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# STABILITY RELATIONS OF AMPHIBOLES IN MAFIC-ULTRAMAFIC SCHISTS FROM THE GREENSTONE BELT AROUND JACUI, SOUTHWESTERN MINAS GERAIS

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RESUMO

Anfibólios que coexistem nos xistos máfico-ultramáficos da região de Jacuí, SW Minas Gerais, são combinações de tremolita, antofilita e cummingtonita, às vezes com clorita. Essas paragêneses mostram claramente que os protólitos dos xistos sofreram metamorfismo no fácies anfibolito. Os anfibólios vistos em lâminas delgadas ocorrem lado a lado ou como intercrescimentos homotaxiais, indicando sua formação simultânea durante o metamorfismo, embora em outros lugares no greenstone belt encontram-se antofilitos em forma de porfiroblastos de crescimento tardio. Exsoluções paralelas a (Ī01) são comuns em alguns anfibólios, como no caso de tremolita e cummingotnita, enquanto que exsoluções (100) são menos frequentes; existem também texturas que sugerem uma transformação de cummingtonita para antofilita de modo análogo às transformações de tipo monoclínico para ortorrômbico nos piroxênios. As composições alto magnésio dos anfibólios indicam temperaturas elevadas para sua coexistência. Em consequência, as temperaturas são muito superiores às necessárias para a mineralização de ouro, e o ouro deve ter migrado no gradiente de temperatura para temperaturas baixas. Cisalhamento intenso nas zonas de falhas causou retrometamorfismo dos xistos para talco.

## INTRODUCTION

Metamorphosed mafic-ultramafic rocks in greenstone belts are characterized by greenschist facies parageneses which grade into amphibolite facies at the border of intrusive granitic bodies or along margins of gneiss domes. Examples of such gradations have been reported from the Abitibi belt of Canada (Jolly, 1980), from the northern Guiana greenstone belt (Gibbs, 1980) and from Rio Itapicuru in Bahia (Kishida, 1979). With the exception of Canada, little attention has been paid to metamorphic parageneses in the greenstones. As a part of a wider study of greenstone belts in southern Minas Gerais, we discuss here the occurrence and stability of coexisting amphiboles in mafic-ultramafic schists from the Jacui area, and show that they are high temperature assemblages belonging to the amphibolite facies. This has important implications for gold mineralization.

## GEOLOGY

Just north of Jacui there is a WSW trending belt, some 5 km broad and 50 km long, in which we find several rock types occurring together, as for example mafic-ultramafic amphibolites, chlorite-talc schists, serpentinites, biotite gneisses, micaceous quartzites and calc-silicates.

According to Teixeira et al. (1987) they belong to the Colonia Unit and thus form a part of the Morro do Ferro belt considered to be an Archaean greenstone belt.

The above belt is surrounded by migmatites and orthogneisses which extend as far south as São Pedro de União (Crosta et al., 1986) where they are overlain by paragneisses; to the north they reach up to Itau de Minas and are there covered by phyllites, calcareous dolomites and sericite quartzites of the Canastra Group. Within the migmatite terrain there are also tonalite and granodiorite bodies some of which lack effects of migmatization such as the semi-circular São José granite half-way between Jacuí and the Morro de Ferro belt. At places the migmatites contain small mafic bodies while the large tonalite to grano diorite bodies enclose xenoliths of mafic-ultramafic rocks.

Although Teixeira et al. (1987) include the Jacuí rocks in the Morro do Ferro belt, the relation between them is far from clear. This is also true for their lithologies, their internal stratigraphy and relation to the migmatites. We have observed, however, that these rocks lie within a vertical ductile shear zone with a sinistral sense of movement. The effect of this shearing on the gneisses gives rise to centimetric sheath folds with a sub-horizontal N 90 E axis as well as conspicuous stretching lineation with the same direction in micaceous quartzites and gneisses.

On the other hand, there are some rocks for which it is difficult to say where they belong. To the NW of Jacuí, for example, we find coarse grained meta-orthopyroxenites associated with similarly coarse grainded serpentinized peridotites which appear to be differentiated intrusives in the interior of the belt. Besides these rocks, we also find a thick succession of interlayed paragneiss and amphibolite in the outskirts of Jacuí going towards Fortaleza de Minas whose protolith could well be a basic turbidite sequence compositionally similar to the ones which make up the Upper Group of the Piumhi Massif. Furthermore, the quartzites and calc-silicates SW of Jacuí could be similar to the clastic and chemical sediments of either the Upper Group of Piumhi or the Canastra Group which crops out only a few kilometers NW of Jacuí (Serra do Chapadão) and whose NS trend is interrupted by a trancurrent zone parallel to the ones described above.

In view of the many doubts which remain regarding all these lithologies, we can at the moment best say that the Jacuí zone is a mixture of several rock types belonging partly to the greenstone belt and its rock cover and partly to the nearby Proterozoic metasediment cover. As regards the extensive shear zone, it should be pointed out that it is strictly parallel to the stretching fabric observed in the metasediments of the Araxá and Canastra Groups and in the granulites, migmatites and charnockites of the Guaxupé Massif, and might be related to large-scale tectonic events of the Brazilian cycle (Schrank, in prep.). In any case, we shall regard the mafic-ultramafic schists of Jacuí as being a part of the greenstone belt which has also been subjected to the strong shearing.

## NATURE OF MAFIC-ULTRAMAFIC SCHISTS

### Field Description

Mafic-ultramafic rocks occur in the form of low-lying hills around Jacuí and extend from the west or northwest of the town to east and southeast. In fresh outcropos the rocks are either dark green and massive or light green and schistose in the case of mafic and ultramafic varieties respectively. Weathered outcrops are much more common and these can be recognised by their weathering colour; it is interesting to note that in these outcrops there are also pegmatite lenses and quartz-feldspar veining, possibly as a result of migmatitic effects or due to the intrusion of the São José granite which is just north of the town and which is easily recognisable by the light-coloured, quartz-rich soil to which the red weathering ultramafics give way on going northwards from Jacuí. Owing to the deep and extensive weathering of the rocks in the area, closer field observations are warranted to be able to establish a clearer relations between these rocks, however.

## Petrography

Some of the ultramafic rocks examined in the course of routine petrographic study were found to be coarse grained types which range from meta-orthopyroxenites and peridotites serpentinized to varying degrees to polygonized gabbroic anorthosite. Here again a closer mapping and field observation are needed to mark these bodies in a satisfactory manner. An important feature of the meta-pyroxenites is the presence of orthopyroxene relics which are in the process of being replaced by jagged, saw-tooth cummingtonite along the margins. The effect of shearing is also visible in the form of orthopyroxene clusters surrounded by stretched amphiboles, the latter undergoing transformation to chlorite in cleavages and fractures.

The amphibolites are finer grained than the above rocks and consist of olive-green hornblende, plagioclase, epidote, sphene and opaques. These rocks are also sheared and show a fine, leucocratic banding of quartz diorite composition. The lighter green ultramafic schists, the object of the present study, occur close to these amphibolites, and consist essentially of tremolite-actinolite, anthophyllite and cummingtonite with minor amounts of colourless to pale green chlorite and talc. The several kinds of paragenetic combinations met with in the metamorphosed mafic ultramafic rocks of the area are listed in Table 1. Considering that the protoliths of these rocks are not exclusively serpentinites, their parageneses do not always match those given by Winkler (1976) or for that matter by Evans (1982), rather they are much closer to those described by Jolly (1982) from the Abitibi belt.

Calcic amphibole, tremolite-actinolite, is frequently the most abundant mineral in these schists, and is accompanied by either anthophyllite or cummingtonite plus some chlorite. In the matted schistose texture, colourless tremolite or very pale green actinolite form short prismatic crystals coexisting with the magnesium amphiboles; the pale green actinolite shows homotaxial intergrowth with colourless anthophyllite or when it coexists with cummingtonite it contains fine $(\bar{1}01)$ exsolution lamellae of latter amphibole (Fig. 2a & 2b). Anthopyllite and cummingtonite occur in long prismatic form or are even fibrous, sometimes with overgrowths of the former on the latter and sometimes with gradational transition from the monoclinic to the orthorhombic amphibole (Fig. 3a & 3b). These textures are considered to indicate simultaneous growth during metamorphism while the transitions are likely to be transformations which take place on cooling from high temperatures as in the case of clino- and orthopyroxene. Around Alpinópolis, however, anthophyllite forms slender porphyroblasts over the pre-existing textures in ultramafic rocks. Samples collected from the shear zone NE of Jacuí contain much talc as a retrograde product of anthophyllite. Obviously much aqueous fluid was available to bring about this transformation.

Confirmation of the amphibole varieties was obtained by x-ray diffractograms which were also used to estimate the Mg content of the magnesium amphiboles according to the method of Popp et al. (1976). The estimated compositions in terms of Fe-Mg for anthophyllites are given in Table 2 and are in good agreement with previous preliminary estimates by Choudhuri (1980).

## STABILITY RELATIONS

Mafic-ultramafic rocks of greenstone belts commonly pass through a stage attributed to low-grade ocean-floor metamorphism (see e.g. Jolly, 1980, 1982), and this is probably the case for the ultramafic rocks of Piumhi (Schrank, 1982). With increasing temperature the low-grade paragenesis is replaced by mineralogy typical of upper greenschist to amphibolite facies. In rocks of basaltic composition, this passage is registered by the replacement of chlorite-epidote-actinolite albite assemblages by hornblende-epidote-albite or hornblende plagioclase. Depending on the bulk composition this takes place around $500^{o}$-$550^{o}$ in the pressure range 2 to 6 kb (Liou et al., 1974). In ultramafic rocks, however, magnesian chlorite can be stable to relatively high temperatures. Pure Mg-chlorite breaks down according to:

chlorite = orthopyroxene + forsterite + spinel + $H_2O$, at 750°/ 4 kb (Jenkins and Chernosky, 1986). Nevertheless, chlorite could break down much earlier if $P_{H_2O} < P_T$ and if other phases are present for it to react with. In the amphibole-bearing schist from Jacuí, the retrograde replacement of amphiboles by chlorite and its frequent absence as a stable phase in amphibole assemblages suggests that most of it must have already reacted away when the amphiboles formed.

The stable coexistence of amphiboles is due to a compositional miscibility gap between them. Thus, there is such a gap even among the calcic amphiboles so that actinolite and hornblende can coexist at low pressures and moderate temperatures (Oba and Yagi, 1987). Since this is not observed in the rocks of the area, it may be assumed that the metamorphism was in the medium pressure range of around 3 or 4 kb. The coexistence of Ca-rich and Ca-poor amphiboles is because of a very wide miscibility gap and restricted solid solution. Several examples of this have been reported in the literature (Klein, 1968; Ross et al. 1969; Stout, 1972; Robinson et al., 1982). The extremely Mg-rich compositions of the anthophyllite in this study is used as a basis to construct a schematic paragenetic diagram, and this is depicted in Fig. 4 in which the mineralogy is shown near the Mg-rich corner of the $CaO-Al_2O_3-MgO-FeO$ tetrahedron. The formation of these amphiboles from lower grade assemblages necessarily requires temperatures well within the amphibolite facies.

## P-T Relations

In view of the fact that the amphiboles from Jacuí are very Mg-rich, their formation and stability can safely be considered with respect to experimental investigations in Fe-free systems. In these systems, anthophyllite stability has been dealt with by Greenwood (1963) and recently by Chernosky et al. (1985), while for the stability of hornblende the data of Spear (1981) are pertinent. Some of the reactions referable to mafic-ultramafic rocks in relation to the formation and upper stability limits of these amphiboles are shown in the P-T diagram of Fig. 5. The reactions considered to be relevant are as follows:

1. antigorite = forsterite + talc + water
2. tremolite + chlorite = actinolite + anthophyllite + water
   & talc + $chlorite_1$ = anthophyllite + $chlorite_2$ + quartz + water

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   talc + tremolite + $chlorite_1$ = actinolite + anthophyllite + $chlorite_2$ + quartz + water
3. talc = anthophyllite + quartz + water
4. anthophyllite = enstatite + quartz + water
5. $hornblende_1$ + $plagioclase_1$ = $hornblende_2$ + $plagioclase_2$ + clinopyroxene + water
6. $hornblende_2$ + $plagioclase_2$ = $hornblende_3$ + $plagioclase_3$ + Clinopyroxene + orthopyroxene + water

In these reactions the subscripts denote changes in composition in the course of the transformations to higher temperature assemblages. Reaction 1 is responsible for the formation of talc which might also account for the antigorite-talc-chlorite or tremolite-chlorite-talc assemblages in the present case (Table 1). These low to medium grade minerals then react to give the higher temperature amphibole parageneses.The P-T data from Fig. 5 indicate that amphiboles begin to form already at the beginning of amphibolite facies as chlorite diminishes, but as discussed earlier on, Mg-chlorite can be stable to even higher temperatures before it is eliminated from the paragenesis. Temperature estimates for its participation in Mg-rich amphibole systems are not available but should be faily high. Considering that the miscibility gap between Ca- and Mg-amphibole is narrowest around 700°/5kb (Oba and Nicholls, 1986) and broadens at 2 kb (Cameron, 1975), in view of the estimated composition of Mg-amphibole it is suggested that cooling must have taken place from at least above 600° to form exsolution lamellae in Mg-rich actinolite. This temperature was possibly attained at higher pressures, as indicated before for such amphibole pairs (Choudhuri, 1980), and a pressure range above 2 kb and approaching 5 kb seems reasonable. It may be concluded, therefore, that the amphibole parageneses from Jacui represent high temperature medium pressure metamorphic conditions. The amphibole breakdown temperatures in Fig. 5 set an upper stability limit not reached in the examined rocks; rather, the Mg-amphiboles revert to talc in retrogression of Reaction 3 with the access of water at lower temperatures along the extensive NW-SE shear zones which cut across the region.

## Metallogenic Implications

According to models proposed by Fyfe (1974) one of the mechanisms for gold mineralization is its mobilization and transport in hydrothermal fluids and its deposition in a thermal gradient. Fyfe has shown that the solubility of gold rises rapidly with increasing temperature so that high solubilities are expected under amphibolite facies conditions; gold is then deposited when the temperature drops to values in the greenschist facies range. The solubility of quartz follows a parallel pattern and is equally remarkable, and explains the occurrence of gold in quartz veins. Since the Jacui schists belong to the amphibolite facies, it is not unlikely that any gold present in the environment would have long migrated down-temperature to suitable sinks where it could be redeposited. Such sinks could be quartz veins away from granite contacts or shear zones where fluids have easy access.

## CONCLUSIONS

Ca-rich and Ca-poor amphibole coexist stably in the ultramafic schists from Jacui. Their textural relations and high Mg compositions reflect their formation at high temperatures within the amphibolite facies - cooling from higher temperatures gave rise to exsolution in coexisting actinolite and cummingtonite. It is evident that the temperatures were too high for gold to remain in this environment, and whatever gold present must have migrated down-temperature to be redeposited elsewhere. It should be looked for away from the granitic intrusions, possibly in shear zones or quartz veins.

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FIGURE CAPTIONS

Fig. 1 Geological sketch map of granite-greenstone terrain in SW Minas Gerais. Key: G = Guaxupé, J = Jacuí, A = Alpinópolis, P = Passos, 1 = migmatites, orthogneisses, 2 = greenstone, 3 = granulites, 4 = granitic rocks, 5 = paragneisses and metasediments; thick lines = faults, arrows = displacement, barbs = thrust fault; map after Crosta et al. (1986).

Fig. 2 A. Intergrowth of very pale green actinolite and colourless anthophyllite. Scale bar = 1 mm.
B. Exsolution lamellae in actinolite.

Fig. 3 A. long prismatic cummingtonite with exsolution lamellas of tremolite and border of anthophyllite. Scale bar = approx. 1 mm.
B. Basal section of cummingtonite with anthophyllite border.

Fig. 4 $CaO-Al_2O_3-MgO-FeO$ tetrahedron with amphibole parageneses - E = epidote, AC = actinolite, A = anthophyllite, CH = chlorite, C = cummingtonite.

Fig. 5 P-T for lower and upper stability of amphiboles: T = talc, TR = tremolite, CH = chlorite, Q = quartz, AN = antigorite, F = forsterite, HB = hornblende, A = anthophyllite, E = orthopyroxene, W = water; reactions curves after Chernosky et al. (1985) and Spear (1981):

1. AN = F + T + W
2. T + CH + TR + Q = A + H + N
3. T = A + Q + W
4. A = E + Q + W
5. $HB_1 + PL_1 = HB_2 + PL_2 + CPX + W$
6. $HB_2 + PL_2 = HB_3 + CPX + OPX + W$

TABLE 1

Typical mineral assemblages in mafic schists from Jacuí & Alpinópolis, Minas Gerais.

| Low to medium grade | Medium grade |
|---|---|
| antigorite-talc-chlorite | hornblende-epidote-oligoclase |
| tremolite-chlorite-talc | olivine-orthopyroxene-pargasite-spinel |
| tremolite-chlorite-antigorite | olivine-cummingtonite-antigorite-chlorite |
| talc-actinolite | anthophyllite-chlorite-actinolite |
| chlorite-epidote-actinolite | cummingtonite-chlorite-actinolite |
| epidote-albite-actinolite | orthopyroxene-cummingtonite-anthophyllite |
| | talc-chlorite-anthophyllite-tremolite |

TABLE 2

Anthophyllite Compositions

| Sample nº | Mol% Mg end member* | Estimated Composition* |
|---|---|---|
| ACGX 1/2a | 84 | $Mg_{5.88}\ Fe_{1.12}\ Si_8\ O_{22}\ (OH)_2$ |
| ACGX 4/2 | 84 | $Mg_{5.88}\ Fe_{1.12}\ Si_8\ O_{22}\ (OH)_2$ |
| ACGX 1/16c | 78 | $Mg_{5.46}\ Fe_{1.54}\ Si_8\ O_{22}\ (OH)_2$ |
| ACGX 1/19 | 68 | $Mg_{4.76}\ Fe_{2.24}\ Si_8\ O_{22}\ (OH)_2$ |
| ACFM 9a | 68 | $Mg_{4.76}\ Fe_{2.24}\ Si_8\ O_{22}\ (OH)_2$ |

* Composition estimates are with respect to Mg-Fe contents only and are based on 040 and 440 reflections from $CuK_\alpha$ diffractometer traces and 2$\theta$ values after Popp et al. (1976); ACGX 1/16 c is in agreement with previous estimates from refractive index data (Choudhuri, 1980).

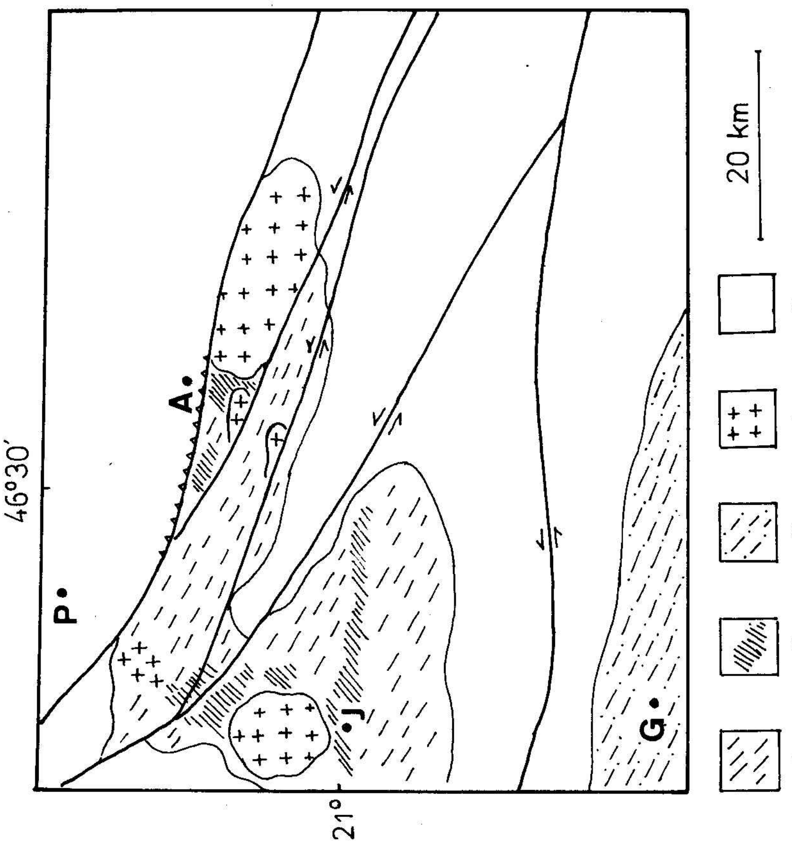
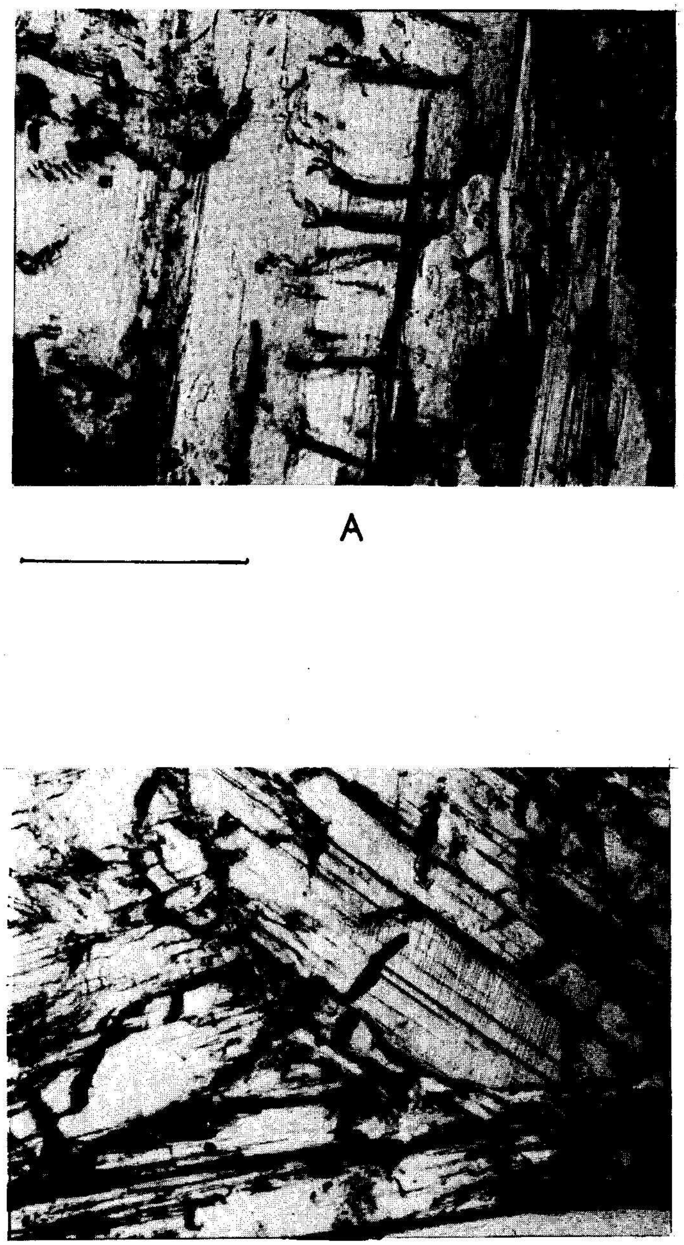



FIG.1



A

B

FIG. 2

A

B

FIG. 3

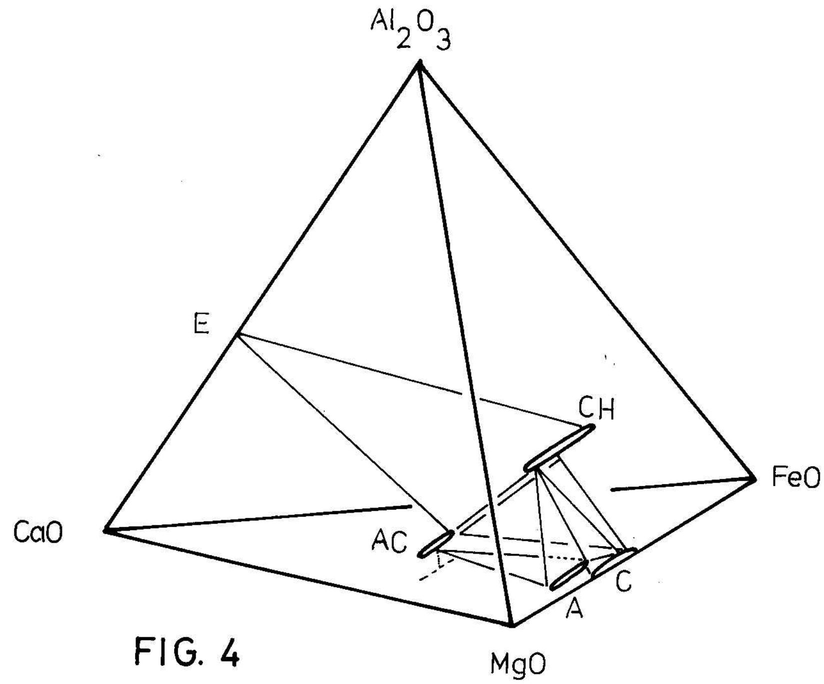



FIG. 4

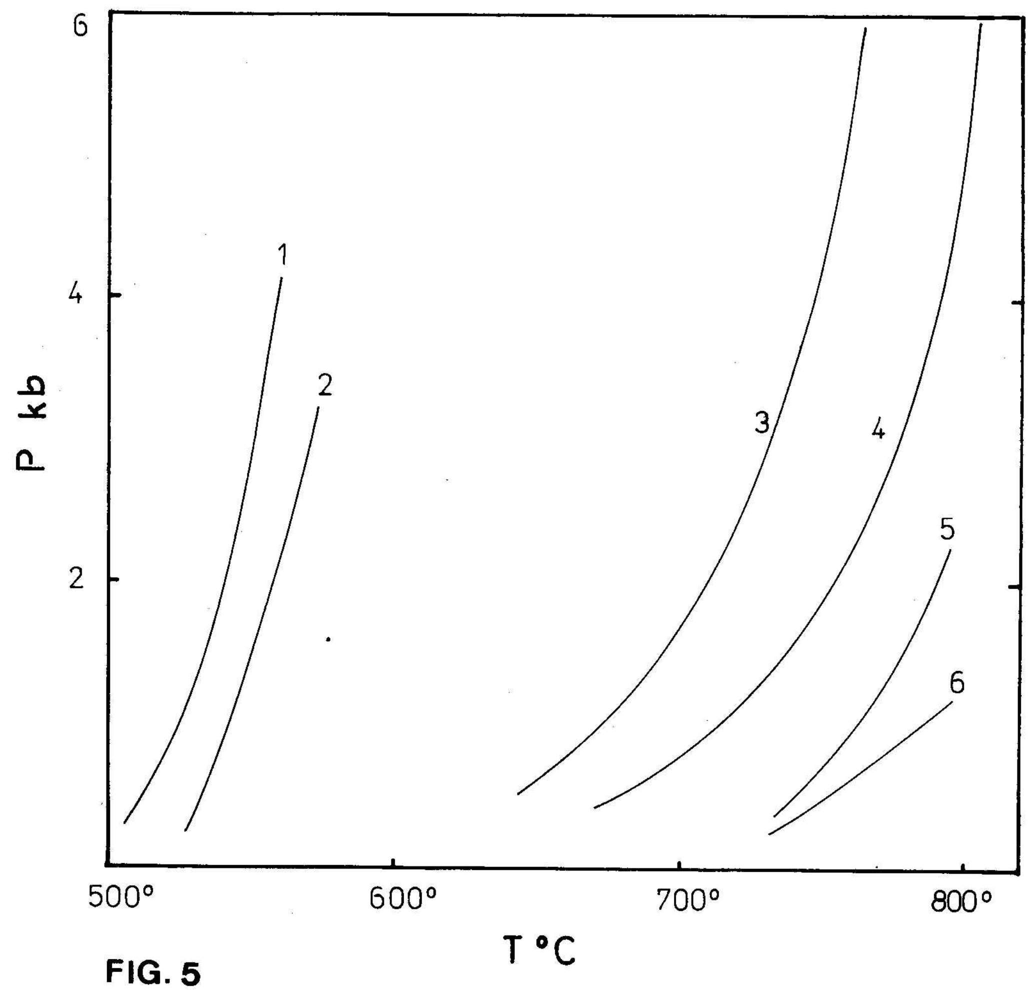



**FIG. 5**