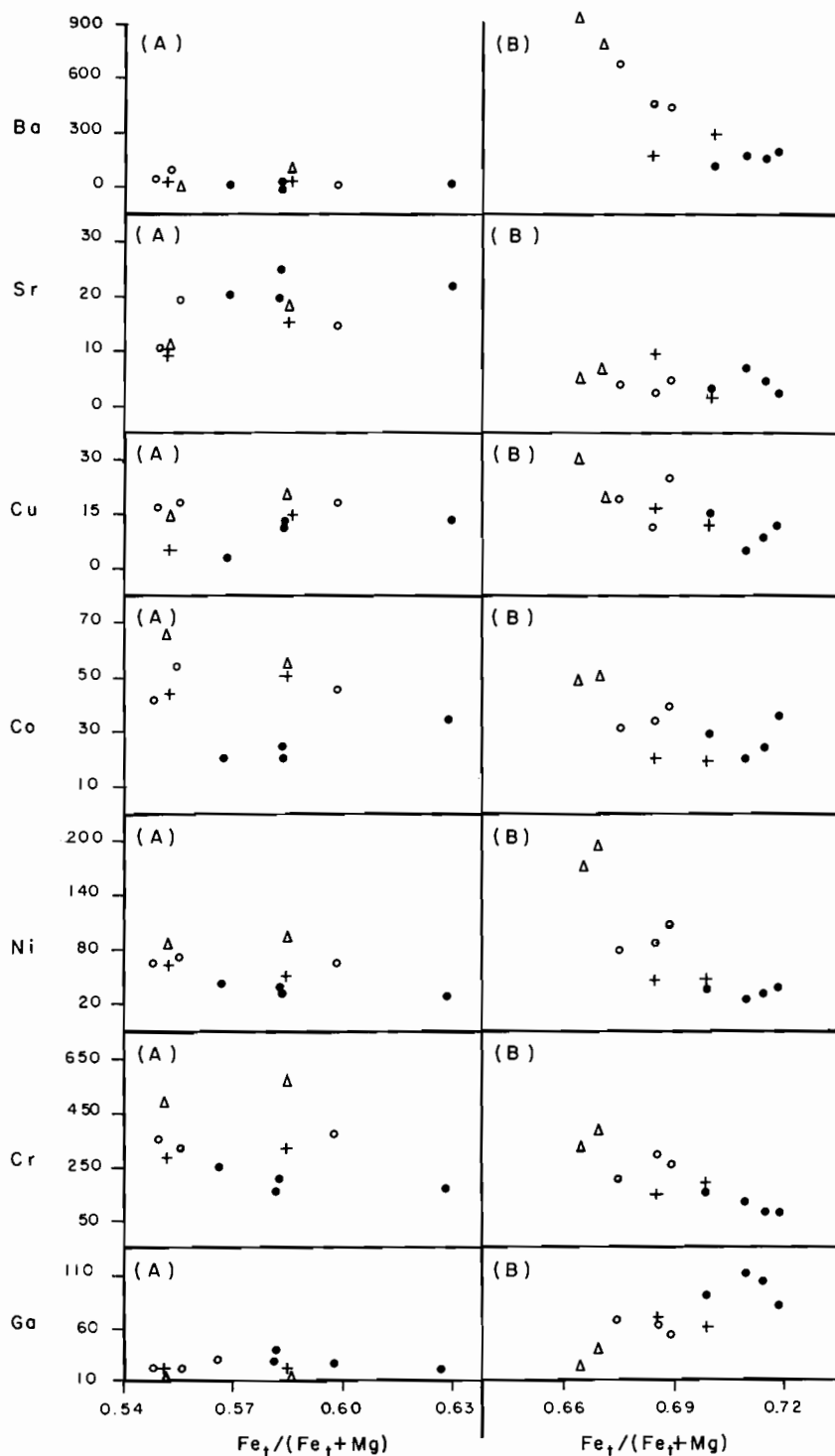


Fig. 9. Variation diagrams of trace elements in biotites (B) and amphiboles (A). Legend as in Fig. 3a.

The pleochroic formulae of both biotites and amphiboles agree to a great extent with the absorption colours based on the chemical composition in which the biotites have brown absorption colour in the Y and Z directions (Hayama 1959) while the absorption colours of the amphiboles vary from green to dark green along the Z direction (Binns 1965). Fe^{3+} contents (Tables 2 and 3) of both biotites (0.073–0.166) and amphiboles (0.209–0.438) are low, indicating low oxygen fugacities in the melt (Semet 1973).

The variable values of each calculated K_D in the coexisting biotites and amphiboles ($K_{D_{\text{Al}^{IV}}}^{\text{B-H}}$, $K_{D_{\text{Fe-Mg}}}^{\text{B-H}}$ and $K_{D_{(\text{Al}^{VI}+\text{Ti}+\text{Fe}^{3+})}}^{\text{B-H}}$) show that both minerals did not attain chemical equilibrium at the end of the reaction series during the late magmatic stage of Zaker granitic batholith. The different values of K_D support also the view that both mafic minerals were crystallised under variable conditions of temperature and pressure (Stephenson 1977). The present authors relate the crystallisation of both mafic minerals under variable conditions to the great differences in the mineralogical and chemical composition of their host granitic rocks which grade from diorites to granites.

According to the $K_{D_{\text{Fe-Mg}}}^{\text{H-B}}$ value (0.83) of Larsen and Draisin (1950), the Zaker biotite–amphibole pairs have low values of the same K_D (0.444 to 0.642) suggesting that their host granitic rocks were crystallised under low temperature and pressure (Albuquerque 1971, 1973). Further evidence is provided by the low Ti content of our amphiboles (0.06–0.08, Table 3). Green & Ringwood (1968) and Holloway & Burnham (1972) consider that the low Ti content of amphiboles is one of the indicators which reflect a low crystallisation temperature.

The distribution of trace elements between coexisting biotite and amphibole shows that biotites have high contents of Ga, Ba and Ni as compared to the amphiboles, whereas the Sr, Cr and Co are more concentrated in the amphiboles than in the biotites. It is evident that a higher content of Ga in the biotites and of Sr in hornblendes is observed with increasing SiO_2 in their host granitic rocks whereas the Cu and Ba content of the biotites decreases as their host rocks become more felsic. Cr, Ni and Co in both biotites and amphiboles decrease gradually toward the felsic end member. The action of late hydrothermal solution causes some disturbances in the chemical composition of Zaker biotites and hornblendes. These chemical disturbances of both mafic minerals in the granites are attributed to the hydrothermal granitisation process, whereas those in biotites and hornblendes of the preexisting granodioritic rocks are due to a solid solution reaction at late magmatic stage of Zaker granitic batholith.

The biotites investigated have high K/Rb ratios, i.e. low Rb and high K contents whereas the amphiboles have low Ti values and rather high Si values. According to Stavrov (1971) and Leake (1965), the biotites and hornblendes fall in the field of metamorphic complexes.

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Table 1. Major elements (%) of biotites and hornblendes from Zaker granitic rocks

<i>Biotites</i>											
Sample no.:	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	38.62	37.91	37.42	37.51	35.82	38.21	37.12	35.62	35.41	36.42	36.74
TiO ₂	3.11	2.89	2.78	3.15	2.91	3.51	2.52	2.91	3.41	3.01	2.34
Al ₂ O ₃	15.43	16.21	15.49	15.99	16.12	15.98	15.61	17.91	15.36	16.15	16.86
Fe ₂ O ₃	0.99	1.05	1.21	0.98	1.21	0.90	1.06	1.36	0.84	1.50	0.99
FeO	18.35	17.99	18.11	18.32	18.51	18.43	18.71	17.61	18.99	17.11	16.83
MnO	0.36	0.14	0.29	0.28	0.23	0.25	0.20	0.32	0.34	0.33	0.25
MgO	9.81	9.45	10.60	10.09	11.45	10.61	11.42	11.51	11.41	11.63	11.43
CaO	0.54	0.55	0.61	0.48	0.65	0.55	0.37	0.46	0.49	0.66	0.57
Na ₂ O	0.29	0.25	0.24	0.29	0.36	0.34	0.26	0.34	0.50	0.39	0.41
K ₂ O	9.11	9.88	9.64	8.21	9.73	7.24	9.03	9.73	10.53	9.63	10.81
H ₂ O	2.87	3.51	3.19	2.91	2.99	3.22	3.21	2.34	2.78	3.01	2.88
Total	99.48	99.83	99.58	99.21	99.98	99.24	99.50	100.11	100.06	99.84	100.11
Fe _t /(Fe _t + Mg)	0.715	0.719	0.699	0.709	0.687	0.699	0.687	0.677	0.689	0.670	0.665

<i>Hornblendes</i>											
Sample no.:	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	47.81	46.53	46.39	45.91	48.51	46.53	47.07	48.61	49.44	46.11	47.30
TiO ₂	0.71	0.62	0.61	0.87	0.73	0.65	0.55	0.79	0.82	0.80	0.60
Al ₂ O ₃	8.31	9.91	8.52	10.21	8.63	9.00	8.82	8.39	7.93	9.21	8.42
Fe ₂ O ₃	2.81	3.12	2.00	3.95	3.51	2.93	2.81	2.01	1.86	3.02	2.91
FeO	11.21	10.51	11.73	11.06	10.51	10.51	11.63	11.91	11.78	11.68	10.31
MnO	0.69	0.72	0.55	0.53	0.77	0.56	0.67	0.53	0.65	0.49	0.59
MgO	12.61	12.21	13.24	11.21	12.39	13.60	14.86	12.11	13.89	13.13	13.40
CaO	12.33	12.42	13.21	12.96	11.64	11.73	10.21	12.67	10.53	12.51	12.87
Na ₂ O	0.72	0.64	0.49	0.58	0.75	0.63	0.66	0.55	0.67	0.59	0.69
K ₂ O	0.45	0.48	0.53	0.46	0.53	0.57	0.50	0.46	0.39	0.43	0.55
H ₂ O	2.01	1.99	2.36	2.12	1.98	1.89	2.10	1.80	1.89	2.11	2.31
Total	99.99	99.15	99.63	99.86	99.95	99.60	99.88	99.83	99.85	100.08	100.00
Fe _t /(Fe _t + Mg)	0.583	0.583	0.567	0.626	0.586	0.553	0.550	0.594	0.556	0.586	0.553

Explanation of sample nos. and rock types.

White granites: 1, Biotite and hornblende from coarse-grained granite; 2, Biotite and hornblende from porphyritic granite. Pink granites: 3, Biotite and hornblende from coarse-grained granite. Red granites: 4, Biotite and hornblende from coarse-grained granite. Adamellites: 5, Biotite and hornblende from medium-grained perthite adamellite. 6, Biotite and hornblende from coarse-grained adamellite. Granodiorites: 7, Biotite and hornblende from coarse-grained adamellite. 8, Biotite and hornblende from porphyritic granodiorite; 9, Biotite and hornblende from coarse-grained perthite granodiorite. Quartz diorites: 10, Biotite and hornblende from medium-grained quartz diorite; 11, Biotite and hornblende from porphyritic quartz diorite. N.B. Sample numbers referring to various granitic rocks are the same throughout the present study.

Table 2. Structural formulae and some element ratios of biotites from Zaker granitic rocks

Sample no.	1	2	3	4	5	6	7	8	9	10	11
Si	5.912	5.751	5.754	5.782	5.580	5.778	5.604	5.483	5.599	5.876	5.634
Al ^{iv}	2.088	2.249	2.246	2.218	2.420	2.222	2.396	2.517	2.401	2.124	2.366
Al ^{vi}	0.686	0.646	0.558	0.688	0.535	0.617	0.375	0.733	0.466	0.649	0.668
Ti	0.358	0.328	0.323	0.361	0.337	0.399	0.285	0.333	0.408	0.325	0.267
Fe ³⁺	0.110	0.127	0.147	0.111	0.149	0.109	0.127	0.166	0.095	0.158	0.073
Fe ²⁺	2.341	2.275	2.323	2.350	2.402	2.322	2.354	2.261	2.205	2.087	2.150
Mn	0.046	0.018	0.037	0.037	0.028	0.036	0.027	0.037	0.047	0.044	0.037
Mg	2.249	2.148	2.443	2.331	2.673	2.403	2.589	2.658	2.705	2.552	2.628
Ca	0.092	0.091	0.101	0.083	0.112	0.091	0.074	0.085	0.105	0.092	0.092
Na	0.092	0.072	0.074	0.092	0.112	0.090	0.072	0.092	0.152	0.106	0.128
K	1.780	1.912	1.900	1.610	1.944	1.396	1.738	1.920	1.310	1.790	2.114
OH	2.920	3.550	3.264	2.998	2.542	3.248	3.222	2.240	2.922	2.930	2.940
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	5.790	5.542	5.831	5.878	6.124	5.886	5.757	6.188	5.926	5.815	5.823
X	1.964	2.075	2.075	1.785	2.168	1.572	1.873	2.086	1.549	2.001	2.334
Fe ³⁺ /Fe ²⁺ + Fe ³⁺	0.044	0.052	0.059	0.045	0.058	0.044	0.051	0.068	0.043	0.075	0.033
Ti/Fe ²⁺	0.152	0.144	0.139	0.153	0.140	0.145	0.121	0.147	0.185	0.155	0.124
Fe ²⁺ /Mg	1.040	1.059	0.950	1.008	0.898	0.966	0.909	0.850	0.815	0.817	0.818
X _{Al^{iv}} ^B = Al ^{iv} /Al ^{iv} + Si	0.261	0.281	0.282	0.277	0.302	0.278	0.299	0.314	0.300	0.265	0.295
X _{Fe²⁺-Mg} ^B = Fe ²⁺ /Fe ²⁺ + Mg	0.510	0.514	0.487	0.471	0.473	0.491	0.476	0.459	0.439	0.449	0.449
X _{Al^{iv}} ^B = Al ^{iv} + Ti + Fe ³⁺ /Y	0.199	0.198	0.174	0.197	0.166	0.191	0.136	0.199	0.163	0.194	0.173
Mg %	39.15	38.88	42.25	39.90	43.60	41.07	45.18	43.21	46.01	44.22	45.41
Fe ²⁺ %	40.75	41.18	40.18	40.23	39.40	39.69	41.08	36.75	37.50	36.16	37.15
(Al ^{iv} + Fe ²⁺ + Ti) %	20.09	19.93	17.55	19.85	16.74	19.23	13.73	20.02	16.48	19.61	17.42

See Table 1 for explanation of sample numbers.

Table 3. Structural formulae and some element ratios of hornblendes from Zaker granitic rocks

Sample no.:	1	2	3	4	5	6	7	8	9	10	11
Si	6.997	6.847	6.795	6.750	7.051	6.871	6.961	7.110	7.154	6.770	6.882
Al ^{iv}	1.003	1.163	1.204	1.250	0.949	1.129	1.039	0.890	0.846	1.230	1.265
Al ^{vi}	0.421	0.558	0.268	0.512	0.521	0.438	0.475	0.549	0.492	0.361	0.318
Ti	0.076	0.070	0.071	0.097	0.079	0.071	0.062	0.079	0.087	0.088	0.070
Fe ³⁺	0.316	0.353	0.230	0.438	0.385	0.321	0.317	0.211	0.209	0.238	0.315
Fe ²⁺	1.364	1.273	1.438	1.350	1.262	1.294	1.410	1.448	1.426	1.425	1.728
Mn	0.087	0.088	0.071	0.061	0.096	0.062	0.079	0.061	0.078	0.062	0.070
Mg	2.755	2.677	2.921	2.454	2.690	3.014	3.248	2.651	3.016	2.884	2.918
Ca	1.924	1.949	2.082	2.025	1.811	0.178	0.192	0.158	0.192	0.176	0.192
Na	0.210	0.176	0.142	0.158	0.208	0.178	0.192	0.158	0.192	0.176	0.192
K	0.088	0.140	0.088	0.070	0.088	0.106	0.088	0.088	0.070	0.088	0.104
OH	1.942	1.932	2.312	2.910	1.932	1.862	2.032	1.754	1.826	2.040	2.230
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	5.019	5.019	4.999	4.912	5.033	5.200	5.591	4.999	5.308	5.058	4.919
X	2.222	2.265	2.312	2.253	2.107	2.137	1.874	2.230	1.896	2.225	2.300
Ti/Fe ²⁺	0.056	0.055	0.044	0.072	0.062	0.055	0.043	0.055	0.065	0.062	0.057
Fe ²⁺ /Mg	0.495	0.475	0.550	0.469	0.429	0.429	0.434	0.546	0.472	0.494	0.420
Al ^{vi} +Fe ³⁺ +Ti	0.813	0.981	0.569	1.047	0.985	0.830	0.854	0.739	0.788	0.687	0.703
X _{Al^{iv}} =Al ^{iv} /Al ^{iv} +Si	0.125	0.145	0.150	0.156	0.118	0.141	0.129	0.111	0.105	0.153	0.158
X _{Fe²⁺-Mg}} =Fe ²⁺ /Fe ²⁺ +Mg	0.331	0.322	0.329	0.354	0.319	0.300	0.302	0.353	0.321	0.330	0.296
X _{Al^{vi}} =Al ^{vi} +Ti+Fe ³⁺ /Y	0.161	0.195	0.113	0.213	0.195	0.159	0.152	0.147	0.148	0.135	0.142

See Table 1 for explanation of sample numbers.

Table 4. Distribution coefficients for coexisting biotites and hornblendes from Zaker granitic rocks

Sample no.:	1	2	3	4	5	6	7	8	9	10	11
$K_{DAI}^{B-H}_{VI}$	2.471	2.299	2.221	2.072	3.228	2.345	2.875	3.660	3.532	1.992	2.223
$K_{DFe^{2+}-Mg}^{B-H}$	2.101	2.224	1.935	1.758	1.914	2.249	2.098	1.553	1.853	1.652	1.935
$K_{DAI}^{B-H}_{VI}$	1.292	1.015	1.648	0.905	0.821	1.248	0.875	1.438	1.116	1.536	1.262
$K_{DFe:Mg}^{B-H}$	0.475	0.448	0.517	0.545	0.522	0.444	0.477	0.642	0.577	0.604	0.513
$0.35X_{Al}^{H_{iv}} + 0.24$	0.283	0.290	0.292	0.294	0.281	0.289	0.285	0.278	0.276	0.293	0.295

See Table 1 for explanation of sample numbers.

Table 5. Trace elements (ppm) of biotites and hornblendes from Zaker granitic rocks

Biotites

Sample no.:	1	2	3	4	5	6	7	8	9	10	11
Ga	100	80	90	110	70	65	65	70	55	40	33
Cr	80	90	160	130	150	200	300	220	270	400	320
Ni	32	37	40	25	50	55	90	80	110	195	170
Co	25	36	30	20	20	25	35	32	40	50	47
Cu	8	10	15	5	17	12	10	20	25	20	30
Sr	5	2	3	7	10	2	3	4	5	7	5
Ba	160	200	130	175	200	300	500	700	450	800	950
V	105	8	120	90	110	130	160	140	130	170	165
L	400	350	530	580	390	320	295	250	190	200	169
Rb	490	540	410	430	500	380	400	450	550	290	350
K/Rb	154	151	195	158	160	157	187	179	158	318	255

Hornblendes

Sample no.:	1	2	3	4	5	6	7	8	9	10	11
Ga	35	30	32	20	20	25	20	25	22	15	12
Cr	220	200	250	210	330	290	350	400	310	590	500
Ni	30	35	42	28	53	60	60	70	75	95	85
Co	25	20	30	35	50	45	42	48	55	54	65
Cu	10	11	9	12	15	13	17	20	18	20	15
Sr	25	20	21	23	15	10	10	15	20	18	9
Ba	15	10	13	16	18	18	20	25	22	24	30
V	350	390	280	290	295	230	200	210	150	140	100

See Table 1 for explanation of sample numbers.

جيوكيميائية البايوتيت والامفيبولات الكلسية المتواجدة معا
في الصخور الجرانيتية بزاكير ، مقاطعة زانجان ، شمال غرب ايران

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خلاصة

تميز البايوتيت والامفيبولات المتواجدة معا في الصخور الجرانيتية بزاكير بمحتوى منخفض من ايونات الحديدك ، ويعكس ذلك ان البايوتيت والامفيبولات قد تكونت تحت نشاط اوكسيجينى منخفض . ان تغيرات الوان الامتصاص لكل من البايوتيت والامفيبول تتأثر كثيرا بنسبة التيتانيوم إلى الحديدوز فيها ، وكذلك بنسبة الحديدك إلى الحديدك + الحديدوز . لقد وجد ان اختلاف معامل التوزيع للبايوتيت والامفيبول يشير إلى تبلورها تحت ظروف متغيرة من الحرارة والضغط ، كما يثبت أيضا وجود مرحلة عدم اتزان كيميائي بين البايوتيت والامفيبول أثناء تكوينهما . ان ارتفاع نسبة البوتاسيوم إلى الروبيديوم في البايوتيت وكذلك انخفاض عنصر التيتانيوم في الامفيبولات يدل على انها قد تأثرت أثناء تكوينها بعوامل تحولية .