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Kyanite-staurolite ortho-amphibolite from the Chapada region, Goiás, central Brazil

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ABSTRACT

This study deals with the kyanite–staurolite assemblage from a metabasite (ortho-amphibolite) in the Chapada area of the Neoproterozoic Mara Rosa volcano-sedimentary sequence of Goiás state, Brazil. It is closely associated with hydrothermally altered rocks and contains the assemblage hornblende, epidote, quartz, kyanite, staurolite, plagioclase and rutile. The staurolite from the amphibolite shows lower values of SiO_2 and higher values of MgO, MnO, ZnO and X_{mg} than those in staurolites from the metasediments of the same area. In the Al–Na–Ca–(Fe+Mg) diagram, the amphibolite plots in the aluminous part of the diagram and the phase volume encloses the area of mafic volcanic bulk compositions. Field relations and compositions in both kyanite–staurolite amphibolite and staurolite are consistent with formation of this amphibolite as a result of metamorphism of metasomatised basalts.

KEYWORDS: staurolite, ortho-amphibolite, Brazil.

Introduction

ALTHOUGH staurolite is most commonly regarded as a typical product of regional metamorphism of pelites, it has been recorded as a rare constituent in regionally metamorphosed igneous rocks. Staurolite has been described in metabasites in the Sambagawa metamorphic belt of Japan (Miyashiro, 1973), in amphibolite of the Timurgara ultramafic complex, Pakistan (Jan *et al.*, 1971), in epidote amphibolite of the Ovala Sequence, Gabon (Demange, 1976), in sheets of interlayered amphibolite and hornblendite in the metamorphosed gabbroic anorthosite of the Upper Seaforth River, Central Fiordland, New Zealand (Gibson, 1979), in amphibolites of the Laurel Greece mafic-ultramafic complex, northeastern Georgia Blue Ridge, U.S.A. (Helms *et al.*, 1987), in metabasic eclogite from Jiangsu Province, East China (Enami and Zang, 1988), in amphibolite in the Vinjamuru area of the Nellore granite–greenstone terrain of India (Moeen, 1991), and in amphibolites from the Beltic Cordillera, Spain (Soto and Azañón, 1993). The literature contains little reference to kyanite-amphibolites of igneous origin. In addition to being found in some eclogites and eclogitic amphibolites in the northeast of Bavaria (Mattheus *et al.*, 1970), kyanite is found in amphibolites (Tilley, 1928) which also represent the product of eclogite retrograde metamorphism, in amphibolites from central Fiordland, New Zealand (Gibson, 1979) and in amphibolites from southern Alps, New Zealand (Cooper, 1980).

Among the rather common amphibolites from the Mara Rosa volcano-sedimentary sequence, central Brazil, there is an ortho-amphibolite which is unusual for its hornblende-epidote-quartz-staurolite-kyanite-rutile assemblage. Selverstone *et al.* (1984) suggested that rocks of basaltic composition stabilize hornblende + staurolite (and/or kyanite) at pressures higher than those appropriate for the stability of the common amphibolite assemblage (calcic amphibole + plagioclase + epidote + chlorite + garnet) in medium-pressure metamorphic terranes. According to Helms *et al.* (1987) amphibolites bearing kyanite-staurolite + hornblende result from a pressure higher than 7.7 kbar at temperatures appropriate for the amphibolite facies. On the other hand, Demange (1976) has studied the staurolite-amphibole paragenesis in amphibolites from Ovala, Gabon, and concluded that the particular character of this paragenesis is merely the expression of a chemistry which was already special before metamorphism, and suggested that those amphibolites derived from metasomatised igneous rocks.

In this communication, data concerning the development of the Chapada region staurolite–kyanite amphibolite are presented and discussed with the aim of determining whether this amphibolite resulted from unusual bulk rock composition or from unusual physical conditions.

Geological setting

Throughout the Chapada region, the dominant host rocks to the granitic and gabbroic plutons are metabasalts and metasediments of the Mara Rosa sequence which have been metamorphosed to the amphibolite facies. In the study area (Fig 1), three lithologic units can be distinguished in the sequence to which a Neoproterozoic age has been attributed (Richardson *et al.*, 1986; Pimentel *et al.*, 1993). The lower one consists of feldspathic gneisses, staurolite- and kyanite-bearing metapelites, garnet amphibolites and quartz amphibolites. The middle unit is made up of pillowed clinopyroxene amphibolites with minor iron formation. The upper unit consists essentially of feldspathic garnet gneisses.

The amphibolites occur in schistose and massive varieties and are generally composed of hornblende, andesine, quartz, epidote, opaques, ±garnet, ±clinopyroxene, and have an igneous parentage of island-arc settings (Kuyumjian, 1989).

The staurolite–kyanite amphibolite constitutes a subordinate amphibolite in the Mara Rosa sequence. It is about 50 metres in width and extends approximately parallel to and closely associated with a NNE–SSW trending shear zone. The rocks in the vicinity of the shear zone have been subjected to hydrothermal alteration (Kuyumjian, 1991).

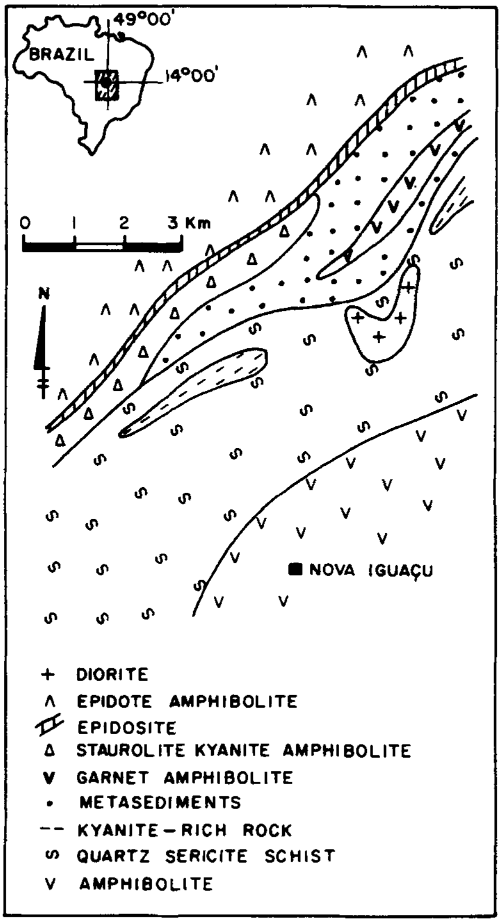

FIG. 1. A simplified map showing the lithological units of the hydrothermal zone in the Chapada area.

Assemblage and mineral chemistry

The Chapada amphibolites are composed of subsets of the assemblage hornblende + plagioclase + garnet + clinopyroxene + epidote + quartz + rutile + magnetite + ilmenite. Retrograde assemblages include chlorite, muscovite and paragonite. Of special note is the coexistence of hornblende + epidote + quartz + kyanite + staurolite + plagioclase + rutile , a mineral association not common in the literature dealing with amphibolites of igneous origin. A similar assemblage has been described in the high-pressure epidote amphibolite in the Sambagawa belt, Japan (Miyashiro, 1973).

The amphibole in the staurolite–kyanite amphibolite is mostly homogeneous and its composition is that of ferroan pargasite with maximum Al_2O_3 of 17.43%, according to the nomenclature of Leake (1978). Plagioclase is very rare, and this suggests that the paragonite present in the amphibolite probably is a retrograde product of plagioclase alteration. Deer *et al.* (1982) point out that at temperatures >400°C and P_{tot} = 15,000 lb/in^2 albite is altered to paragonite plus quartz. The composition of the epidote corresponds to that of zoisite–clinozoisite (Table 1). Retrograde muscovite, paragonite and, to a lesser extent, chlorite, are not abundant and they occur as randomly oriented flakes discordantly to foliation.

Staurolite and kyanite occur randomly distributed in the amphibolite. Under the microscope, grains of staurolite are xenomorphic and show the characteristic golden yellow pleochroism, while kyanite grains, often hypidiomorphics, commonly contain several inclusions. Staurolite in the metapelites occurs as idioblasts in association with micas, garnet, plagioclase and quartz. The Al–Na–Ca–(Fe+Mg) diagram (Fig. 2) illustrates the plotting positions of the principal Chapada staurolite–kyanite amphibolite phases. This figure demonstrates that the present rock plots in the aluminous part of the diagram and shows that the phase volume overlaps with the phase volumes of typical amphibolite-facies assemblages (see Spear, 1982).

According to Deer *et al.* (1982) natural staurolites are ferroan with X_{Fe} ratios most commonly in the range 70–80. In staurolites from the Chapada amphibolite this ratio has values between 73.49 and 89.44. Table 2 compares chemical data of staurolites from the Chapada amphibolite and metapelites with those from other regions. It can be seen that the staurolite from the Chapada amphibolite has lower values of SiO_2 and higher values of MgO, MnO, ZnO and X_{Mg} than those in staurolites from the metasediments of the same area. These data indicate the influence of bulk composition upon staurolite composition at Chapada.

In relation to other regions in the world, the staurolites from the Chapada amphibolites have $X_{Mg} = 27-28.4$, higher than those in metapelites, which tipically have a X_{Mg} about 20 (Griffen and Ribbe, 1973), and are similar to those in staurolites from ortho-amphibolites, typically X_{Mg} between 27 and 39 (Helms *et al.*, 1987).

In the FeO+MnO–MgO–ZnO diagram the staurolites from the Chapada amphibolites plot in the field of staurolites from ortho-amphibolites as defined by Kuang-Yuan *et al.* (1984) while the staurolites from the Chapada metasediments plot

TABLE 1. Representative microprobe analysis of amphibole (1, 2 and 3), plagioclase (4, 5 and 6), epidote (7 and 8) and paragonite (9 and 10) from Chapada kyanite-staurolite ortho-amphibolite

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
SiO_2	42.16	41.95	41.51	60.62	60.32	57.16	37.99	38.10	43.95	42.96
Al_2O_3	17.31	15.99	17.25	25.28	27.61	29.30	27.84	27.18	40.78	39.98
TiO_2	0.46	0.53	0.46	–	–	–	0.03	0.13	0.27	0.20
FeO	14.38	15.72	15.42	0.06	0.06	–	6.58	7.43	0.71	0.95
Fe_2O_3	–	–	–	–	–	–	–			
MgO	9.81	9.75	9.14	–	–	–	0.22	0.53	0.49	0.43
CaO	10.00	10.11	10.29	6.27	7.73	7.32	23.92	23.37	1.94	1.89
Na_2O	2.81	2.45	2.80	7.56	4.06	5.61	–	–	5.97	6.39
K_2O	0.24	0.27	0.29	0.02	0.18	0.16	–	–	1.02	1.11
MnO	0.37	0.32	0.42	–	–	–	0.25	0.14	–	0.09
Total	98.06	97.09	97.58	99.81	99.96	99.55	96.83	96.88	95.13	94.00
Si	6.13	6.20	6.10	10.75	10.62	10.19	6.04	6.06	5.68	5.65
Al^{IV}	1.87	1.80	1.90	5.33	5.69	6.15	5.20	5.09	6.19	6.19
Al^{VI}	1.10	0.99	1.09	–	–	–	–	–	–	–
Ti	0.05	0.06	0.05	–	–	–	–	0.01	0.03	0.02
Fe^{2+}	1.43	1.58	1.48	0.01	0.09	–	0.86	0.99	0.08	0.10
Fe^{3+}	0.39	0.36	0.42	–	–	–	–	–	–	–
Mg	2.15	2.15	2.00	–	–	–	0.05	0.13	0.09	0.08
Ca	1.56	1.60	1.62	1.19	1.46	1.40	4.07	3.76	0.27	0.26
Na	0.28	0.21	0.28	2.60	1.38	1.93	–	–	1.51	1.61
Mn	0.05	0.04	0.05	–	0.04	–	0.03	0.02	–	0.01
K	0.04	0.05	0.05	–	0.04	0.04	–	–	0.17	0.17
Total	15.05	15.04	15.04	19.88	19.32	19.71	16.25	16.06	14.02	15.09

TABLE 2. Representative microprobe analysis for (1) Chapada staurolite (this study, average of 10 analysis) compared to staurolites from (2) New Zealand amphibolite (Gibson, 1978), (3) Dir amphibolite (Jan *et al.*, 1971), (4) Ovala amphibolite (Demange, 1976), (5) Georgia Blue Ridge amphibolite (Helms *et al.*, 1987), (6) Chapada metasediments (this study, average of 10 analyses), (7) metasediments mean (Griffen and Ribbe, 1973) and (8) New Zealand metasediments (Gibson, 1978)

Weight %	1	2	3	4	5	6	7	8
SiO_2	27.22	27.28	28.14	28.51	27.60	29.57	27.84	27.42
Al_2O_3	51.90	54.45	52.68	53.31	51.76	51.73	53.35	53.63
TiO_2	0.78	0.58	0.50	0.55	0.54	00.74	0.55	0.74
FeO	13.32	10.66	11.76	11.85	11.70	13.26	13.96	11.52
MnO	0.18	0.20	0.40	0.29	0.22	0.00	0.13	0.00
MgO	2.81	2.78	1.69	1.97	4.12	0.89	2.01	1.98
CaO	0.03	0.02	0.00	0.00	0.00	0.06	0.00	0.00
ZnO	1.09	1.00	1.40	0.86	0.28	0.47	–	2.00
Total	97.33	96.97	96.57	97.34	98.22	96.72	97.84	97.29
Si	3.84	3.78	3.89	8.04	3.78	4.31	7.73	7.65
Al	8.54	8.90	8.59	17.70	8.69	8.88	17.46	17.62
Ti	0.08	0.12	0.05	0.12	0.05	0.08	0.00	0.15
Fe	1.55	1.20	1.36	2.79	1.32	1.61	3.24	2.68
Mn	0.02	0.02	0.04	0.07	0.03	0.00	0.03	0.00
Mg	0.58	0.57	0.34	0.83	0.83	0.19	0.83	0.82
Ca	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Zn	0.11	0.10	0.14	0.15	0.03	0.05	–	0.14
Total	14.72	14.69	14.41	29.70	14.73	15.13	29.29	29.33
X_{Mg}	28.40	33.30	20.00	23.00	38.00	10.50	20.00	23.00
X_{Fe}	73.49	67.04	78.16	75.61	60.55	89.44	79.02	76.57

X_{Mg} = 100Mg/(Mg+Fe) and X_{Fe} = 100Fe/(Mg+Fe+Mn).

within the field of staurolites from regional metamorphic sedimentary rocks (Fig. 3).

Discussion

As we have already seen, X_{Mg} in the staurolites from the Chapada amphibolite ranges from 27 to 28.4. Schreyer (1988) noted that Mg-staurolite is restricted to pressure >12 kbar and is stable between 700 and 1000°C, while Fe-staurolite, as found in Chapada, is stable in a $P-T$ field bounded by near isothermal reactions between 500 and 700°C for pressure >1.5 kbar (Richardson, 1966, in Enami and Zang, 1988), but that the stability field narrows towards lower temperatures at pressure >9 kbar (Ganguly, 1972). Experimental and theoretical support for a high-pressure origin for kyanite-bearing amphibolites is given by Schreyer and Seifert (1969).

Biotite–garnet geothermometry was applied to the Chapada metasediments and it indicates a temperature of 650°C for the metamorphism of metapelites which are closely associated with the staurolite-kyanite amphibolite (Kuyumjian, 1989). The presence of kyanite suggests a minimum pressure of 6.0 kbar at 633°C, and Richardson *et al.* (1988) estimated a pressure of 9 kbar for the metamorphism at Chapada, which would place the sequence at the high-pressure end of the amphibolite facies. Therefore, the occurrence of the hornblende–staurolite–kyanite assemblage at Chapada could be related to higher-pressure metamorphism at temperatures of the amphibolite facies, and in this sense, the amphibolite did not necessarily result from unusual bulk rock composition.

Hellman and Green (1979) demonstrated that staurolite, kyanite and hornblende are stable in mafic composition at high pressures. The coexistence of staurolite–kyanite amphibolite and amphibolites with the assemblage hornblende + plagioclase + garnet + epidote in the Chapada

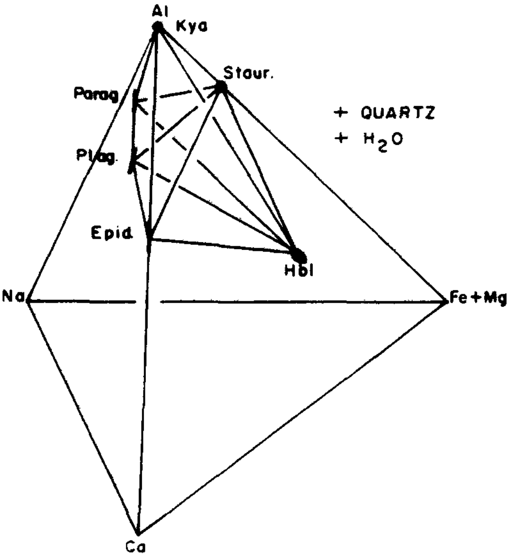

FIG. 2. Al–Ca–Na–(Fe+Mg) diagram projected from quartz + H_2O + CO_2 , showing plotting positions and ranges of compositional variability of the kyanite–staurolite ortho-amphibolite minerals from Chapada.

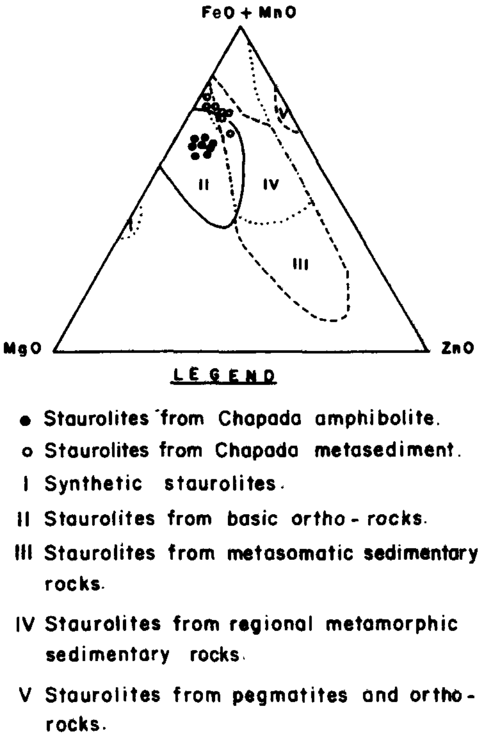

FIG. 3. Comparison of staurolites from the ortho-amphibolite with staurolites from the metasediments of Chapada area, on an FeO+MgO–MnO–ZnO diagram (after Kuang-Yuan *et al.*, 1984).

sequence is not an incompatibility. The compability of the coexistence of hornblende + garnet + epidote + plagioclase and hornblende + staurolite + kyanite assemblages for Fe-rich bulk compositions has already been shown through field and experimental work (Hellman and Green, 1979; Selverstone *et al.* 1984; Helms *et al.*, 1987). According to Helms *et al.* (1987) for relatively Fe-rich bulk compositions, hornblende + garnet+ epidote + plagioclase can occur at the same grade at which hornblende coexists with kyanite and staurolite. Therefore, the staurolite–kyanite amphibolite at Chapada may represent a facies type, and in this sense it does not reflect an unusual bulk composition.

On the other hand, and mainly because the staurolite–kyanite amphibolite is associated with hydrothermally altered rocks at Chapada, the hypothesis of hydrothermal alteration and subsequent metamorphism for the origin of this amphibolite must be also considered. The development of staurolite as a product of hydrothermal alteration and subsequent metamorphism in the staurolite–garnet amphibolites of the Ogoone series, Ovala, Gabon, has been described by Demange (1978). Beach (1973) recorded staurolite–kyanite bearing assemblages (Scourie, northwest Scotland) which formation is considered to have been associated with intense metasomatism in shear zones.

The geological sketch in Fig. 1 shows the main lithologies closely associated with the staurolite–kyanite amphibolite in the Chapada sequence. Quartz–sericite schist, kyanite-rich schist and epidote–quartz rock represent hydrothermal reaction zones, and in this case the precursor of the saturolite–kyanite amphibolite must also have been affected by hydrothermal fluids.

When compared with the least altered amphibolites from the Chapada sequence, the staurolite–kyanite amphibolite shows enrichment in Al_2O_3 and H_2O^+ (Kuyumjian, 1989). Shand (1951) and Vallance (1969) have stressed that, through the process of hydrothermal alteration, metabasic rocks may acquire a peraluminous character. According to Gelinas *et al.* (1982) what happens in this process is that the molecular proportion of Al_2O_3 exceeds the combined molecular proportion of Na_2O, K_2O and CaO. The peraluminous composition of the staurolite–kyanite amphibolite can result from calcium leaching during hydrothermal alteration prior to the amphibolite metamorphism.

Thus, the particular character of the amphibolite paragenesis focused in this paper, mainly in relation to the minerals staurolite and kyanite, can be interpreted as merely the expression of a chemistry which was special before metamorphism.

The fact that the staurolite–kyanite amphibolite occurs very closely associated with hydrothermally altered rocks at Chapada, makes the hypothesis of metamorphism of metasomatised basalts for the origin of that amphibolite more likely than considering the assemblage hornblende + staurolite + kyanite as a result of unusual physical conditions.

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